Doctoral Thesis in Industrial Ecology

Assessing circular economy progress in urban areas

An Industrial Ecology perspective

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KTH ROYAL INSTITUTE OF TECHNOLOGY

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Abstract

Rapid urbanization in recent decades, combined with unsustainable production and consumption practices rooted in the linear “take-make-use-waste” model, has transformed urban areas into global hotspots of resource consumption, waste, and emissions. As a consequence, urban areas today exert tremendous pressure on natural resources and contribute to severe environmental problems both within and beyond their boundaries. To address the challenges of unsustainable urbanization, an increasing number of local governments worldwide are embracing the circular economy (CE) concept and are actively working to develop and implement circular strategies at the urban level. In this context, it is crucial to equip local decision-makers, such as policy makers and urban planners, with effective tools to assess progress toward the CE, enabling them to design impactful strategies and monitor their implementation based on comprehensive information.

This thesis aims to advance knowledge on approaches to monitor and assess CE progress at the urban level to support informed decision-making within the CE context. To achieve this, it investigates how the indicator-based approach and urban metabolism (UM) assessment methods can be used to assess CE progress in urban areas. Specifically, the research focuses on indicator-based frameworks and two UM assessment methods: material and energy flow analysis (MEFA) and urban metabolic life cycle assessment (UM-LCA), which integrates MEFA with life cycle assessment (LCA). The aim of the thesis is addressed by answering the following research questions:

1. What is the availability of indicator-based frameworks for assessing and monitoring CE progress at the urban level, and what are their strengths and limitations?
2. What is the applicability and utility of MEFA and UM-LCA in supporting the design and monitoring of urban-level circular strategies?
3. How can the indicator-based and UM-LCA approaches be integrated to provide a comprehensive assessment of UM and circularity in urban areas, supporting decision-making within the context of the CE?

To address these research questions, a combination of methods is employed, including literature reviews, indicator-based assessments, MEFA, and UM-LCA, with the urban area of Umeå in Sweden serving as a study area. Additionally, a novel framework that integrates the indicator-based and UM-LCA approaches is developed and applied to the study area.

The results indicate that existing indicator-based frameworks have potential for monitoring and assessing CE progress at the urban level. However, they also have limitations, particularly in relation to data constraints and their scopes, which are not comprehensive enough to capture all aspects related to the CE.

Thus, relying solely on indicator-based frameworks cannot provide all the necessary information for decision-making in the CE context.

The applications of MEFA and UM-LCA to the study area demonstrate that these two methods can provide detailed quantitative information on material and energy flows and environmental impacts caused by urban areas, thus offering insights that indicators alone cannot provide. This makes them particularly useful tools for supporting the design and monitoring of circular strategies. Nevertheless, applying these methods without the use of appropriate indicators cannot fully support decision-making within the CE context, as they have limited potential to capture specific aspects of the CE, such as resource efficiency, waste management performance and governance aspects.

As the use of the indicator-based apprach and UM assessment approaches in isolation can only provide fragmented and incomplete insights, this thesis advocates for their integration. For this purpose, it introduces a novel framework that combines the UM-LCA approach with an indicator-based framework comprising 27 CE indicators. The application of the framework demonstrates its great potential to inform decision-making in the CE context by providing detailed insights into material and energy flows, environmental impacts and urban circularity. However, the proposed framework also has limitations, including complexity of application, extensive data requirements, and limited capacity to assess socio-economic aspects. Thus, further research is recommended to address these limitations.

Keywords
Circular economy; urban areas; circular strategies; indicators; indicator-based frameworks; urban metabolism; life cycle assessment; material and energy flow analysis; urban metabolic life cycle assessment

Sammanfattning

Den snabba urbaniseringen under de senaste decennierna tillsammans med ohållbars produktions- och konsumtionsmönster baserade på den linjära "ta-tillverka-använd-släng"-modellen har gjort urbana områden till globala ”hotspots” av resursförbrukning, avfall och utsläpp. Detta har lett till att dessa områden idag utgör en enorm belastning på naturresurser och bidrar till allvarliga miljöproblem både inom och utanför deras gränser. För att möta utmaningarna med ohållbar urbanisering, har ett växande antal lokala myndigheter världen över anammat konceptet cirkulär ekonomi (CE) och arbetar aktivt för att utveckla och implementera cirkulära strategier på urban nivå. I detta sammanhang är det avgörande att ge lokala beslutsfattare, såsom politiker och stadsplanerare, effektiva verktyg för att bedöma utvecklingen mot CE för att stödja dem att utforma effektfulla cirkulära strategier och följa deras genomförande baserat på heltäckande information.

Denna avhandling syftar till att främja kunskap om metoder för att övervaka och utvärdera utvecklingen mot CE i urbana områden för att stödja beslutsfattande inom CE-sammanhang. För att uppnå detta undersöker avhanlingen hur indikatorbaserade metoder och bedömningsmetoder för urban metabolism (UM) kan användas för att bedöma utvecklingen mot CE i urbana områden. Forskningsfokus ligger specifikt på indikatorbaserade ramverk och två UM-bedömningsmetoder: material- och energiflödesanalys (MEFA) och urban metabolic livscykelanalys (UM-LCA), som kombinerar MEFA med livscykelanalys (LCA). Avhandlingens syfte uppfylls genom att besvara följande forskningsfrågor:

1. Vilka indikatorbaserade ramverk finns för att bedöma och övervaka utvecklingn mot CE i urbana områden, och vilka är deras styrkor och begränsningar?
2. Vilken är användbarheten och nyttan av MEFA och UM-LCA för att stödja utformning och övervakning av cirkulära strategier i urbana områden?
3. Hur kan indikatorbaserade och UM-LCA-metoder integreras för att ge en heltäckande bedömning av UM och cirkularitet i urbana områden för att stödja beslutsfattande inom CE-sammanhang?

För att svara på dessa forskningsfrågor används en kombination av metoder, inklusive litteraturöversikter, indikatorbaserade bedömningar, MEFA och UM-LCA, med tätorten Umeå i Sverige som studieområde. Dessutom utvecklas ett nytt ramverk som integrerar de indikatorbaserade och UM-LCA metoderna och tillämpas på studieområdet.

Resultaten visar att befintliga indikatorbaserade ramverk har potential att övervaka och bedöma utvecklingen mot CE i urbana områden. Däremot har de också vissa begränsningar, särskilt vad gäller tillgång till data och dess omfattning, som inte är tillräckligt för att fånga alla aspekter relaterade till CE. Att använda enbart indikatorbaserade ramverk kan alltså inte ge all nödvändig information för beslutsfattande i CE-sammanhang.

Tillämpningarna av MEFA och UM-LCA på studieområdet visar att dessa två metoder kan ge detaljerad kvantitativ information om material- och energiflöden samt den miljöpåverkan som urbana områden orsakar, vilket ger insikter som indikatorer ensamma inte kan ge. Detta gör dem särskilt användbara verktyg för att stödja utformningen och övervakningen av cirkulära strategier. Däremot kan enbart användning av dessa metoder utan att integrera lämpliga indikatorer inte fullt ut stödja beslutsfattande inom CE-sammanhang, eftersom de har begränsad potential att fånga specifika aspekter av CE, såsom resurseffektivitet, avfallshanteringsprestanda och förvaltningsaspekter.

Således kan användningen av indikatorbaserade metoder och UM-bedömningsmetoder var för sig endast ge fragmenterade och ofullständiga insikter. För att ta itu med detta problem förespråkar denna avhandling att de integreras. Därför introducerar avhandlingen ett nytt ramverk som kombinerar UM-LCA med ett indikatorbaserat ramverk som omfattar 27 CE-indikatorer. Tillämpningen av ramverket visar dess stora potential att stödja beslutsfattande i CE-sammanhang genom att ge detaljerade insikter om material- och energiflöden, miljöpåverkan och urban cirkularitet. Det föreslagna ramverket har dock också begränsningar, såsom komplexiteten i tillämpningen, omfattande datakrav och begränsad kapacitet att bedöma socioekonomiska aspekter. Därför rekommenderas ytterligare forskning för att hantera dessa begränsningar.

Nyckelord

Cirkulär ekonomi; Urbana områden; cirkulära strategier; indikatorer; indikatorbaserade ramverk; urban metabolism; livscykelanalys; material- och energiflödesanalys; urban metabolic livscykelanalys

Preface

My research journey began in June 2018, after completing my master's thesis, when I joined the Department of Sustainable Development, Environmental Science, and Engineering (SEED) at KTH Royal Institute of Technology as a research engineer. In my first months at SEED, I focused on refining a material flow accounting model for urban areas, which I originally developed for my master’s thesis, gaining deeper understanding of the utility and challenges of urban metabolism analysis.

Following this research work, I was given the opportunity to pursue my Licentiate thesis in Industrial Ecology from 2019 to 2021. In my Licentiate, I assessed the environmental performance of emerging technologies that can be implemented in urban areas to contribute to achieving climate neutrality and sustainable urban development. Specifically, I analysed a solar microgrid and biochar systems for managing wood waste and remediating contaminated soils in urban settings. This research expanded my knowledge and practical experience in applying Industrial Ecology tools, such as Material and Energy Flow Analysis and Life Cycle Assessment, in conducting environmental assessments. It also made me realize that beyond technological solutions, a fundamental paradigm shift in the current way urban areas are developed is crucial for achieving sustainable urban development. This insight sparked my interest in circular economy (CE) as a promising approach to enable this shift.

This interest motivated me to embark on a PhD focusing on the implementation of the CE at the urban level. I began this journey as a full-time PhD student from 2021 to 2023 and continued as a part-time student thereafter. The research work was carried out within the context of two research projects: the “Urban Circularity Assessment Framework” project, funded by Sweden’s innovation agency (Vinnova), and the “Quantifying future worlds” project, funded by the Swedish Research Council (Formas).

The “Urban Circularity Assessment Framework” project aimed to support urban areas in becoming more circular by developing and applying a framework to assess circularity level in urban areas. The project involved collaboration among researchers from KTH and the Stockholm Environment Institute, private sector actors and Umeå municipality. Papers I and II of this thesis contributed to the project by offering insights into available indicator-based frameworks for monitoring and evaluating circularity in urban areas.

The “Quantifying future worlds” project aimed to develop and implement a systematic approach for applying future scenarios to prospective life cycle environmental assessments. This project was conducted by researchers at KTH. Papers III-V of this thesis contributed to the project’s objective to quantitatively assess various policy measures under different possible futures. Paper III provided the necessary data for constructing future scenarios encompassing different circular strategies for urban areas, Papers IV quantitatively assessed environmental impacts associated with these scenarios and Paper V integrated a future-oriented approach to evaluate the environmental performance of circular strategies within a comprehensive assessment framework.

Overall, while this thesis is based on the five papers produced during my PhD, it also reflects knowledge, insights and practical experience gained throughout my entire research journey at SEED. I sincerely hope that the work presented in the thesis will contribute to advancing knowledge on approaches to assess CE progress in urban areas and inspire further research and development in the field of Industrial Ecology.

Acknowledgments

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I would also like to express my gratitude to the former co-supervisor for my Licentiate thesis, Assoc. Prof. Maria E. Malmström as well as to Professor Göran Finnveden for their interest in helping me continue my research journey towards a PhD, after the completion of my Licentiate thesis.

I am very thankful to the KTH internal quality reviewer, Assoc. Professor Dilip Khatiwada, for taking the time to review my PhD thesis and offering valuable comments and suggestions that greatly enhanced its quality.

I would like to extend my thanks to the co-authors of the appended papers: Maryna Henrysson, Cali Nuur, Cecilia Sundberg, Fedra Vanhuyse, Maria Livia Real de Almeida and Bernhard Steubing. A special thanks to Dr. Maryna Henrysson for our excellent collaboration in Papers I and II, as well as for the all the engaging discussions during the first years of my PhD. I am also deeply grateful to Prof. Bernhard Steubing for providing the prospective Life Cycle Inventory databases in Paper IV. Without your help, the prospective assessment presented in this paper would not have been possible.

A big thank you to all my colleagues and staff at SEED for creating a welcoming and supportive working environment during my time at the department.

I am deeply thankful to my family and all my dear friends in Greece and Sweden for their love and support.

Last but not least, I would like to thank the two loves of my life, my wife Jenny and my daughter Vicky, for their unconditional love and for their patience and support all these years. This thesis is dedicated to you.

Stockholm, May 2025

Asterios Papageorgiou

List of publications

Paper I

Papageorgiou, A., Henrysson, M., Nuur, C., Sinha, R., Sundberg, C., & Vanhuyse, F. (2021). Mapping and assessing indicator-based frameworks for monitoring circular economy development at the city-level. *Sustainable Cities and Society*, 75, 103378. https://doi.org/10.1016/J.SCS.2021.103378

> **Author contribution**: The author of the thesis led the authorship of this paper collaboratively with co-author M. Henrysson. This includes leading the conceptualization, design of methodology, investigation, formal analysis, visualization and writing of the original draft. All co-authors supported the conceptualisation and contributed to writing and revising the paper.

Paper II

Henrysson, M., **Papageorgiou, A.**, Björklund, A., Vanhuyse, F., Sinha, R. (2022). Monitoring progress towards a circular economy in urban areas: An application of the European Union circular economy monitoring framework in Umeå municipality. *Sustainable Cities and Society*, 87, 104245. https://doi.org/10.1016/j.scs.2022.104245

> **Author contribution**: The author of the thesis led the authorship of this paper collaboratively with co-author M. Henrysson. This includes leading the conceptualization, design of methodology, investigation, formal analysis, visualization and writing of the original draft. All co-authors supported the conceptualisation and contributed to writing and revising the paper.

Paper III

Papageorgiou, A., Björklund, A., Sinha, R., 2024. Applying material and energy flow analysis to assess urban metabolism in the context of the circular economy. *Journal of Industrial Ecology*, 28, 885–900. https://doi.org//10.1111/jiec.13504

> **Author contribution**: The author of the thesis led the authorship of this paper. This includes leading the conceptualization, design of methodology, investigation, formal analysis, visualization and writing of the original draft. Co-authors A. Björklund and R. Sinha supported the conceptualisation and methodology and contributed to writing and revising the paper.

Paper IV

Papageorgiou, A., Björklund, A., Sinha, R., de Almeida, M.L.R., Steubing, B. (2024). Coupling material and energy flow analysis with life cycle assessment to support circular strategies at the urban level. International Journal of Life Cycle Assess 29, 1209–1228. https://doi.org/10.1007/s11367-024-02320-y

> **Author contribution**: The author of the thesis led the authorship of this paper. This includes leading the conceptualization, design of methodology, investigation, formal analysis, visualization and writing of the original draft. Co-author B. Steubing provided the prospective life cycle inventory databases. Co-authors A. Björklund and R. Sinha supported the conceptualisation and methodology. All co-authors contributed to writing and revising the paper.

Paper V

Papageorgiou, A., Björklund, A., Sinha, R. (2025). A novel assessment framework for circular urban areas with its application to a Swedish municipality. (*Under revision for the journal of Sustainable Production and Consumption*)

> **Author contribution**: The author of the thesis led the authorship of this paper. This includes leading the conceptualization, design of methodology, investigation, formal analysis, visualization and writing of the original draft. Co-authors A. Björklund and R. Sinha supported the conceptualisation and methodology and contributed to writing and revising the paper.

Scientific papers not included in the thesis

Papageorgiou, A., Azzi, E.S., Enell, A. & Sundberg, C. 2021. Biochar produced from wood waste for soil remediation in Sweden: Carbon sequestration and other environmental impacts. *Science of the Total Environment*, 776, https://doi.org/10.1016/j.scitotenv.2021.145953

Papageorgiou, A., Ashok, A., E.S., Farzad, T.H. & Sundberg, C. 2020. Climate change impact of integrating a solar microgrid system into the Swedish electricity grid. *Applied Energy*, 268, 114981. https://doi.org/10.1016/j.apenergy.2020.114981

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Papageorgiou A., Karagiannidis A., Barton J.R. and Kalogirou E., 2009. Municipal solid waste management scenarios for Attica and their greenhouse gas emission impact. *Waste Management and Research*. 27(9), 928-937. https://doi.org/10.1177/0734242X09350787

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Licentiate thesis

Papageorgiou, A. (2020). *Emerging technologies for climate-neutral urban areas - An Industrial Ecology perspective*. KTH Royal Institute of Technology, Stockholm, Sweden. https://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1543263&dswid=-1470

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List of abbreviations

BS	Background scenarios
CA	Circularity assessment
CDW	Construction and demolition waste
CEMF	Circular Economy Monitoring Framework
EC	European Commission
EMAF	Ellen MacArthur Foundation
FS	Foreground scenarios
IE	Industrial Ecology
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MFA	Material Flow Analysis
MEFA	Material and Energy Flow Analysis
MSW	Municipal Solid Waste
pLCA	Prospective Life Cycle Assessment
pLCI	Prospective Life Cycle Inventory
pMEFA	Prospective Material and Energy Flow Analysis
pUM-LCA	Prospective urban metabolic life cycle assessment
rMEFA	Retrospective Material and Energy Flow Analysis
rUM-LCA	Retrospective urban metabolic life cycle assessment
SFA	Substance Flow Analysis
sLCA	Social LCA
UM	Urban metabolism
UM-LCA	Urban metabolic life cycle assessment
WCED	World Commission on Environment and Development

Glossary

Circular strategy - a set of policies, targets and measures aimed at advancing the CE within a system.

Indicator - a single variable that is applied to assess progress or changes in relation to an intended outcome.

Indicator-based framework - a curated collection of single indicators that have a broader scope aiming to capture multiple aspects.

Index - an aggregation of multiple individual indicators into a single composite score following a predefined methodology.

Life Cycle Assessment (LCA) - an analytical method that aims to assess the potential environmental impacts of a product or system from cradle to grave, i.e., from raw material extraction to production, use and end of life.

Metric - a quantitative measure of a phenomenon, encompassing indicators, indices, indicator-based frameworks and other assessment tools.

Material and Enegry Flow Analayis (MEFA) - a systematic method for assessing the state and changes of material and energy flows and stocks in a spatially defined system over a specified timeframe.

Urban metabolism (UM) - a metaphorical concept that describes an urban area as a living organism or natural ecosystem that exchanges matter and energy with its environment to sustain its functions and growth.

Urban metabolic life cycle assessment (UM-LCA) - An approach that integrates MEFA with LCA under an UM perspective to assess the environmental impacts associated with the flows of materials and energy used by the urban system

1. Introduction

1.1 Background

Rapid urbanization in the last decades has led to the concentration of human activity in cities and other urban settlements, henceforth referred to as urban areas (Levoso et al., 2020). Today, urban areas host more than half of global population, approximately 4.4 billion people, and generate about 80% of global gross domestic product, even though they occupy only 2-3% of the global land area (Paiho et al., 2020; UN-Habitat, 2022). This urbanization trend is expected to continue in the coming decades, with projections indicating that the population of urban dwellers will exceed 6.5 billion by 2050, raising the global share of people living in urban areas to nearly 70% (United Nations, Department of Economic and Social Affairs, Population Division, 2019).

The rapid growth of urban populations, coupled with unsustainable production and consumption practices rooted in the linear “take-make-use-waste” paradigm, has turned urban areas into hotspots of resource consumption, waste and emissions (Campbell-Johnston et al., 2019; Fernandes & Ferrão, 2023). Urban areas today account for about three quarters of global resource use, GHG emissions and solid waste generation (Campbell-Johnston et al., 2019; Paiho et al., 2020), contributing to severe environmental problems at local, regional and global scales, including air and water pollution, global warming and ecosystems degradation (Bai, 2007; Satterthwaite, 2011). As such, they are often seen as the root of many (un)sustainability challenges (Nevens & Roorda, 2014).

In this context, the Circular Economy (CE) concept has gained attention in the past two decades as a potential solution to the challenges of unsustainable urbanization (Gravagnuolo et al., 2019; Petit-Boix et al., 2022). The CE is an umbrella concept encompassing a range of principles and system-wide innovations that aim to increase resource efficiency, maintain resource value, minimize waste and emissions, and build environmental, social and economic capital (Blomsma & Brennan, 2017; Kristensen & Mosgaard, 2020; Voulvoulis, 2022). Despite critiques concerning its definitional vagueness, unclear theoretical foundations and implementation difficulties (Corvellec et al., 2022), the CE is widely seen as a promising development model that can be implemented at the micro (products, consumers, companies), meso (eco-industrial parks) and macro (cities, regions, countries) levels to advance sustainable development (Abunyewah et al., 2023; Kirchherr et al., 2017).

Recognizing the benefits and opportunities of the CE, local governments worldwide have made CE a political priority and are actively developing or implementing circular strategies, i.e., sets of policies, measures and targets to advance the CE at the urban level (Kopp et al., 2024; Vanhuyse et al., 2021). In this context, it is increasingly important to provide local decision-makers (e.g., policy makers, urban planners) with the necessary information to design effective strategies and monitor their progress. For instance, at the early design phase of a strategy, detailed data on resource and waste flows can help appraise the level of CE development in the urban area (referred to as circularity level), identify priority areas and set benchmarks (Paiho et al., 2020; Petit-Boix et al., 2022; Saidani et al., 2019). Moreover, insights into the potential environmental impacts of various future strategies at this stage can guide the selection of the most environmentally beneficial options (Kravchenko et al., 2019). During the implementation phase, information on resource use, waste and environmental impacts can help decision-makers evaluate the progress of implemented strategies and make necessary adjustments (Paiho et al., 2020).

A commonly used approach to inform decision-making in the CE context is to use single indicators, indices (i.e., aggregated indicators) and indicator-based frameworks (i.e., curated collections of single indicators) to assess and monitor circularity across all system levels, including the urban level (Brändström & Eriksson, 2022; Purvis & Genovese, 2023). This approach, referred to as the indicator-based approach, is particularly effective for summarizing and conveying complex information in a simplified yet meaningful way (Singh et al., 2012; Tapia et al., 2021). As such, it can contribute to a better understanding of the CE, facilitating informed decision-making (Parchomenko et al., 2019; Saidani et al., 2019).

Among the different types of indicator tools, indicator-based frameworks offer the advantage of capturing various CE aspects, enabling more comprehensive assessments compared to single indicators and indices, which typically focus only on one aspect (EC, 2018a). However, while some studies (Fusco Girard & Nocca, 2019; Kopp et al., 2024; OECD, 2021; Paoli et al., 2022; Superti et al., 2021) have investigated the availability and utility of single indicators and indices at the urban level, there has been limited research on the availability, strengths and limitations of indicator-based frameworks for evaluating and monitoring urban circularity. This is the first research gap that this thesis attempts to address, seeking to increase the understanding of how existing indicator-based frameworks can support decision-makers in their efforts to advance the CE at the urban level.

While the indicator-based approach has gained prominence in CE research and practice in recent years, it has been also subject of critiques due to its limitations. A key limitation highlighted in the literature (Gasparatos et al., 2008; Purvis & Genovese, 2023) is that it is inherently reductionist due to its focus on simplifying complex information. This reductionism limits its ability to fully capture the complexities and potential trade-offs of transitioning towards a CE (Harris et al., 2021; Purvis & Genovese, 2023). To address this limitation, alternative assessment approaches, which could be used independently or in tandem with the indicator-based approach, have been proposed in the literature.

One such alternative is the use of urban metabolism (UM) assessment methods (Kalmykova & Rosado, 2015; Kopp et al., 2024; Petit-Boix et al., 2022).

The UM is a metaphorical concept that represents an urban area as a living organism or natural ecosystem that exchanges matter and energy with its environment to sustain its functions and growth (Céspedes Restrepo & Morales-Pinzón, 2018; Kennedy et al., 2007). Over the past 25 years, UM has evolved as an approach to study urban areas based on a rich toolbox of quantitative methods, providing insights into their resource demands and environmental sustainability (Beloin-Saint-Pierre et al., 2017; Pincetl et al., 2012). Two widely used UM assessment methods are Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) (Beloin-Saint-Pierre et al., 2017; X. Wang et al., 2023).

MFA is a systematic method to track and quantify material flows and stocks within a system defined by specific spatial and temporal boundaries (Brunner & Rechberger, 2017). It is a versatile method that can be applied to a wide range of systems, including industrial, urban, national and global systems, using different units of analysis (e.g., goods, substances). The scope of MFA is often expanded to also include energy flows, a method known as material and energy flow analysis (MEFA) (Derrible et al., 2021). By analyzing material and energy flows together, MEFA provides a more comprehensive perspective on UM, enhancing the understanding of how the urban system interacts with the environment (Hoekman & Bellstedt, 2020). This broader perspective could make MEFA a potentially valuable decision support tool in the CE context.

MEFA can be applied for UM analysis following either a top-down or bottom-up approach (Derrible et al., 2021). The former analyzes the total flows and stocks of the urban system without necessarily considering its internal components (or sectors), while the latter accounts for flows and stocks within individual sectors, which are then aggregated for the entire system (Augiseau & Barles, 2017; Loiseau et al., 2012; X. Wang et al., 2020). The bottom-up approach, therefore, can offer a more in-depth analysis, shedding light on the internal processes of UM (X. Wang et al., 2023). However, the potential of applying MEFA with a bottom-up approach to inform decision-making in the CE context remains poorly understood, as no prior study has specifically explored this aspect.

LCA is another method that has been used in UM studies. It is a standardized method used to evaluate the environmental impacts of products, processes, or large-scale systems, including urban systems, from a life-cycle perspective (Finnveden et al., 2009; Loiseau et al., 2018). For urban areas, LCA can be coupled with MEFA under an UM perspective, in an approach known as urban metabolic life cycle assessment (UM-LCA) (Goldstein et al., 2013). The main advantage of this approach is its ability to assess environmental impacts embodied in material and energy flows, something that MEFA alone cannot achieve (García-Guaita et al., 2018; Goldstein et al., 2013). This makes UM-LCA a powerful tool for conducting environmental assessments of urban systems, as demonstrated by previous studies (Dias et al., 2018; García-Guaita et al., 2018; Goldstein et al., 2013; González-García & Dias, 2019; Rama et al., 2021).

This capacity of UM-LCA to provide detailed, quantitative information on urban flows and their associated environmental impacts could make it a potentially valuable decision-support tool in the CE context. UM-LCA can be applied retrospectively to assess the environmental profile of an urban area, providing insights that could guide the design of new circular strategies and evaluation of existing ones. It can also be applied prospectively, based on future scenarios, to assess the potential environmental impacts of future circular strategies, helping to identify the most environmentally sound options. Nevertheless, no study to date has fully explored how the UM-LCA approach can be applied for both retrospective and prospective assessments to inform the design and evaluation of urban-level circular strategies.

Considering the above, the second research gap that this thesis attempts to address is the limited understanding of the applicability and utility of MEFA and UM-LCA as decision-support tools within the CE context.

Furthermore, there is limited understanding of how the UM-LCA approach can be integrated with the indicator-based approach. This integration could help evaluate urban circularity while also providing deeper insights into how urban areas metabolize resources and exert environmental pressures, and it has been proposed in the literature (Kopp et al., 2024; Purvis & Genovese, 2023; Walzberg et al., 2021) as a way to enable more comprehensive assessments in the CE context. However, no prior study has yet explored how this integration can be effectively implemented and how it can support decision-making in advancing the CE in urban areas. This is the third research gap that this thesis seeks to address.

In summary, this thesis seeks to address the following three research gaps: i) the lack of knowledge about the availability, strengths and limitations of existing indicator-based frameworks for assessing and monitoring circularity at the urban-level, ii) the limited understanding of the applicability and utility of two specific UM assessment methods, MEFA and UM-LCA, as decision-support tools in context of the CE, iii) the lack of understanding of how the indicator-based and UM-LCA approaches can be effectively integrated to support decision-making within the CE. Addressing these research gaps is crucial for advancing knowledge on approaches to monitor and assess CE progress at the urban level, which is essential for enabling informed decision-making in the CE context. This thesis addresses these three research gaps by pursuing the aim and answering the research questions outlined in the next section.

1.2 Aim of the thesis and research questions

The overall aim of this thesis is to advance knowledge on approaches to monitor and assess CE progress at the urban level to support informed decision-making within the context of the CE. This includes investigating how indicator-based frameworks and specific UM assessment methods, i.e., MEFA and UM-LCA, can be used to assess the level of circularity in urban areas and guide the design and implementation of urban-level circular strategies.

To achieve the stated aim, the following research questions (RQs) are addressed in the thesis:

> **RQ1:** What is the availability of indicator-based frameworks for assessing and monitoring CE progress at the urban level, and what are their strengths and limitations? (**Paper I** and **II**)
>
> **RQ2:** What is the applicability and utility of MEFA and UM-LCA in supporting the design and monitoring of urban-level circular strategies? (**Paper III** and **IV**)
>
> **RQ3:** How can the indicator-based and UM-LCA approaches be integrated to provide a comprehensive assessment of UM and circularity in urban areas, supporting decision-making within the context of the CE? (**Paper V**)

The three RQs are addressed through the five papers appended to this thesis. For **Papers II-V**, the urban area of Umeå, in northern Sweden, was used as the study area for applying the methods and approaches explored in this thesis. Figure 1 provides an overview of how each paper relates to the RQs. **Papers I** and **II** contribute to address RQ1. **Paper I** maps and assesses existing indicator-based frameworks through a literature review, while **Paper II** applies to Umeå one of the frameworks identified in **Paper I**, offering empirical insights into its strengths and weaknesses. **Papers III** and **IV** address RQ2. **Paper III** applies MEFA to analyze Umeå's UM, and **Paper IV** applies the UM-LCA approach to retrospectively assess Umeå's environmental performance and to prospectively assess the environmental impacts of different future circular strategies. Through these applications, the two papers shed light into the applicability and utility of MEFA and UM-LCA in designing and monitoring urban-level circular strategies. Building on insights from **Papers I-IV** and data from **Papers III** and **IV**, **Paper V** addresses RQ3 by introducing a novel framework that integrates the indicator-based and UM-LCA approaches. The paper also demonstrates the applicability of the framework and examines its strengths and weaknesses as a decision support tool in the CE context, through its implementation in Umeå.

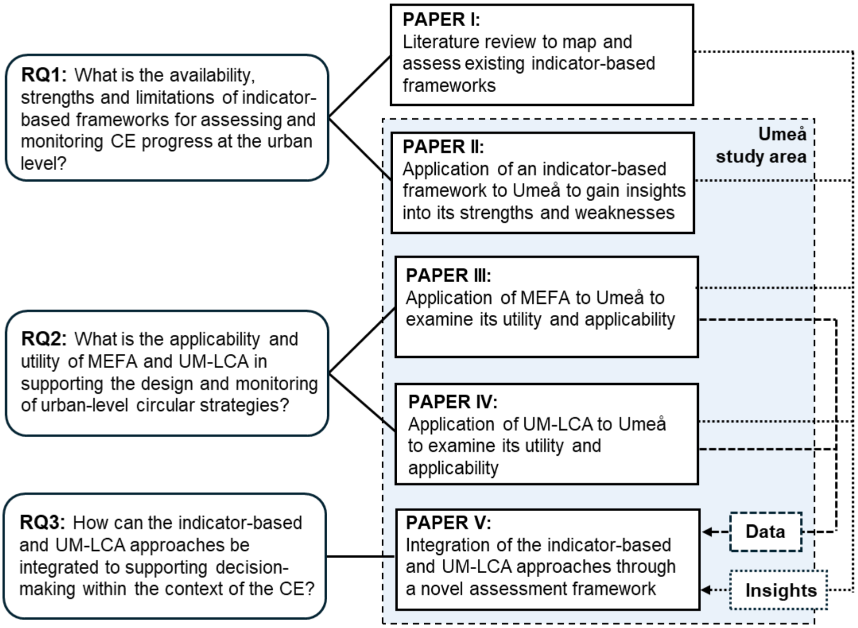

Figure 1: The logical structure of the thesis.

1.3 Scope

This thesis explores the potential of using the indicator-based approach and UM assessment methods, either separately or in combination, to support informed decision-making within the context of the CE. Among the various types of indicator tools, the focus is on indicator-based frameworks. The main reason for focusing on indicator-based frameworks is that they are seen as more effective for monitoring and assessing circularity than single indicators and indices, as they provide a broader scope for analyzing multiple CE aspects. Regarding UM assessment methods, the thesis focuses on MEFA and UM-LCA. The rationale for choosing these two methods among the wide range of UM assessment methods (see Section 2.4.1) is their potential to facilitate a bottom-up approach to modeling urban systems, which enables a more in-depth analysis of UM, offering enhanced insights for decision-making.

Umeå serves as the case study area for Papers **II**-**V**. Umeå is a rapidly growing, medium-sized urban area, where the local government (municipal council) is actively working to promote the CE model (see Section 3.1.1). This makes it an ideal study setting for exploring how the methods and approaches examined in the papers can provide meaningful insights to support decision-making. Moreover, using Umeå as a single study area provides a consistent study setting for investigating the strengths, weaknesses and application challenges of the investigated methods and approaches. Nevertheless, due to the use of a single study setting, some of the findings of the thesis may be limited to the specific context of Umeå, including its demographics, socio-economic conditions and climate (see further discussion in Section 5.3).

In Papers **II**-**V**, the spatial boundary of the urban area was assumed to align with the administrative boundaries of Umeå municipality, even though the urbanized area occupies only a small fraction of the total municipal area (see Section 3.1.1). This assumption was based on three factors: i) the majority of Umeå's population (about 90%) resides within the urbanized area (SCB, 2025b), ii) most of the available data are reported at the municipal level, iii) this spatial boundary can simplify the implementation of measures based on the assessment results, as political and administrative stakeholders can more easily carry them out within their respective administrative areas (Brunner and Rechberger, 2017).

As regards the temporal scope, the timeframes of the assessments in Papers **II**-**V** varied due to differences in objectives, data availability, study timing and practical constraints, as explained in Sections 3.2.2-3.2.5. In Papers **II** and **III**, the assessments were retrospective, while Papers **IV** and **V** included both retrospective and prospective short-term assessments. The time resolutions of the assessments were annual, as more granular data (e.g., monthly) that would allow more refined analyses were unavailable. Nonetheless, even with an annual resolution, it was still possible to identify trends (e.g., in material and energy flows, recycling rates) and observe temporary effects on the overall results, such as notable fluctuations in material consumption driven by varying levels of construction activity (see Section 4.2 and Paper **III**).

1.4 Outline of the thesis

This thesis comprises this cover essay and the five appended papers. Chapter 1 of the cover essay (this chapter) introduces the overall context of the thesis and outlines the research aim and questions. Chapter 2 presents the theoretical background, including key terms, concepts, methods and approaches relevant to the thesis. Chapter 3 explains the research design and provides an overview of the methods and approaches used in the appended papers. Chapter 4 discusses the main results of the papers in relation to the research questions. Chapter 5 provides a broader discussion of the key findings, highlights the contributions and limitations of the thesis, and suggests directions for future research. Lastly, Chapter 6 presents the conclusions of the thesis.

2. Theoretical background

This chapter lays the theoretical foundation of the thesis, providing details about the research background and explaining the key terms, concepts, methods and approaches that are essential for understanding themes explored in the thesis.

2.1 Sustainable urban development

The concept of sustainable development gained widespread attention in 1987 with the release of the report *Our Common Future* by the UN's World Commission on Environment and Development (WCED), commonly known as the Brundtland Commission. This seminal report highlighted the connection between human activities and escalating environmental degradation, calling for an alternative development model, one that balances environmental protection with social and economic progress (Spiliotopoulou & Roseland, 2020). It introduced this model as sustainable development, defining it as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987).

Since the publication of the Brundtland report, the concept of sustainable development has been widely embraced by governments, organizations, civil society and businesses worldwide (Drexhage & Murphy, 2010), becoming a central element in policy agendas and academic research (Moldan et al., 2012). However, despite its broad acceptance, sustainable development has remained conceptually ambiguous, being intentionally vague from the outset and open to diverse interpretations (Koglin, 2009; Spiliotopoulou & Roseland, 2020). This ambiguity is reflected in the common tendency to use the terms "sustainable development" and "sustainability" interchangeably, despite their semantic differences: sustainability represents the desired outcome, while sustainable development is the process of achieving it (Korhonen, 2004; Robèrt, 2000).

Although sustainable development remains a widely debated and evolving concept, its conceptualization based on three-pillars–environmental, social and economic–has emerged as the dominant approach to describe it (Purvis et al., 2019; Ruggerio, 2021). This tripartite model is often depicted with three overlapping circles representing the three pillars, with sustainable development located at their intersection. While widely adopted, this three-pillar model is not universal (Purvis et al., 2019), with some scholars proposing additional pillars, including governance (also referred to as institutional) (Chao et al., 2020; Spangenberg, 2004; Waas et al., 2011) and culture (Soini & Birkeland, 2014). Furthermore, it has faced criticism for lacking a rigorous theoretical foundation (Purvis et al., 2019) and for reinforcing the prevailing global economic paradigm, which prioritizes economic growth without considering environmental limits (Gómez-Baggethun & Naredo, 2015; Robinson, 2004).

Nevertheless, its simplicity and ease of communication have made it appealing to diverse audiences and applicable in different contexts (Geissdoerfer et al., 2017; McCormick et al., 2013). As a result, it has been embedded into key political, business and other strategic documents (Moldan et al., 2012), such as the 2030 Agenda for Sustainable Development (UN, 2015).

The 2030 Agenda, unanimously adopted by the UN member states in September 2015, established the 17 Sustainable Development Goals (SDGs) along with 169 associated targets. The SDGs are grounded in the three-pillar model of sustainable development, as noted in the 2030 Agenda (UN, 2015; p.1): "*they are integrated and indivisible and balance the three dimensions of sustainable development: the economic, social and environmental*". These 17 goals embody an integrated approach to achieving sustainable development by fostering actions across a wide range of interconnected key areas (Le Blanc, 2015). One of the goals, SDG 11, explicitly focuses on cities, or more broadly, urban areas.

In general, there is no unified approach to defining urban areas, and definitions vary significantly across local or national contexts and research disciplines (Lutzkendorf & Balouktsi, 2019). In this thesis, an urban area is seen as "*a human settlement characterized – economically, politically and culturally – by a significant infrastructural base; a high density of population, whether it be as denizens, working people, or transitory visitors; and what is perceived to be a large proportion of constructed surface area relative to the rest of the region*" (James, 2014, p.26). According to James, an urban area can also include smaller non-built-up zones used for recreation, agriculture and waste disposal.

Urban areas today are centres of global economic activity and are home to over half of the world's population, a share projected to rise to nearly two-thirds by the mid-century (United Nations, Department of Economic and Social Affairs, Population Division, 2019). This growing concentration of human activity in urban areas brings with it numerous sustainability challenges (Alizadeh et al., 2024). Urbanization is a major driver of rising resource consumption, waste generation and emissions (Campbell-Johnston et al., 2019; Levoso et al., 2020), contributing to unsustainable environmental changes at local, regional and global scales (Bai, 2007; Satterthwaite, 2011). At the same time, it contributes to a wide range of socio-economic challenges, including concentrations of poverty and inequalities, segregation, safety concerns and tensions between different groups (McCormick et al., 2013; Opschoor, 2011).

Nonetheless, urban areas are not only the origin of many of today's sustainability challenges but also key locations for addressing them (Levoso et al., 2020; Nevens & Roorda, 2014). As centers of economic growth, knowledge and innovation, they possess the required resources and tools to respond to pressing sustainability problems (Johnson et al., 2011; Mi et al., 2019). Moreover, the concentration of human activity and resource use in urban areas makes them the optimal scale for fostering individual behavioral changes (Nevens & Roorda, 2014) and promoting integrated solutions and efficiency improvements (McCormick et al., 2013), such as realizing economies of scale in energy supply, public transport and waste management (EEA, 2015).

Thus, urban areas have a critical role in advancing sustainable development, as on the one hand contribute to a wide range of sustainability challenges, while on the other, they serve as ideal settings for developing solutions to these challenges (Grimm et al., 2008; Johnson et al., 2011). Their importance has been emphasized in key policy documents and frameworks, such as the New Urban Agenda (UN-Habitat, 2020) and the abovementioned SDGs framework (Sharifi, 2021). Within the SDGs framework, SDG 11 explicitly aims to "*make cities and human settlements inclusive, safe, resilient, and sustainable*" (UN 2015, p.14). It encompasses 10 targets and 15 indicators that address multiple issues related to urban areas, including transport, housing, environment and governance, providing a roadmap towards sustainable urban development. Beyond SDG 11, the cross-cutting nature of urban issues makes many other targets and indicators in other SDGs also highly relevant (Marvuglia et al., 2020; Zhou et al., 2022). This is exemplified by Kolada, Sweden's open data platform for municipal and regional statistics, which includes indicators to track progress on all SDGs except SDG 17 at the local level (Kolada, 2025).

Despite the increasing emphasis on sustainable urban development, a universal definition has not yet been established, and like the concepts of sustainability and sustainable development, its definitions and interpretations vary (Tatham et al., 2014). In this thesis, no specific definition of sustainable urban development is adopted. Instead, it is viewed as urban development that is aligned with the Brundtland definition and balances environmental protection with social and economic progress. Moreover, governance is regarded as the fourth pillar of sustainable urban development, given its crucial role to achieving this balance (Spangenberg, 2004; Waas et al., 2011).

Achieving sustainable urban development necessitates a shift from traditional urban development models to more sustainable alternatives (Spiliotopoulou & Roseland, 2020; Zou & Zhao, 2023). Among the numerous urban development models proposed in the literature (for reviews see de Jong et al., 2015; Zou & Zhao, 2023), the CE has gained significant traction over the past 15-20 years (Kopp et al., 2024; Petit-Boix & Leipold, 2018). The following section delves into the CE model and its implementation at the urban level.

2.2 Circular economy in urban areas

2.2.1 The circular economy concept and its principles

The concept of the CE originates in diverse academic fields, including industrial ecology (IE), ecological economics, general systems theory and systems ecology (Ghisellini et al., 2016; Velenturf & Purnell, 2021). Its theoretical roots can be traced back to ideas introduced decades ago, such as the "spaceship economy" (Boulding, 1966), the irreversible degradation of natural resources when used for economic activity (Georgescu-Roegen, 1971), the limits to growth (Meadows et al., 1972), the closed-loop economy (Stahel, W.R., Reday, 1976), and industrial ecosystems (Frosch & Gallopoulos, 1989). However, the formal introduction of the CE concept is attributed by some scholars (Ghisellini et al., 2016; Su et al., 2013) to Pearce & Turner (1989), who used the term CE to describe an alternative to the linear and open-ended contemporary economic system (Geissdoerfer et al., 2017). As the concept evolved through the years, it became interwoven with several related concepts, including the regenerative design (Lyle, J.T, 1996), industrial symbiosis (Chertow, 2000), "cradle to cradle" design (McDonough & Braungart., 2002), performance economy (Stahel, W.R., 2010) and blue economy (Pauli, 2010).

Although the theoretical foundations of the CE are not new, the concept has gained prominence within the last two decades as a response to the linear “take–make–use–waste” model that has long dominated the global economic system (Chizaryfard et al., 2020). As noted in the literature (Korhonen, Honkasalo, et al., 2018; Voulvoulis, 2022), this linear model is unsustainable, being characterized by mass production and consumption, planned obsolescence and a throw-away culture, resulting in unprecedented resource consumption and severe environmental harm. In contrast, CE promotes the responsible and cyclical use of resources to retain their value within the economy as much as possible aiming to decouple prosperity from environmental degradation (Corona et al., 2019; Moraga et al., 2019; Petit-Boix & Leipold, 2018).

Inspired by this potential, the academic community, companies, and policy makers worldwide, primarily in the Global North and China, have embraced the CE concept (Haswell et al., 2024). Academic research in CE has become a burgeoning field with a significant rise in the number of published articles in recent years (Geissdoerfer et al., 2017; Kirchherr et al., 2023). Companies have developed new business models based on CE principles, aspiring to increase value creation while reducing social and environmental costs (Geissdoerfer et al., 2020; Rashid et al., 2013). In the policy arena, CE has become a key priority, with policy makers introducing CE-related policies both nationally and internationally (Fratini et al., 2019). For example, the Chinese central government designated CE as a national priority in 2003 and passed the Circular Economy Promotion Law in 2008 (Geng et al., 2012), and the European Commission (EC) has introduced several CE-related policies, like the Circular Economy Action Plan (EC, 2020). In this landscape, advocacy organizations like the Ellen MacArthur Foundation (EMAF) have been instrumental in catalyzing the growing momentum of the CE (Vann Yaroson, 2024).

Despite the broad adoption of the CE, a single consensus definition of the concept is still lacking. In a recent literature review, Kirchherr et al. (2023) emphasized the increasing diversity in CE definitions, revealing that 221 different definitions of CE have emerged since 2017, when an earlier study (Kirchherr et al., 2017) identified 114 definitions up to that point. According to the authors, this divergence may result in conceptual contestation and ambiguity, potentially resulting in a conceptual deadlock and eventual collapse.

Furthermore, there is no consensus on the conceptualization of CE principles, i.e., rules that explain how the CE operates (Suárez-Eiroa et al., 2019). As shown in Table 1, multiple conceptualizations of CE principles have been proposed in the literature, with the R-principles being probably the most well-known. For the R-principles, Reike et al. (2018) highlighted the variability in how they have been conceptualized across literature, noting varying numbers of the R-imperatives, ranging from 3Rs to 10Rs (see Table 1). They also observed that different scholars attribute different meanings and characteristics to these principles, contributing to the confusion surrounding CE.

Table 1 - Different conceptualizations of CE principles in the literature.

	Description	**Source**
R-principles		
3Rs	Reduce, Reuse, Recycle	Lieder & Rashid (2016)
4Rs	Reduce, Reuse, Recycle, Recover	Kirchherr et al. (2017)
5Rs	Rethink, Reduce, Reuse, Recycle, Repair	Li (2011)
6Rs	Reduce, Reuse, Recycle, Recover, Remanufacture, Redesign	Yan & Feng (2014)
7Rs	Reduce, Reuse, Recycle, Recover, Rethink, Resilient, Regulate	Xing et al. (2017)
8Rs	Rethink, Redesign, Reduce, Re-use, Return, Repair, Recycle/recover, Refuse	Maia et al. (2019)
9Rs	Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	van Buren et al. (2016)
10Rs	Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Potting et al. (2017)
Other CE principles		
	1) Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows, 2) Optimize resource yields by circulating products, components and materials in use at the highest utility at all times in both technical and biological cycles, 3) Foster system effectiveness by revealing and designing out negative externalities	EMAF (2015b)
	1) Narrowing loops, 2) Slowing loops, 3) Closing loops	Bocken et al. (2016)
	1) Reduction, 2) Reuse, 3) Recycle, 4) Appropriate design, 5) Reclassification of materials into “technical” and “nutrients, 6) Renewability.	Ghisellini et al. (2016)
	1) Systems thinking, 2) Stewardship, 3) Transparency, 4) Collaboration, 5) Innovation, 6) Value optimization	BSI (2017)
	1) Adjusting inputs to the system to regeneration rates, 2) Adjusting outputs from the system to absorption rates, 3) Closing the system, 4) Maintaining the value of resources within the system, 5) Reducing the system's size, 6) Designing for CE, and 7) Educating for CE.	Suárez-Eiroa et al. (2019)
	1) Beneficial reciprocal flows of resources between nature and society, 2) Reduce and decouple resource use, 3) Design for circularity, 4) Circular business models to integrate multi-dimensional value, 5) Transform consumption, 6) Citizen participation in sustainable transitions, 7) Coordinated participatory and multi-level change, 8) Mobilise diversity to develop a plurality of circular economy solutions, 9) Political economy for multi-dimensional prosperity, 10) Whole system assessment	Velenturf & Purnell (2021)

Another point of ambiguity and debate concerns the exact relationship between the CE and sustainable development (Evans, 2023). Some scholars argue that the two concepts are closely linked, with the CE being at least beneficial (Bocken et al., 2014; Suárez-Eiroa et al., 2019) or even a precondition (Webster, 2017) for attaining sustainable development. Recent studies (Garcia-Saravia Ortiz-de-Montellano et al., 2023; Schroeder et al., 2019; Vann Yaroson, 2024) further support such views, demonstrating that CE strategies can help achieve several SDGs. However, other scholars question the potential of the CE to support sustainable development, especially with regards to the social pillar (Corvellec et al., 2022; Murray et al., 2017).

This lack of consensus on defining and conceptualizing the CE and the ambiguity surrounding the concept may impede its consolidation (Kirchherr et al., 2023) and hamper its further dissemination (Kalmykova et al., 2018). At the same time, a single, universally accepted definition of CE might be both elusive and even undesirable, given that the field is dynamic, constantly evolving, and involves multiple stakeholders with differing interests and priorities (Kirchherr et al., 2023; Korhonen, Nuur, et al., 2018). In this context, adopting an explicit definition as the foundation of a research study is essential to ensure conceptual clarity (Corona et al., 2019). The definition endorsed for the papers appended to this thesis and the cover essay itself is that by Kirchherr et al. (2017, p.229)[1]:

> *"A circular economy describes an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers."*

This comprehensive definition is adopted in this thesis, as it makes a clear reference to a core CE principle, i.e., the 4Rs (Reduce, Reuse, Recycle, Recover) principle, and emphasizes the potential of the CE as a pathway toward sustainable development. Moreover, it frames CE from a systems perspective, highlighting that the transition to CE must occur across three system levels: micro, meso and macro. Importantly, it explicitly includes urban areas within the macro level, highlighting their key role within the CE context. The following section further explores the implementation of CE at the urban level.

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[1] In a more recent study Kirchherr et al. (2023) provided a meta-definition based a review of CE definitions proposed after 2017. While this meta-definition more accurately reflects recent advancements in the field, it was not adopted for this thesis, as it was unavailable during the development of Papers I-V.

Lastly, it is important to note that the term circularity is often used as a synonym of CE in the literature, despite distinct differences between the two concepts. As described by Kirchherr et al. (2017), the CE concept specifically refers to an economic model promoting the efficient and cyclical use of resources to foster sustainable development. In contrast, the concept of circularity has been broadly used to describe the degree to which a product, process, or system aligns with circular practices or principles (de Oliveira et al., 2021). For example, it has been used to describe the proportion of a product made from recycled or reused materials (Linder et al., 2017) or to characterize circular flows of materials at the national or regional level (Mayer et al., 2019). In this thesis, circularity specifically refers to the level of CE development in an urban area, where higher circularity reflects greater alignment with CE principles.

2.2.2 Implementing the circular economy at the urban level

At the urban level, the implementation of the CE model is often framed through the ‘circular city’ concept (Brglez et al., 2024). As with the CE, there is no universal definition of the circular city concept, and it has been interpreted differently by policy makers and scholars depending on their interests and perspectives (Herrador et al., 2023; Paiho et al., 2020). For example, it has been interpreted as a strategic vision by local governments (Jones & Comfort, 2018), an umbrella concept encompassing multiple CE initiatives for urban areas (Petit-Boix & Leipold, 2018), or an approach to shift the UM of urban areas from linear to circular (Gravagnuolo et al., 2019).

These differing perspectives on the circular city are reflected in Table 2, which presents different definitions of the concept identified in the literature. According to Prendeville et al. (2018), this diversity of definitions is symptomatic of the broader ambiguity surrounding CE, posing challenges for policy makers attempting to integrate the concept into day-to-day practices. Given this conceptual ambiguity, this thesis does not adopt a specific definition of the circular city. Instead, it adheres to the broader definition of the CE by Kirchherr et al. (2017) (Section 2.2.1), which explicitly acknowledges urban areas as critical settings for implementing the CE model.

Despite the conceptual ambiguity surrounding its implementation at the urban level, the CE is increasingly recognized as a promising approach to achieving sustainable urban development (Lakatos et al., 2021). This is reflected in the growing number of local governments around the world, particularly in Europe and China, committing to advancing the CE transition, with many already in the process of designing or implementing strategies to accelerate this shift (Kopp et al., 2024; Vanhuyse et al., 2021). For instance, 85 municipalities from 22 European countries have signed the Circular Cities Declaration, pledging to promote the implementation of the CE model (Circular cities declaration, 2024).

The growing interest in promoting the CE model at the urban level is further demonstrated by the rise of various international initiatives that aim to assist local governments in advancing the CE transition. Besides the abovementioned Circular Cities Declaration initiative, other notable examples include: 1) the ICLEI Circulars, a global platform for promoting the CE at the urban level by raising awareness, supporting implementation and scaling best practices (ICLEI, 2025), 2) the EMAF, which provides a range of tools for policy makers and practitioners to implement circular practices in urban settings (EMAF, 2019), and 3) the Circular Cities & Regions Initiative, launched as part of the EC's Circular Economy Action Plan with the aim to support the implementation of CE solutions at both urban and regional levels (EC, n.d.).

In this context, as local governments around the world intensify their efforts to advance the CE at the urban level, it is crucial to provide decision-makers with the necessary information to design and implement effective circular strategies. As discussed in the Introduction, two potential approaches to inform decision-making in the CE context are the indicator-based approach and the application of UM assessment methods. Section 2.3 provides more details regarding the indicator-based approach, while Section 2.4 delves deeper into the UM concept and specific UM assessment methods.

Table 2 - Definitions of the circular city concept identified in the literature.

Description	**Source**
"A circular city embeds the principles of a circular economy across all its functions, establishing an urban system that is regenerative, accessible and abundant by design. These cities aim to eliminate the concept of waste, keep assets at their highest value at all times, and are enabled by digital technology. A circular city seeks to generate prosperity, increase liveability, and improve resilience for the city and its citizens, while aiming to decouple the creation of value from the consumption of finite resources"	EMAF (2017, p.7)
Circular city "is a city that practices CE principles to close resource loops, in partnership with its stakeholders (citizens, community, business and knowledge stakeholders), to realize its vision of a future-proof city".	Prendeville et al. (2018, p.187)
"A circular city is one that promotes the transition from a linear to a circular economy in an integrated way across all its functions in collaboration with citizens, businesses and the research community. This means in practice fostering business models and behaviour which decouple resource use from economic activity by maintaining the value and utility of products, components, materials and nutrients for as long as possible, in order to close material loops and minimize harmful resource use and waste generation. Through this circular transition, we seek to improve human wellbeing, reduce emissions, protect and enhance biodiversity, and promote social justice, in line with the Sustainable Development Goals".	Circular cities declaration (2020)
Circular city is "a city based on closing, slowing and narrowing the resource loops as far as possible after the potential for conservation, efficiency improvements, resource sharing, servitization and virtualization has been exhausted, with remaining needs for fresh material and energy being covered as far as possible based on local production using renewable natural resources"	Paiho et al. (2020, p.6)
A circular city is a city that functions through the usage of circular economy practices.	Lakatos et al. (2021, p.13)

2.3 Indicator-based approach to assess CE progress in urban areas

The indicator-based approach has been central to the sustainability assessment paradigm (Purvis & Genovese, 2023) and is increasingly recognized as a useful assessment tool within the context of the CE (Brändström & Eriksson, 2022). According to OECD (2010, p.25), an indicator is "*quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect changes connected to an intervention, or to help assess the performance of a development actor*". The main advantage of indicators is their ability to synthesize and communicate complex information in a simplified and meaningful manner (Singh et al., 2012; Tapia et al., 2021). This makes them particularly effective in monitoring and evaluating the progress of a specific system or process in relation to a target or desired outcome (de Oliveira et al., 2021; Eurostat, 2014), which, in turn, makes them valuable tools for supporting decision-making, policy development and analysis, research, and awareness-raising, among other (Saidani et al., 2019; Superti et al., 2021).

At this point, it is important to highlight that the term 'indicator' is often used interchangeably with the terms 'index' and 'metric' in the literature. Nevertheless, there are semantic differences among these terms that need to be clarified. An indicator is a single variable that is applied to assess progress or changes in relation to an intended outcome (Corona et al., 2019). An index (also known as aggregated indicator) is typically an aggregation of multiple individual indicators into a single composite score following a predefined methodology (Gasparatos et al., 2008; Purvis & Genovese, 2023). A metric, on the other hand, is a broader term that refers to a quantitative measure of a phenomenon and encompasses indicators, indices, indicator-based frameworks and other assessment tools (Parchomenko et al., 2019).

Indicators are often integrated into indicator-based frameworks (also known as indicator dashboards), which are curated collections of single indicators designed to capture multiple aspects (Purvis & Genovese, 2023). These frameworks provide greater context and meaning to the individual indicators they include, offering a more comprehensive picture of a system or phenomenon (Gudmundsson, 2003). Unlike single indicators and indices, which typically focus only on a specific aspect, indicator-based frameworks have broader scopes, enabling the analysis of multiple aspects (Purvis & Genovese, 2023). This makes them more well-suited for capturing the complexity and multiple dimensions of the transition to a CE (EC, 2018a). Thus, in this thesis, they are regarded as more effective tools for monitoring and evaluating CE progress at the urban level compared to single indicators and indices.

In recent years, several studies have attempted to map the availability of urban-level CE metrics. Fusco Girard and Nocca (2019), Gravagnuolo et al. (2019), OECD (2021) and Paoli et al. (2022) identified indicators and indices in the literature, and categorised them based on their thematic connections, though without further analysing them. Superti et al. (2021) carried out a comparative analysis of indicators used to assess circularity or sustainability at the urban level, examining their interrelationships. More recently, Kopp et al. (2024) examined indicators linked to municipal CE policies to evaluate their relevance to environmental concerns. Collectively, these studies have highlighted that there is a plethora of indicators and indices for measuring urban circularity. However, a large share of these metrics primarily focuses on resource and waste flows, indicating a lack of diversity in evaluating multiple CE aspects. Moreover, the identified metrics differ in their contents and scopes, reflecting the lack of standardization in CE assessment, an issue previously noted in the literature (Baratsas et al., 2022; Svarc et al., 2021).

While the abovementioned studies have offered valuable insights into urban-level indicators and indices, they have not contributed to advancing knowledge on indicator-based frameworks, as they overlooked these tools in their reviews. As a result, there is limited understanding of the availability of such frameworks for monitoring and assessing CE progress in urban areas. Additionally, empirical applications of these frameworks in urban settings are rather scarce (Kirchherr & van Santen, 2019; Petit-Boix et al., 2022), leaving gaps in understanding their applicability, strengths, and weaknesses. This thesis seeks to address this research gap in **Papers I** and **II**.

2.4 Industrial ecology: principles and methods

Often referred to as the "science of sustainability" (Ehrenfeld, 2008), IE is a scientific field that takes a systems perspective to study the society-wide use of materials and energy and to address the related environment impacts (van Ewijk et al., 2023). The contemporary origins of IE can be traced back to the publication of the article "Strategies for Manufacturing" by Frosch & Gallopoulos (1989), which is widely recognized as the foundational article of the field (Graedel T.E. & Allenby B.R., 2010; Kapur & Graedel, 2004). In this seminal article, the authors argued that the traditional model of industrial manufacturing, characterized by resource depletion, waste generation and environmental degradation, must be transformed into a more integrated model that mirrors the functions of natural ecosystems. In this "industrial ecosystem", materials and energy use are optimized, waste generation is minimized, and the by-products of one process become inputs for another.

Since the publication of "Strategies for Manufacturing", IE has grown into a broad, transdisciplinary field that encompasses various concepts (e.g., industrial symbiosis, loop closing), design approaches (e.g., design for the environment), and powerful tools for modelling material and energy flows and stocks (e.g., MFA) and assessing environmental impacts from a life cycle perspective (e.g., LCA) (Ferrão et al., 2016; van Ewijk et al., 2023). Graedel T.E. and Allenby B.R. (2010, p.41) define IE as "*the study of technological organisms, their use of resources, their potential environmental impacts, and the ways in which their* *interactions with the natural world could be restructured to enable global sustainability*", with the term 'technological organisms' referring to industrial and other human socio-economic systems, such as urban areas and countries.

The guiding principle of IE is the biological metaphor, which embodies the idea that human systems can be restructured to mimic the efficiency of biological organisms or natural ecosystems in using materials and energy (Lifset & Graedel, 2002). Industrial ecologists have used this metaphor as a foundation for developing concepts, including the concept of metabolism (Ayres, 1989), which views technological systems as having metabolisms analogous to those of biological organisms (Lifset & Graedel, 2002). Metabolism, whether biological or technological, refers to the sum of all physical and chemical processes within an organism that transform materials and energy into the forms necessary for its functioning (Graedel T.E. & Allenby B.R., 2010). Today, IE studies three types of metabolism, industrial, socio-economic and urban (Kennedy, 2016), to understand the structure and efficiency of society's metabolic processes in terms of material and energy use (Rweyendela, 2022).

Another core principle of IE is systems thinking. According to Meadows (2008), a system is "*an interconnected set of elements that is coherently organized in a way that achieves something*". Systems thinking is an approach to understand systems, predict their behaviours and design changes that produce desired outcomes (Arnold & Wade, 2015). It involves examining how the system's elements interact with each other and their environment, identifying cause-effect feedback loops, recognizing types of stocks and flows, and understanding the system's dynamic behaviour (Arnold & Wade, 2015; Rios et al., 2022). This holistic approach helps avoiding narrow, fragmented analyses that might disregard important variables and lead to unintended consequences (Lifset & Graedel, 2002). Two ways in which systems thinking is manifested in IE are by using a life cycle perspective (e.g., via LCA) and MFA (Lifset & Graedel, 2002).

Overall, IE, with its concepts, principles and methods, is highly relevant for designing a sustainable CE (Bocken et al., 2017; van Ewijk et al., 2023). According to Saavedra et al. (2018), IE contributes to CE at three different levels: 1) conceptual, 2) technical, and 3) political and standards levels. At the conceptual level, many theoretical foundations underpinning the CE concept originate from IE concepts, including industrial symbiosis, loop closing, metabolism and biomimicry. At the technical level, IE provides a range of robust analytical methods (e.g., MFA, LCA), which can help guide CE implementation. Lastly, at the political and standards level, IE can play a key role in shaping policies, laws and standards relevant to CE.

Among the various IE concepts and methods, the concept of UM serves as a foundational concept for this thesis, while MEFA and LCA are key methods employed in the research. UM is discussed in Section 2.4.1, and MEFA and LCA are covered in Sections 2.4.2 and 2.4.3, respectively.

2.4.1 Urban metabolism

The urban metabolism (UM) is a metaphorical concept that describes an urban area as a living organism or natural ecosystem that exchanges matter and energy with its environment to sustain its functions and growth (Céspedes Restrepo & Morales-Pinzón, 2018; Kennedy et al., 2007; Lucertini & Musco, 2020). The origins of the concept trace back to the 19th century, in particular to the introduction of the neologism 'metabolism' by Schwann in 1839 and the use of the term metabolism by Karl Marx to describe material and energy exchanges between the society and nature within his economic theory (Céspedes Restrepo & Morales-Pinzón, 2018). Nevertheless, the first use of the term 'urban metabolism' is most often attributed by scholars (Kennedy et al., 2007; Zhang, 2013) to Abel Wolman and the publication of his article 'The Metabolism of Cities' (Wolman, 1965). In this influential article, Wolman, a pioneer of sanitary engineering, conceptualized a hypothetical North American city of 1 million inhabitants as a metabolic system and quantified its material, energy, water and waste flows (Pincetl et al., 2014).

Wolman's article spurred the interest of scholars, who recognized the usefulness of the UM concept for studying how urban systems utilize resources and interact with nature (Céspedes Restrepo & Morales-Pinzón, 2018). As a result, three studies in the 1970s examined the UM of real urban areas, i.e., Tokyo (Hanya & Ambe, 1976), Brussels (Duvigneaud & Denayeyer-De Smet, 1977) and Hong Kong (Newcombe et al., 1978). Around the same time, H.T. Odum, an American systems ecologist, introduced emergy analysis (Odum, 1971), a method that normalizes all energy flows into solar energy equivalent, or 'emergy', to analyse ecosystems or social systems (Pincetl et al., 2012). Zucchetto (1975) later applied emergy analysis to assess Miami's UM, marking its first use in UM studies. Despite early interest, UM research progressed slowly over the next two decades, until the late 1990s, when renewed interest spurred ongoing growth in the field (Kennedy et al., 2011; Shahrokni et al., 2015).

Over the last 25 years, UM has evolved as a systems approach to analyse the resource demands of urban systems and understand their interactions with the environment, gaining insights into their environmental sustainability (Beloin-Saint-Pierre et al., 2017; Pincetl et al., 2012). IE has been at the forefront of UM research, offering a wide array of scientifically rigorous quantitative methods for analysing material and energy flows and environmental impacts (Chrysoulakis et al., 2013), including MFA, Substance Flow Analysis (SFA), MEFA, LCA and Input-Output Analysis (for comprehensive reviews see Beloin-Saint-Pierre et al., 2017; Hoekman & Bellstedt, 2020; Zhang 2013). In addition, other fields, including urban ecology, political science, ecological economics, sociology and social geography, have also contributed to advancing UM research (Haberl et al., 2019; John et al., 2019). These contributions have shaped UM into a transdisciplinary approach for multidimensional analysis of urban areas that can support urban planning (Chrysoulakis et al., 2013), policy making and analysis (Pincetl et al., 2014) and sustainability assessment (Beloin-Saint-Pierre et al., 2017), among others.

The UM approach can also support the implementation of the CE at the urban level, as suggested in the literature. Specifically, Kalmykova & Rosado (2015) proposed the use of UM as framework for CE design in urban area, Lucertini & Musco (2020) integrated the UM and CE concepts in a conceptual framework aimed to support urban planning and decision-making, Cui (2022) introduced and applied the circular urban metabolism framework to assess the circularity of material flows in urban areas, Petit-Boix et al. (2022) and Kopp et al. (2024) suggested the use of UM methods in monitoring the progress of circular strategies, and Fernandes & Ferrão (2023) proposed UM-based strategies to promote CE in buildings refurbishment. Inspired by these studies, the UM is used in this thesis as the foundation for developing a conceptual model that represents the studied urban area as a metabolic system consisting of multiple interacting sectors (see Fig. 2). This model then serves as a basis for defining the system boundaries to apply specific UM assessment methods in **Papers III-V**. The following sections detail the UM assessment methods applied in this thesis.

2.4.2 Material and energy flow analysis

MEFA belongs to the family of flow analysis methods that are used to assess the sustainability of a specific system by analyzing its material, substance or energy flows (Hoekman & Bellstedt, 2020). It builds upon MFA[2], a systematic method for assessing the state and changes of material flows and stocks in a spatially defined system over a specified timeframe (Brunner & Rechberger, 2017). The core principle of MFA is the law of mass conservation, which is applied to determine the mass balance of the studied system. In MEFA, the scope of MFA is expanded to analyze material and energy flows in tandem, based on the principles of mass and energy conservation (Derrible et al., 2021). This capacity to analyze material and energy flows together makes MEFA a valuable tool in UM studies, as it can offer comprehensive insights into how urban systems function and interact with the environment (Hoekman & Bellstedt, 2020).

MEFA can be applied for UM analysis following two distinct approaches: the top-down and the bottom-up (Augiseau & Barles, 2017). The top-down approach models the urban system without necessarily considering its internal components (Augiseau & Barles, 2017; Loiseau et al., 2012). It relies on aggregated national or regional data that are disaggregated to the urban level using proxy factors, such as population or workforce (Beloin-Saint-Pierre et al., 2017). A common example of this approach is the adaptation of Eurostat's economy-wide material flow accounting framework (Eurostat, 2001, 2018) to

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[2] In this thesis, the term MFA specifically refers to the analysis of goods, i.e., economic entities of matter with either positive or negative economic value, while the term SFA denotes the analysis of specific substances (e.g., carbon, phosphorus), as in Baccini & Brunner (2012).

the urban scale, as demonstrated in previous studies (Bahers et al., 2019; Barles, 2009; Browne et al., 2009; Niza et al., 2009; Voskamp et al., 2017). The main advantage of the top-down approach is that it relies on widely available data, making its application relatively straightforward (Derrible et al., 2021). However, a key limitation is that it models the urban system as a "black box", resulting in less detailed analyses that may overlook specific processes and flows within the system (X. Wang et al., 2023). Moreover, the process of downscaling macro-scale data using proxies entails the risk of producing less accurate results.

The bottom-up approach, in contrast, models the urban system at a more granular, disaggregated level (Loiseau et al., 2012). It begins by calculating the flows and stocks of individual internal system components, which are then aggregated to represent the entire system (X. Wang et al., 2020). It relies on data that are specific to the urban system, such as municipal statistics, measurements and published reports and articles (Beloin-Saint-Pierre et al., 2017). A bottom-up approach to UM analysis can be based on the MFA methodology developed by Brunner and Rechberger (2017). A key strength of this methodology is its versatility, which allows applications to wide range of systems, from industrial processes to urban areas and entire nations (Hoekman & Bellstedt, 2020). This versatility allows for the modeling of the internal components of the urban system, helping to open the 'black box' of its UM. Moreover, it facilitates the inclusion of energy flows in the analysis, enabling the application of MEFA.

Despite the advantages of applying MEFA following a bottom-up approach, no previous study has applied this approach to analyze UM at the sectoral level. Previous studies that analyzed material and energy flows in Hong Kong (Warren-Rhodes & Koenig, 2001), Los Angeles (Ngo & Pataki, 2008), Toronto (Sahely et al., 2003), Bogota (Martínez et al., 2021; Piña & Martínez, 2014), Brussels (Athanassiadis et al., 2017) and Cairo (Khalil & Al-Ahwal, 2021), modelled the urban systems without focusing on their sectors or the interactions between them. Furthermore, to the author's knowledge, no study has yet explored the potential of applying MEFA with a bottom-up approach to support decision making within the context of the CE. This thesis attempts to address this research gap in **Paper III**.

2.4.3 Life cycle assessment

LCA is an analytical method that aims to assess the potential environmental impacts of a product or system from cradle to grave, i.e., from raw material extraction to production, use and end of life (ISO, 2006a). Originally, LCA was applied only to products, but today it is also used to assess large-scale systems, including urban areas (Hellweg et al., 2023; Loiseau et al., 2018). Its key feature is its comprehensive life cycle perspective, which enables a thorough evaluation of environmental impacts, helping to identify environmental 'hotspots' in the life cycle of the studied system and preventing burden shifting between life cycle stages, regions or environmental problems (Finnveden et al., 2009).

The principles, requirements and framework for LCA are specified in ISO standards 14040 and 14044 (ISO, 2006b, 2006a). According to these standards, an LCA study comprises four iterative phases: 1) Goal and scope definition, 2) Life cycle inventory (LCI) analysis, 3) Life cycle impact assessment (LCIA), and 4) Interpretation. In the first phase, the purpose of the study, the system boundaries and the functional unit are defined. In the second phase, the elementary flows, i.e., inputs (resources) and outputs (emissions) from and to the environment across the life cycle of the studied system, are quantified. In the third phase, the quantified elementary flows from the LCI analysis are converted into a common unit and aggregated into environmental impact categories using impact assessment models. In the fourth and final phase, the results of the LCI and LCIA are interpreted in relation to the goal and scope through methods like contribution analysis, sensitivity analysis and uncertainty analysis, leading to conclusions and recommendations.

Different methodological choices made across the four phases result in different types of LCA (Guinée et al., 2018; Hellweg et al., 2023). Perhaps, the most common distinction is between attributional and consequential LCA. The former aims to estimate the portion of global environmental burdens related to the product system studied, while the latter examines how environmental burdens are affected (directly or indirectly) by decisions associated with the product system (Ekvall, 2020). The choice between these two approaches is crucial, as it shapes other methodological decisions in an LCA, such as the choice of system boundary and the type of data used in the LCI (average vs marginal) (Finnveden et al., 2009). Despite efforts to align these approaches with different decision contexts, such as in the International Reference Life Cycle Data System Handbook by (JRC, 2010), the debate on attributional and consequential approaches remains inconclusive (Guinée et al., 2018; Hellweg et al., 2023).

Another distinction in LCA types is between retrospective and prospective LCA. Typically, LCA has been applied retrospectively to assess commercially mature technologies and product systems (Moni et al., 2020). Recently, however, there has been growing interest in prospective LCA (pLCA), which assesses the environmental performance of technologies and product systems in the future based on different scenarios (Arvidsson et al., 2018; Cucurachi et al., 2018; Steubing & de Koning, 2021). While pLCA has been mainly applied to assess emerging technologies (van der Giesen et al., 2020), it has also been used to evaluate the environmental sustainability of large-scale systems, including urban water systems (Loubet et al., 2016) and national energy systems (Martín-Gamboa et al., 2019), and to understand the impact of future energy policies (Dandres et al., 2012). Nonetheless, such applications have been scanty, and the potential of pLCA to inform decision-making at the urban level, specifically within the CE context, remains largely unexplored.

In the CE context, LCA has been commonly used to evaluate the environmental sustainability of circular solutions and strategies across the micro, meso and macro system levels (Hellweg et al., 2023). For instance, it has been applied to assess the environmental performance of circular solutions for building components (van Stijn, 2021), material recycling options (Diener & Tilman, 2015), circular business models in manufacturing (Bjørnbet & Vildåsen, 2021), industrial symbiosis systems (Daddi, 2017), and circular strategies for plastics on a global scale (Bachmann et al. 2023). The use of LCA in assessing circular solutions and strategies is driven by its comprehensive perspective, which allows the identification of potential environmental benefits and trade-offs of increased circularity (Corona et al. 2019; Walzberg et al., 2021). This makes LCA an essential tool in understanding the conditions and contexts under which circular solutions and strategies can be environmentally beneficial (Hellweg et al., 2023).

At the urban level, LCA has primarily been used for evaluating circular solutions and strategies targeting specific sectors within urban settings. For example, it has been applied to assess circular solutions and strategies for urban agriculture systems (Rufí-Salís et al., 2021), municipal waste management systems (Peiris & Dayarathne, 2023), and the urban built environment (Saadé et al., 2022). However, the potential of LCA to assess how the implementation of the CE model could influence the environmental performance of entire urban areas has not yet been explored in the literature. A potential option to conduct such an evaluation is to apply the UM-LCA approach, described in the following section.

2.4.4 Urban metabolic life cycle assessment

The UM-LCA approach integrates MEFA with LCA under an UM perspective to assess the environmental impacts associated with the flows of materials and energy used by the urban system (referred to as metabolic flows). The coupling of the two methods is performed by integrating the accounting of metabolic flows performed though MEFA into the LCI analysis phase of LCA (Pincetl et al., 2012). More specifically, the foreground system (i.e., the urban system) is modeled based on the quantified metabolic flows, while the background system (i.e., processes taking place outside the urban boundaries) is modeled based on available LCI databases (e.g., Ecoinvent). Based on the compiled LCI and a specific LCIA method, the environmental impacts of urban metabolic flows can then be estimated.

The key strength of the UM-LCA is its ability to account for environmental impacts associated with upstream (i.e., resource extraction, processing, manufacturing) and downstream (i.e., end of life) processes in the life cycle of urban metabolic flows (Goldstein et al., 2013). In this way, it provides a comprehensive assessment of the environmental impacts associated with an urban area's metabolism from a life cycle perspective (García-Guaita et al., 2018). Additional strengths reported in the literature include: i) its ability to aggregate model results into standardized, easily communicated indicators (Chester et al., 2012), ii) the standardization of LCA (through the ISOs 14040 and 14044), which provides standard guidelines and requirements for consistent applications of the UM-LCA (Pincetl et al., 2012), iii) the growing number of LCA users, who continuously improve the methodology and increase the availability of LCI data (Goldstein et al., 2013).

Building on its strengths, several scholars have employed the UM-LCA approach to evaluate the environmental performance of urban areas. Goldstein et al. (2013) pioneered the approach by assessing the environmental performance of Beijing, Hong Kong, Cape Town, Toronto and London. Subsequently, Dias et al. (2018) applied the UM-LCA approach to Aveiro in Portugal, García-Guaita et al. (2018) to Santiago de Compostela in Spain, González-García & Dias (2019) to Sevilla and Bilbao in Spain, Westin et al. (2019) to Stockholm, Gothenburg and Malmö in Sweden, and González-García et al. (2021) to Madrid. Other scholars have used it to assess the environmental performance of specific urban sectors (Dorr et al., 2022; Lopes Silva et al., 2015; Stelwagen et al., 2021) or smart city initiatives (Ipsen et al., 2019).

These studies clearly illustrated the potential of UM-LCA as a tool to evaluate the environmental sustainability of urban systems. However, it remains unclear whether UM-LCA can inform decision-making related to CE implementation at the urban level, as no study has investigated this aspect yet. Moreover, no prior study has applied the UM-LCA approach prospectively to assess environmental impacts with a future-oriented perspective. This thesis attempts to address this research gap in **Papers IV** and **V**.

3. Research design and methods

This chapter outlines the research design of the thesis (Section 3.1) and describes the methods applied in the five appended papers (Section 3.2).

3.1 Research design

The research design was structured to address the three RQs through a combination of qualitative and quantitative methods, which include literature reviews, indicator-based assessments, MEFA and UM-LCA. For **Papers II-V,** Umeå urban area (see Section 3.1.1) serves as the study setting for applying the chosen methods. An overview of the employed methods in relation to the RQs and the appended papers is provided in Table 3, while details on the application of each method are provided in the following sections and the appended papers.

As shown in Table 3, to address RQ1, a literature review was carried out in **Paper I** to map available indicator-based frameworks for monitoring and evaluating CE progress at the urban level, and to evaluate their strengths and limitations. Furthermore, an indicator-based assessment was carried out in **Paper II** using the EC's circular economy monitoring framework (CEMF) (EC, 2018a), which was identified as one of the best-performing frameworks in the assessment conducted in **Paper I**. The CEMF was applied to Umeå, offering empirical insights into the framework's strengths and limitations, contributing to addressing RQ1.

RQ2 was addressed by applying MEFA and UM-LCA to Umeå to gain insights into the applicability and utility of these two UM assessment methods in supporting the design and monitoring of urban-level circular strategies. MEFA was applied in **Paper III** to analyze the UM of Umeå, while the UM-LCA approach was used in **Paper IV** to retrospectively assess Umeå's environmental performance and prospectively assess the environmental impacts of different future circular strategies.

Finally, to address RQ3, a novel framework that integrates the indicator-based and UM-LCA approaches to assess the UM and circularity of urban was introduced in **Paper V**. The framework was developed by combining the UM-LCA approach (MEFA + LCA) with a structured dashboard of CE indicators identified in the literature. The proposed framework was also applied to Umeå to test its applicability and utility and examine its strengths and weaknesses.

Table 3 - Overview of the methods used in the papers in relation to the RQs and the appended papers of the thesis.

Research questions	Literature review	Indicator-based assessment	MEFA	UM-LCA	Paper
RQ1: What is the availability of indicator-based frameworks for assessing and monitoring CE progress at the urban level, and what are their strengths and limitations?	√				**I**
		√			**II**
RQ2: What is the applicability and utility of MEFA and UM-LCA in supporting the design and monitoring of urban-level circular strategies?			√		**III**
			√	√	**IV**
RQ3: How can the indicator-based and UM-LCA approaches be integrated to provide a comprehensive assessment of UM and circularity in urban areas, supporting decision-making within the context of the CE?	√	√	√	√	**V**

3.1.1 Study area

The urban area under study in **Papers II-V** is Umeå municipality, the capital of Västerbotten County in northeastern Sweden. Located at 63°49′ latitude and 20°15′E longitude, Umeå has a subarctic climate (Kottek et al., 2006), characterized by long, cold winters and short, mild summers. The coldest month is February, with an average daily temperature of -6.5^{o}C, while the warmest is July, with an average daily temperature of +16.0^{o}C (SMHI, 2025).

Table 4 presents some key demographic and socio-economic data for Umeå and compares them to those in Sweden. Umeå is the most populous municipality in northern Sweden and the 11th one nationwide, with a population of 133,091 residents in 2023, 13.3% of whom were born abroad. It is also one of the fastest growing Swedish urban areas. Over the past 20-25 years, the population has shown a steady growth, rising from 104,512 residents in 2000 to 133,091 in 2023 (SCB, 2025d), with projections estimating a further increase to 200,000 by 2050 (Umeå municipality, 2018). Despite the population growth, Umeå municipality remains sparsely populated overall. It covers 2,317 km^2 of land, of which only 70 km^2 is urbanized, with the remainder mostly consisting of forested land (SCB, 2025c).

Umeå is the main centre of education and research in northern Sweden. It is home to two universities: Umeå university and a branch of the Swedish University of Agricultural Sciences (SLU). In 2023, the two institutions hosted together nearly 40,000 students (Umeå University, 2025), about 30% of Umeå's total population. As a university hub, Umeå is characterized by a young and highly educated population (OECD, 2020b). In 2023, the average age of the population was 39.6 years old, lower than the national average of 41.9 years, and nearly 60% of residents aged 25 to 64 possessed a post-secondary degree.

Furthermore, Umeå is an important regional, economic center, with a GDP per capita of 655,900 SEK in 2023, 15% higher than the national average. In the same year, the average monthly income before tax was 29,325 SEK per capita, and the unemployment rate was 3%, well below the national rate of 5.3%. A total of 10,171 businesses were based within the municipality, with the vast majority (99.2%) being small companies with fewer than 50 employees (Företagarna, 2024). The largest sectors in terms of employees were the care sector (14,973), education (10,573), business services (7,584) and retail (6,665) (SCB, 2025a).

Table 4 – Key demographics and socio-economic data for Umeå and Sweden in 2023

	Umeå	**Sweden**
Population	133,091	10,551,707
% of population born abroad	13.3%	20.6%
Average age	39.6 years	41.9 years
Number of households	65,708	4,931,974
- Single-person households	50.7%	48.6%
- Cohabiting households	44.2%	45.5%
- Other households	5.2%	5.9%
Residents aged 25-64 with post-secondary education	58.1%	46.9%
Unemployment,18-65 years, % of employed	3%	5.3%
GDP per capita	655,900 SEK	557,400 SEK
Average income before tax per month and capita	29,325 SEK	32,358 SEK

Sources: Kolada (2025); SCB (2025b)

As Umeå is projected to continue growing and reach a population of 200,000 by 2050, the need for new housing is also expected to rise. Over the past decade, an average of 800 new homes have been built every year (Kolada, 2025), a number that is expected to increase, as the municipal council plans for the construction of 32,000 new homes by 2050 (Umeå municipality, 2024). The growing population will also necessitate the development of new infrastructure, including public buildings, roads, green areas, and water supply and sewer systems, and will increase the demand for energy supply, public transport, and waste management services, among others (OECD, 2020b). This rise in demand for housing, infrastructure and services will, in turn, place greater pressures on natural resources and the environment.

To address these challenges, the municipal council has embraced the CE as a potential approach to promote sustainable use of resources and reduce waste and emissions, while creating socio-economic benefits (OECD, 2020b). Since 2016, the transition to a CE has been a political priority (Umeå municipality, 2016). To accelerate this transition, the council has adopted a comprehensive waste plan that emphasizes resource efficiency, material reuse and recycling

(Umeå region, 2020). It also supports local organizations that promote product sharing and circular business models (Circular Regions, 2024), collaborates with international organizations including ICLEI and EMAF, and has signed the Circular Cities Declaration (Umeå municipality, 2023). Moreover, the council has committed to developing a circular strategy with targeted measures across various sectors (Circular regions, 2023; OECD, 2020b).

The municipality's strong commitment and ongoing efforts to promote the CE was a key reason for selecting Umeå as the study area for applying the methods and approaches examined in this thesis, as their application could provide meaningful insights into Umeå's UM and circularity level, assisting local decision-makers in designing an effective strategy. An additional reason was the availability of open-access databases, such as Kolada (2025) and Opendata Umeå (2025), and reports from municipal companies, such as Vakin (2022), which could facilitate the collection of some of the necessary data for applying the assessment methods and approaches.

3.2 Methods

3.2.1 Literature review

A literature review is a systematic method for gathering, analyzing and synthesizing previous research to address a wide range of research questions (Snyder, 2019). In **Paper I**, a literature review was conducted to identify and assess indicator-based frameworks for monitoring and evaluating CE progress at the urban level. As detailed below, the literature review involved three main steps: (1) identifying and selecting relevant indicator-based frameworks, (2) defining assessment criteria, and (3) assessing the frameworks.

In the first step, literature describing macro-level indicator-based frameworks was identified following a comprehensive search strategy to include both scientific peer-reviewed literature and gray literature. Scientific sources were identified in the Web of Science Core Collection using keywords, such as "indicator", "metric", "framework" and "scoreboard", and focusing on literature published in English from 2010 to 2021. Gray literature was identified using combinations of the above keywords in the Google search engine. After screening irrelevant sources, seven peer-reviewed articles and five reports were selected. Next, the snowball method was employed to identify relevant literature in the reference lists of the selected documents, resulting in three more reports.

In the second step, eight assessment criteria (outlined in Table 5) were established to guide the evaluation of the identified indicator-based frameworks. The assessment criteria were defined based on recommendations from the literature regarding key attributes that monitoring tools should possess. The criteria were also validated by different partners in the Urban Circularity Assessment Framework project (SEI, 2020).

In the third step, the identified frameworks were assessed against the eight assessment criteria to determine if they exhibit the necessary attributes. For Criteria 1–6, the evaluation involved assessing whether each framework met each criterion fully, partially, or not at all. Criterion 7 involved determining the validity of the frameworks, i.e., the extent to which they measure what they intend to measure (Corona et al., 2019; Linder et al., 2017). This was done by evaluating whether the indicators included within each framework align with any of the 12 validity requirements in Table 6, which reflect specific CE aspects. Lastly, Criterion 8 was assessed by determining to what extent a framework includes indicators that capture aspects related to the environmental, social, economic and governance pillars of sustainable development.

Table 5 - Key attributes that CE monitoring frameworks should possess, and the eight criteria used for the assessment of the frameworks (Source: **Paper I**)

Attribute	Criteria
1. Transparency	1. Whether there is a transparent description of the methodology for the development and application of the framework.
2. Stakeholder engagement	2. Whether stakeholders have been engaged through participatory approaches in the development of the framework.
3. Effective communication	3. Whether appropriate techniques are applied to effectively communicate the results from the application of the framework.
4. Ability to track temporal changes	4. Whether the framework has been applied considering temporal changes.
5. Applicability	5. Whether the application of the framework is based on easily accessible and regularly updated data.
6. Alignment with specific CE principles	6. Whether the framework was developed based on specific CE principles.
7. Validity	7. To what extent the framework includes indicators that reflect CE aspects.
8. Relevance to sustainable development	8. To what extent the framework includes indicators that reflect aspects relevant to the four pillars of sustainable development (environmental, social, economic and governance).

Table 6 - The 12 validity requirements (Source: **Paper I**)

No	Validity requirement
1	Reduced input of resources
2	Reduced emission levels (pollutants and GHG emissions)
3	Reduced material losses and waste
4	Increased input of renewable and recycled resources
5	Maximized utility and durability of products
6	Creating business and jobs at all levels of skills
7	Value added creation and distribution, and other outcomes improving economic performance
8	Increased social wellbeing
9	Designing for circular economy
10	Educating for circular economy
11	Investing for circular economy
12	Governance for circular economy

3.2.2 Indicator-based assessment

In **Paper II**, an indicator-based assessment was performed to examine the strengths and weaknesses of this approach based on empirical evidence from a real-world setting. The assessment was carried out using the EC's CEMF (EC, 2018a) in its original form, prior to its 2023 revision (EC, 2023). The CEMF was introduced to monitor progress toward the CE at both national and EU levels. Initially, the framework included 10 key indicators and 23 secondary indicators, organized into four thematic areas: (i) *Production and consumption*, (ii) *Waste management*, (iii) *Secondary raw materials*, and iv) *Competitiveness and innovation*. At the time of the study, the *Green public procurement* indicator was still under development, while the indicators *EU Self-sufficiency for raw materials*, *End-of-life recycling input rates* and *Food waste*, were applicable only at the EU level. In the revised CEMF, the *Food waste* indicator is now measured at the national level, and the *Green public procurement* indicator will begin being measured in 2024.

While the CEMF was originally designed for CE monitoring at the national or EU level, **Paper II** investigated its applicability to urban areas by applying it to Umeå. Several key factors motivated this choice. Firstly, the CEMF stood out as one of the best-performing frameworks in the assessment performed in **Paper I** (section 4.1). Secondly, the CEMF is a well-established indicator-based framework within the European context, which could facilitate its broad adoption as a standardized system for CE monitoring across different scales (urban, national, regional), helping to address the lack of standardization in existing indicator-based frameworks, as identified in Paper I (See Section 4.1). Thirdly, the indicators of the framework were selected based on the RACER (Relevant, Acceptable, Credible, Easy, Robust) criteria, which is in line with the recommendations of the Bellagio declaration on CE monitoring principles (EEA, 2020). Lastly, the study sought to test the validity of claims (Paiho et al., 2020; Urban Agenda for the EU, 2019) suggesting that the limited availability of urban-level data could hinder the CEMF's applicability in urban contexts.

For the assessment in **Paper II**, the CEMF was amended by: i) modifying the description of certain indicators to better fit an urban context, ii) replacing the indicators *Green public procurement* and *Food waste* with the indicators *CE/waste prevention criteria in guidelines for procurement* and *Generation of food waste per capita*, respectively, iii) adding the indicator *Biologically treated food waste, including home composting (%)* to the *Waste management* thematic area, and iv) excluding the indicators *Self-sufficiency for raw materials* and *End-of-life recycling input rates*, as they are applicable only at the EU level. The amended CEMF is presented in Table 7.

Table 7 - The amended CEMF for urban-level monitoring (Source: **Paper II**)

Thematic area	No	Indicators	No	Sub-indicators	Unit
Production and consumption	1	Self-sufficiency for raw materials **(not applicable)**	-	-	%
	2	CE/waste prevention criteria in guidelines for procurement	-	-	No unit (Y/N)
	3	Waste generation	3.1	Generation of municipal waste per capita	kg per capita
			3.2	Generation of waste excluding major mineral wastes per GDP unit	kg per thousand euro
			3.3	Generation of waste excluding major mineral wastes per domestic material consumption	%
	4	Generation of food waste per capita	-	-	kg per capita
Waste management	5	Overall recycling rates	5.1	Recycling rate of municipal waste	%
			5.2	Recycling rate of all waste excluding major mineral waste	%
	6	Recycling rates for specific waste streams	6.1	Recycling rate of overall packaging	%
			6.2	Recycling rate of plastic packaging	%
			6.3	Recycling rate of wooden packaging	%
			6.4	Recycling rate of e-waste	%
			6.5	Recycling of biowaste in municipal waste	kg per capita
			6.6	Recovery rate of construction and demolition waste	%
			6.7	Biologically treated food waste (including home composting)	%
Secondary raw materials	7	Contribution of recycled materials to raw materials demand	7.1	End-of-life recycling input rates **(not applicable)**	%
			7.2	Circular material use rate	%
	8	Trade in recyclable raw materials	8.1	Imports to the urban area from non-EU countries	tonne
			8.2	Exports from the urban area from non-EU countries	tonne
			8.3	Imports to the urban area from EU countries	tonne
Competitiveness and innovation	9	Private investment, jobs and gross value added related to circular economy sectors	9.1	Gross investment in tangible goods	% of GDP at current prices
			9.2	Persons employed	% of total employment
			9.3	Value added at factor cost	% of GDP at current prices
	10	Number of patents related to recycling and secondary materials	-	-	Number

To apply the amended CEMF, a desktop study was performed to map data sources that could support its application at the urban level, with a particular focus on the Swedish context. For the mapping, urban-level data from statistics, databases, surveys and published studies (bottom-up data) were prioritized.

Nevertheless, as these data were not always available, national- or regional-level data that could be downscaled to urban level (top-down data) were also identified. The quality of the identified data was then assessed using the pedigree matrix approach (Funtowicz & Ravetz, 1990; Weidema, 1998).

Using the identified data, the indicators of the framework were calculated for Umeå from 2014 to either 2019 or 2020, depending on data availability. Most indicators were computed annually, apart from indicators 3.2, 3.3, 5.2, 6.6 and 7.2, which were calculated biennially due to lack of available annual data. For indicators computed using top-down data (3.2, 3.3, 5.2, 6.1, 6.2, 6.3, 6.4, 6.6, 7.2, 8.1, 8.2, 8.3, 9.1, 9.3), downscaling was based on proxy factors, e.g., the ratio of workers in different sectors in Umeå relative to Sweden. Moreover, for indicators 3.3 and 7.2, the Domestic Material Consumption (DMC) for Umeå was estimated based on its DMC in 2010, as estimated by Westin et al. (2020), assuming that the trend of DMC in Umeå from 2010 to 2020 was similar to that in Sweden, as reported by Eurostat (2022).

3.2.3 Material and energy flow analysis

In **Paper III**, a MEFA was performed to explore its applicability and utility in analyzing UM to enable informed decision-making in the CE context. The MEFA was conducted following the methodology by Brunner & Rechberger (2017). Although this methodology is mainly intended for material flows and stocks, its scope was expanded to include energy flows. The assessment was carried out in four steps: i) problem definition, ii) system definition, iii) quantification of material and energy flows and stocks, iv) illustration and interpretation of results, as described below.

Problem definition

The goal of MEFA was to analyze the UM of Umeå by accounting for flows and stocks of material and energy across various sectors within the urban system.

System definition

The spatial boundary of the urban system aligned with the administrative boundary of Umeå municipality. The temporal boundary spanned from 2017 to 2021, with an annual resolution. The identification of relevant flows, stocks, and processes within the urban system was guided by the conceptual model shown in Figure 2. This model illustrates the urban area as a metabolic system consisting of 11 sectors, each representing fundamental socio-economic activities within the urban context. It also depicts material and energy flows (metabolic flows) associated with the 11 sectors and the urban stock, which includes the built environment, mobile stock and other (landfills and other sinks). Three of the 11 sectors, the 1) agriculture, forestry and fishing, 2) manufacturing, and 3) service sectors, were excluded from the assessment due to limited data availability at the time of the study.

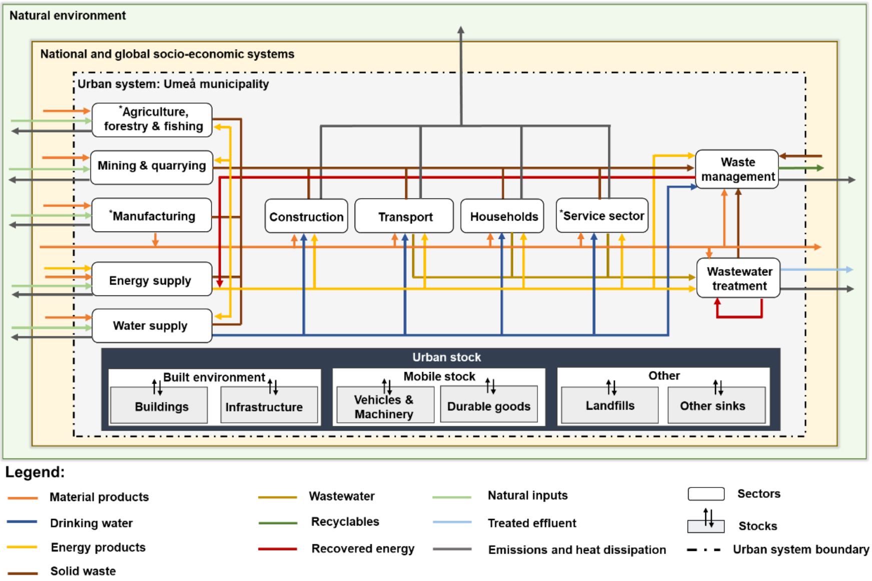


Figure 2: A conceptual model illustrating the urban metabolic system of Umeå and its sectors. Sectors marked with an asterisk (*) were not included in the assessment (Source: **Paper III**)

Quantification of material and energy flows and stocks

The quantification of flows and stocks was based on a model built in Microsoft Excel using urban-level data from statistics, articles and reports specific to Umeå. Data gaps were addressed using national or regional data, data from other Swedish urban areas, or by applying the principles of mass and energy balance. The mass balance principle is described by Equation 1:

$$\sum_{i=1}^{n_i} m_{input,i} = \sum_{o=1}^{n_o} m_{output,o} + \Delta m_{stock} \qquad (1)$$

where n_i and n_o represent the number of inputs and outputs in a process, respectively, $m_{input,i}$ the mass of material input i, $m_{output,o}$ the mass of material output o, and Δm_{stock} material stock changes.

The energy balance principle is described by Equation 2:

$$\sum_{i=1}^{n_i} e_{input,i} = \sum_{o=1}^{n_o} e_{output,o} + \Delta e_{stock} \qquad (2)$$

where n_i and n_o represent the number of inputs and outputs in a process, respectively, $e_{input,i}$ the energy input i, $e_{output,o}$ the energy output o, and Δe_{stock} energy stock changes.

For certain materials, their stock changes were first estimated applying the coefficient-based method, which uses data on the physical size of a stock type along with specific material intensity coefficients associated with it (Gontia et al., 2018). Next, the material inputs to the urban system were determined using the mass balance principle and available data on waste outputs.

Illustration and interpretation of results

The results of MEFA were organized into structured tables (or accounts) per sector and visualized through graphs and Sankey diagrams. Their interpretation was done both for the entire urban system and for individual sectors. Additionally, a qualitative uncertainty analysis was performed to identify key sources of uncertainty and discuss their potential impact on the results.

3.2.4 Urban metabolic life cycle assessment

In **Paper IV**, the UM-LCA approach was applied to Umeå to gain insights into its applicability and utility as a decision-support tool for designing, monitoring and assessing urban-level circular strategies. More specifically, the UM-LCA approach was used to retrospectively analyze the UM and environmental performance of Umeå, and to prospectively evaluate the environmental impacts of potential future circular strategies, as detailed below.

Retrospective UM-LCA

The retrospective UM-LCA (rUM-LCA) was carried out using the results of the retrospective MEFA (rMEFA) from **Paper III** as a basis for compiling the LCI of the retrospective LCA (rLCA). The rLCA was conducted following the four-step procedure of ISO 14040 (ISO, 2006a) (see 2.4.3). The modeling was performed using the open-source LCA software Activity Browser (Steubing et al., 2020), which builds on the Brightway2 LCA framework (Mutel, 2017).

The goal of the rLCA was to assess the environmental performance of Umeå and its sectors in 2021. The analyzed system comprised the foreground and the background systems. The foreground system included the same urban sectors and flows analyzed in rMEFA (see Fig. 2) to enable the integration of the two methods. The background system encompassed all upstream and downstream processes outside the urban boundaries that supply materials and energy to the urban system or handle its residues (e.g., waste).

As regards the functional unit, the study opted not to define an explicit functional unit, following the approach used in previous studies (García-Guaita et al., 2018; Goldstein et al., 2013; González-García et al., 2021). The rationale behind this approach is that urban areas are complex systems performing multiple functions that cannot be captured by a traditional functional unit. Thus, instead of defining a functional unit, the annual environmental impacts of the urban system were normalized on a per capita basis.

For the modeling, the attributional approach was applied considering that the rLCA is primarily descriptive, aiming to account for environmentally relevant physical flows to and from the urban system, rather than directly supporting decisions (Finnveden et al., 2009). This choice aligns with the International Reference Life Cycle Data System (ILCD) handbook, which suggests using the attributional approach for such decision contexts (defined as situation C, accounting) (Bjørn et al., 2018).

The LCI was constructed combining the results of rMEFA with data from the Ecoinvent cut-off system model database (v-3.8) (Wernet et al., 2016), which is consistent with the attributional approach. To ensure consistency with the cut-off Ecoinvent database, the "cut-off approach" was employed to address multi-functionality in end-of-life processes.

For the LCIA, the ReCiPe 2008 Midpoint (H) method (Goedkoop et al., 2009) was used. Among the midpoint impact categories of the method, the following 12 were assessed: Climate change (CC) (with a 100-year time horizon), Ozone depletion (OD), Agricultural land occupation (ALO), Terrestrial acidification (TA), Freshwater ecotoxicity (FET), Particulate matter formation (PMF), Freshwater eutrophication (FE), Terrestrial ecotoxicity (TET), Human toxicity (HTT), Fossil depletion (FD), Metal depletion (MD) and Water depletion (WD).

Prospective UM-LCA

The prospective UM-LCA (pUM-LCA) aimed to evaluate the environmental impacts of implementing different circular strategies in Umeå in 2030, based on future scenarios. As suggested by Arvidsson et al. (2018), future scenarios were defined for both the foreground and background systems (see Figure 3) to avoid temporal mismatches between the two systems. The three foreground scenarios (FSs) describe the implementation or non-implementation of circular strategies in Umeå (i.e., the foreground system) by 2030. The two background scenarios (BSs) represent wider technological, socio-economic and environmental developments in the background system by 2030.

The FSs include a reference scenario (FS1), which depicts Umeå in 2030 without any circular strategy in place, and two scenarios (FS2, FS3), which involve the implementation of specific circular strategies in Umeå by 2030. FS2 ("Promoting reduced consumption") represents the implementation of a circular strategy focused on reducing material consumption in the construction and household sectors. FS3 ("Increased recycling") portrays the implementation of a strategy aimed at promoting recycling in the two sectors. The two scenarios focus on the construction and household sectors, as they were identified as key sectors within Umeå's UM by the rUM-LCA (see Section 4.2). They were defined based on the 4Rs principle of the CE, which emphasize not only the importance of recycling and recovery but also the need to reduce resource consumption. Since the scenarios were shaped by the results of the rUM-LCA, they are context-specific to Umeå and thus not directly applicable to other urban areas. This aligns with the framework proposed in **Paper V**, which suggests defining FSs based on contextual information derived from the rUM-LCA.

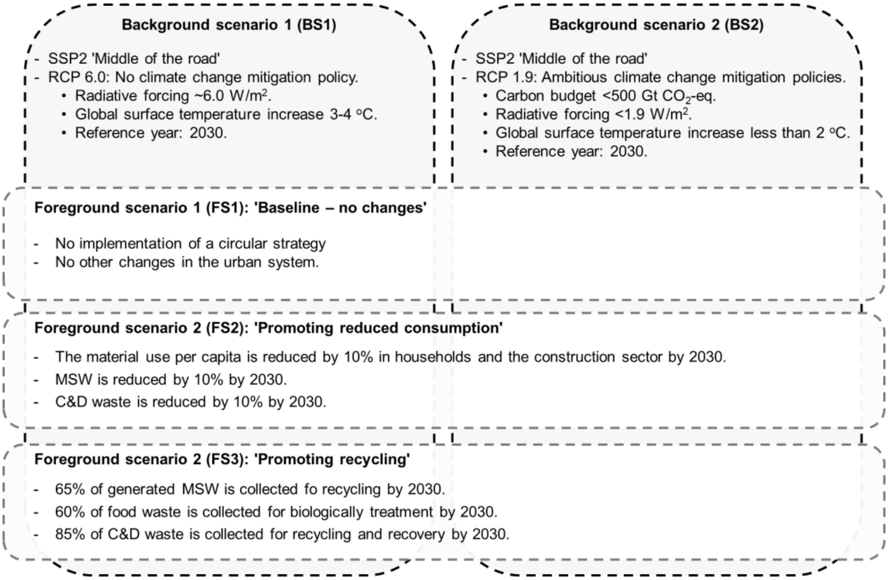


Figure 3: The six combinations of the three FSs and two BSs (Source: **Paper IV**)

The two background scenarios (BSs) were obtained from the *premise* tool (Sacchi et al., 2022), which generates prospective LCIs (pLCIs) by transforming the Ecoinvent database according to scenarios generated by Integrated Assessment Models (IAM). Both scenarios align with the shared socio-economic pathway “Middle-of-the road” (O’Neill et al., 2014), reflecting socio-economic and technological changes according to historical trends. However, they depict two distinct Representative Concentration Pathways (RCPs) for greenhouse gases (GHGs) by the end of the century (van Vuuren et al., 2011). BS1 corresponds to RCP 6.0, a less optimistic trajectory without climate change mitigation policies, projecting global radiative forcing to reach 6 W/m² by the end of the century. Conversely, BS2 corresponds to RCP 1.9, depicting a more optimistic pathway characterized by ambitious climate mitigation policies aimed at limiting radiative forcing to 1.9 W/m².

Based on the FSs, a prospective MEFA (pMEFA) was conducted first to quantify the material and energy flows in Umeå in 2030. For this purpose, the parameters of the MEFA model developed in **Paper III** were adjusted in accordance with the specifications of the three FSs. The results of pMEFA were then used to model the foreground systems for the pLCA, maintaining the same system boundaries as in the retrospective assessment. For the background systems, two pLCIs were created by implementing the two BSs in the *premise* tool. The pLCIs were then integrated in the Activity Browser LCA software. Similar to the rLCA, the assessment was conducted without specifying an explicit functional unit and for the same 12 impact categories of the ReCiPe 2008 Midpoint (H) LCIA method. To handle multifunctionality and ensure that the three FSs are functionally equivalent, the “equal basket of benefits” approach (Barrera et al., 2016; Goronovski et al., 2018; Vandermeersch et al., 2014) was used.

3.2.5 Approach to develop the assessment framework

The framework proposed in **Paper V** builds upon the UM-LCA and indicator-based approaches. As a first step, a five-phase structure integrating the two approaches (see Figure 10) was developed, drawing on existing frameworks from the literature (Brunner & Rechberger, 2017; ENEL and The European House - Ambrosetti, 2020; ISO, 2006a; Luthin et al., 2024).

Next, an indicator-based framework for assessing urban circularity (henceforth referred to as indicator dashboard) was developed. The dashboard is organized around five domains, which represent key pillars of the CE: 1) *Sustainable inputs*, 2) *Extension of useful life*, 3) *Increase of the intensity of use*, 4) *End-of-life*, and 5) *Governance*. The first four pillars were drawn from the CE Scoreboard, a set of CE indicators developed by ENEL and The European House – Ambrosetti (2020) to measure the level of CE development within the EU. These pillars were adopted for the dashboard, as they align with the 4Rs principle of the CE (Kirchherr et al., 2017), emphasizing the need to reduce resource consumption besides promoting recycling and recovery. The fifth pillar, *Governance*, was added to capture governance aspects, which is essential for evaluating a local government’s efforts to promote, enable, and facilitate the CE, as suggested by OECD (2020a).

Most of the dashboard's indicators were sourced from two comprehensive indicator inventories presented in **Paper I** and a study by OECD (2021), which included 305 and 474 CE indicators from the literature, respectively. To ensure validity, transparency, and applicability, the indicators were selected based on the RACER criteria, as suggested by Eisenmenger et al. (2016) and the Bellagio declaration on CE monitoring principles (EEA, 2020). Through this process, 21 indicators were chosen. Additionally, six new indicators were developed by the authors of **Paper V** to enhance the scope of the dashboard.

4. Results and analysis

This chapter presents the main results of the five papers appended to this thesis in relation to the three RQs outlined in Section 1.2.

4.1 Availability, strengths and limitations of indicator-based frameworks

Papers I and **II** addressed the first research question of the thesis: "*What is the availability of indicator-based frameworks for assessing and monitoring CE progress at the urban level, and what are their strengths and limitations?*"

The goal of **Paper I** was to map and assess indicator-based frameworks that can be applied to monitor and assess progress towards the CE at the urban level. The literature review identified 15 macro-level indicator-based frameworks (Table 8), each containing multiple indicators structured in different thematic areas. Among these frameworks, nine (CEMF, MFEML, KIMCE, CB, EISCED, CEEIS, CEAIS, CES, EISCE) were originally designed for CE monitoring at the national or regional level. However, they were included in the study, as their indicators were deemed relevant for assessing circularity in urban settings.

The identified frameworks were assessed against the eight criteria outlined in Table 5. The assessment revealed that none of the frameworks fully meets all the assessment criteria, and that there was a considerable variation in their compliance with these criteria (see Table 8). Overall, most frameworks performed relatively well against Criteria 1-6, though, two frameworks (EISCED and EISCE) do not fully satisfy any of these six criteria. Moreover, it is noteworthy that seven frameworks fail to meet Criterion 6, indicating that these frameworks may not have been developed in line with specific CE principles, potentially lacking solid theoretical foundations.

For Criterion 7, the assessment highlighted that none of the frameworks fulfills all the validity requirements specified in Table 6. The best-performing frameworks (CEMF, CB and UAF) meet eight of the twelve requirements, while the worst-performing ones (ACM and EISCED) satisfy only three. Most frameworks include indicators that measure progress in reducing resource consumption, material losses and waste and increasing the use of renewable and recycled resources. However, they lack indicators to measure emission reductions, maximized product utility and durability, increased social wellbeing and value-added creation and distribution. Furthermore, most frameworks do not include indicators that can monitor intervention efforts to enable the transition towards the CE. This lack of indicators that can capture multiple aspects of the CE in many of the identified frameworks narrows their scope, limiting their potential to comprehensively assess circularity.

It is also important to note that eleven frameworks include various contextual indicators that describe the wider socio-economic, environmental and demographic context in urban areas, such as GDP, unemployment rate and income. Among these, five frameworks (CCAF, ACM, EISCED, CEAIS, and EISCE) predominantly consist of such indicators. While these indicators offer valuable insights into the broader context in which the CE transition can occur, they do not directly evaluate the level of circularity. As a result, the focus of frameworks that include such indicators tend to be less centered on CE aspects.

Table 8 - Assessment of the indicator-based frameworks against the eight assessment criteria (C) (C1: Transparency, C2: Stakeholder engagement, C3: Effective communication, C4: Ability to track temporal changes, C5: Applicability, C6: Alignment with specific CE principles, C7: Validity, C8: Relevance to sustainable development).

Framework	**Acronym**	**Source**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7***	**C8****
The Circular City Analysis Framework	CCAF	Cavaleiro de Ferreira & Fuso-Nerini (2019)	P	Y	P	N	N	N	6 req.	4 pil.
Peterborough Circular Economy Indicators	PCEI	Morley et al. (2018)	Y	Y	Y	N	P	Y	4 req.	4 pil.
Urban Circular Development Index	UCDI	N. Wang et al. (2018)	P	N	N	P	N	Y	4 req.	4 pil.
Urban Agenda Framework	UAF	Urban Agenda for the EU (2019)	Y	Y	N/A	N/A	N/A	N	8 req.	4 pil.
Amsterdam Circular Monitor	ACM	City of Amsterdam (2020)	Y	Y	Y	Y	P	N	3 req.	3 pil.
London Circularity Indicators	LCI	Cambridge Econometrics (2018)	Y	Y	Y	Y	Y	N	6 req.	3 pil.
Circular Economy Monitoring Framework	CEMF	EC (2018a)	Y	Y	Y	Y	Y	N	8 req.	4 pil.
Monitoring Framework for Economy-wide Material Loop closing	MFEML	Mayer et al. (2019)	Y	N	Y	Y	Y	Y	4 req.	1 pil.
Key Indicators for Monitoring the Circular Economy	KIMCE	Magnier et al. (2017)	Y	N	Y	Y	Y	Y	6 req.	3 pil.
Circularity Baseline	CB	EMAF (2015a)	P	N	Y	N	Y	Y	8 req.	4 pil.
Evaluation Index System of Circular Economy Development level	EISCED	Jiang (2011)	N	N	N	N	N	N	3 req.	2 pil.
Circular Economy Evaluation Indicator System	CCEEIS	Geng et al. (2012)	Y	Y	N/A	N/A	N/A	Y	4 req.	2 pil.
Circular Economy Assessment Index System	CEAIS	Yang et al. (2011)	Y	N	N	P	N	Y	6 req.	2 pil.
Circular Economy Scoreboard	CES	ENEL and The European House – Ambrosetti (2020)	Y	Y	Y	Y	Y	Y	7 req.	3 pil.
Evaluation Indicator System for Circular Economy	EISCE	Avdiushchenko & Zajac (2019)	P	N	N	P	N	N	4 req.	2 Pil.

Y: Yes, N: No, P: Partially, N/A: Not applicable

* It shows the number of the validity requirements fulfilled by the framework.

** It shows the number sustainable development pillars reflected by the indicators of the framework

Lastly, for Criterion 8, the assessment revealed that only six frameworks (CCAF, PCEI, UCDI, UAF, CEMF and CB) incorporate indicators that capture aspects related to all four pillars of sustainable development - environmental, social, economic and governance. It also showed that the scopes of most frameworks are primarily focused on environmental aspects, though some also adequately address economic aspects. This finding aligns with prior studies (Corona et al., 2019; De Pascale et al., 2020; Kristensen & Mosgaard, 2020; Superti et al., 2021; Vinante et al., 2021), which highlighted that there is underdevelopment of indicators capturing social and governance aspects across the micro, meso and macro levels of the CE. This unbalanced distribution of indicators within the studied frameworks is a key limitation, as it restricts their ability to capture how progress towards the CE can contribute to sustainable development.

Overall, **Paper I** revealed that although there are several macro-level indicator-based frameworks available, they vary significantly in their structures, scopes and attributes. This lack of standardization could reduce consistency in CE monitoring at the urban level and complicate comparisons among different urban areas. The paper also highlighted that all frameworks have limitations, as none of them fully met all the assessment criteria. However, certain frameworks met most criteria to a considerable extent, amongst which was the EC's CEMF.

Paper II examined further the strengths and limitations of the CEMF as a monitoring tool for urban areas by applying it to Umeå. For this purpose, the CEMF was amended, as described in Section 3.2.2. The application of the amended CEMF to Umeå demonstrated that it is a well-structured framework, with indicators that track progress across four thematic areas (see Table 9). In the *Production and consumption* thematic area, the indicators reveal trends in various waste streams (e.g., municipal waste) and assess the inclusion of CE or waste prevention criteria in municipal procurement processes. In the *Waste management* area, the framework's indicators monitor recycling and recovery rates for different waste streams. In the *Secondary raw materials* area, the *CMU rate indicator* measures the level of circular material use, while the other indicators track the trade of secondary raw materials. Lastly, in the *Competitiveness and innovation* area, the respective indicators shed light on how the CE contributes to the creation of jobs, investment and gross value added, and measure the number of CE-related patents as a proxy for innovation.

This structured approach to monitoring CE progress across different thematic areas is a key strength of the CEMF. Another strength is its ability to facilitate multiscale comparisons, as most of its indicators are calculated and regularly updated for the EU and all EU member countries (Eurostat, 2025). In the case of Umeå, this feature of the framework facilitated direct comparisons of its indicators with those for Sweden, providing a benchmark of Umea's progress against the national level. For instance, Figure 4 highlights that the recycling rates for municipal waste, overall packaging and plastic packaging (indicators 5.1, 6.1 and 6.2) in Umeå are comparable to national averages.

Table 9 - The indicators of the amended CEMF calculated for Umeå.

Thematic area	No	Sub-indicators	2014	2015	2016	2017	2018	2019	2020	Unit
Production and consumption	1	Self-sufficiency for raw materials	-	-	-	-	-	-	-	%
	2	CE/waste prevention criteria developed in guidelines for procurement	No	No	No	No	No	No	No	-
	3.1	Generation of municipal waste per capita	451	464	464	456	451	438	438	kg/cap
	3.2	Generation of waste excl. major mineral wastes per GDP unit	53.8	n/a	59	n/a	56.9	n/a	-	kg/k€
	3.3	Generation of waste excl. major mineral wastes per domestic material consumption	12.9	n/a	14.8	n/a	13.6	n/a	-	%
	4	Generation of food waste per capita	96.3	95.6	95.6	97	95.4	93	93.6	kg/cap
Waste management	5.1	Recycling rate of municipal waste	43	43	43	44	44	41	41	%
	5.2	Recycling rate of all waste excluding major mineral waste	54.2	n/a	52.8	n/a	54.2	n/a	-	%
	6.1	Recycling rate of overall packaging	74.9	66.4	73.5	78.6	76	59.1	-	%
	6.2	Recycling rate of plastic packaging	50.5	45.3	54.7	53.1	54.2	49.5	-	%
	6.3	Recycling rate of wooden packaging	23.7	19.9	33.3	55.3	55.4	27.7	-	%
	6.4	Recycling rate of e-waste	56.0	47.7	59.7	51.6	49.2	-	-	%
	6.5	Recycling of biowaste	66.9	55.6	55.6	63.9	63.1	61.3	65.7	kg/cap
	6.6	Recovery rate of construction and demolition waste	52	n/a	59.5	n/a	89.3	n/a	-	%
	6.7	Biologically treated food waste, including home comp.	32	34	34	37	39	40	44	%
Secondary raw materials	7.1	End-of-life recycling input rates	-	-	-	-	-	-	-	%
	7.2	Circular material use rate	10.5	n/a	11.2	n/a	10.8	n/a	10.6	%
	8.1	Imports to Umeå from non-EU countries	8.5	8.2	8.3	7.7	9.4	9.6	6.8	kt
	8.2	Exports from Umeå non-EU countries	17.8	14.2	19.9	20.4	19.9	20.5	22.5	kt
	8.3	Imports to Umeå from EU countries	7.2	6.3	6.5	6.9	6.9	7.1	5.3	kt
Competitiveness and innovation	9.1	Gross investment in tangible goods	0.09	0.09	0.09	0.07	0.08	0.12	-	% of GDP
	9.2	Persons employed	1.01	1.08	1.04	1.09	1.06	1.05	-	% of total empl.
	9.3	Value added at factor cost	0.69	0.69	0.64	0.69	0.67	0.77	-	% of GDP
	10	Number of patents	0	0	0	0	0	0	-	-

n/a: Not available

An additional strength of the CEMF is that it contains indicators that facilitate comparisons against specific policy targets. For example, Figure 4a compares the recycling rate of municipal waste with the target defined by the regional waste plan (Umeå region, 2020). Similarly, Figures 4b and 4c compare the recycling rates for overall and plastic packaging against targets established by the EU Packaging and packaging waste directive (2018/852) (EC, 2018b). This feature makes CEMF a valuable tool for tracking progress towards existing policy targets and even for informing the development of new ones.

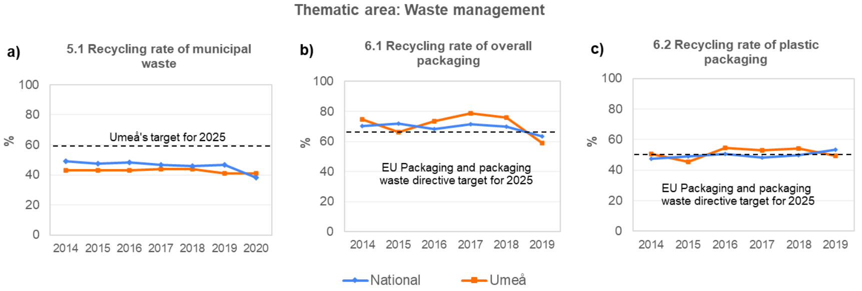


Figure 4: Indicators 5.1 (a), 6.1 (b) and 6.2 (b) of the *Waste management* thematic area in Umeå and Sweden. Fig. 4a displays the target for municipal waste according to the regional waste plan and Fig. 4b and 4c recycling rate targets for overall and plastic packaging according to the EU Packaging and packaging waste directive (2018/852) (Source: **Paper II**)

However, while the application of the CEMF to Umeå demonstrated its strengths as a monitoring tool for urban areas, it also uncovered key limitations. One major limitation is the scarcity of high-quality data for urban-level applications of the framework. The data source mapping revealed that reliable urban-level data were available for only 8 out of the 24 indicators of the framework. For the remaining indicators, the only available data were at the regional or national level, necessitating downscaling to the urban level. This downscaling process diminishes data quality, introducing uncertainty into the results. This limitation is an important factor to consider, as it can restrict the applicability of CEMF as a monitoring tool for urban areas.

Another limitation of the CEMF is that it predominantly comprises indicators focused on waste and material resources, while lacking indicators related to other resources, e.g., energy and water, as previously noted by Paiho et al. (2020). Additionally, it does not include indicators that effectively capture other important aspects of the CE, including material reuse and maximizing product utility and durability. Notably, the CEMF also lacks indicators to measure progress in reducing emission levels (e.g., GHG, pollutants), which limits its potential to identify environmental benefits and trade-offs of transitioning to a CE. This lack of indicators able to capture multiple aspects related to the CE reduce the potential of CEMF to comprehensively monitor and assess progress toward the CE at the urban level.

Moreover, the CEMF lacks a system perspective, as its indicators are organized solely based on their connection to its thematic areas and not based on an explicit system definition that links the indicators to specific processes and flows within the socio-economic system. This is a key limitation. As noted in the literature, the lack of systems perspective may lead to CE monitoring based on incoherent indicators (Pauliuk, 2018) and may limit the ability to capture all key processes and flows within the studied system (Helander et al., 2019).

These limitations of the CEMF could constrain its applicability as a monitoring tool for urban areas. In response to these findings, **Paper II** made three key recommendations for facilitating and improving the application of CEMF and other indicator-based frameworks. First, it proposed establishing appropriate systems and processes, particularly within municipalities, for collecting and managing high-quality urban-level data. Second, it suggested adopting a systems perspective when monitoring progress toward the CE. To achieve this, the paper proposed to combine indicator-based frameworks with UM assessment methods, which offer a comprehensive systems perspective. This idea was further examined in **Papers III**-**V**. Third, it recommended broadening the scope of the CEMF or similar frameworks to encompass multiple aspects in CE monitoring. Specifically, the paper proposed using relevant indicators that capture multiple aspects (e.g., environmental pressures, energy, governance aspects), including the LCIA indicators of the LCA methodology. These ideas were further explored in **Papers IV** and **V**.

4.2 Applicability and utility of UM assessment methods

Papers III and **IV** addressed the second research question of the thesis: *“What is the applicability and utility of MEFA and UM-LCA in supporting the design and monitoring of urban-level circular strategies?”*

Paper III applied a bottom-up approach to analyse the UM of Umeå based on MEFA, with the aim to examine the applicability and utility of MEFA in informing the design and monitoring of urban-level circular strategies.

The application of MEFA offered an in-depth quantitative analysis of material (including water) and energy flows across various sectors of the urban system, revealing critical sectors in terms of resource consumption, waste generation and emissions. As illustrated in Figure 5, the construction sector and households emerged as critical sectors during the study period (2017-2021). The construction sector used the largest amounts of materials (excluding water) and generated the largest quantities of solid waste, primarily construction and demolition waste (CDW), influencing overall trends in material use and waste generation. Households were the largest consumers of energy and drinking water and the primary producers of wastewater and GHG emissions. They were also the second-largest consumers of materials and generators of waste.

Besides indicating critical sectors, the application of MEFA also provided detailed information on the type and magnitude of key flows within the urban system. For example, it highlighted that the main inputs to the urban sectors included construction materials (i.e., aggregates and concrete), food products, drinking water and fossil fuels (i.e., diesel and gasoline). It also showed that the use of fossil fuels, primarily by the transport sector and households (for private transport), was the principal source of fossil GHG emissions in Umeå.

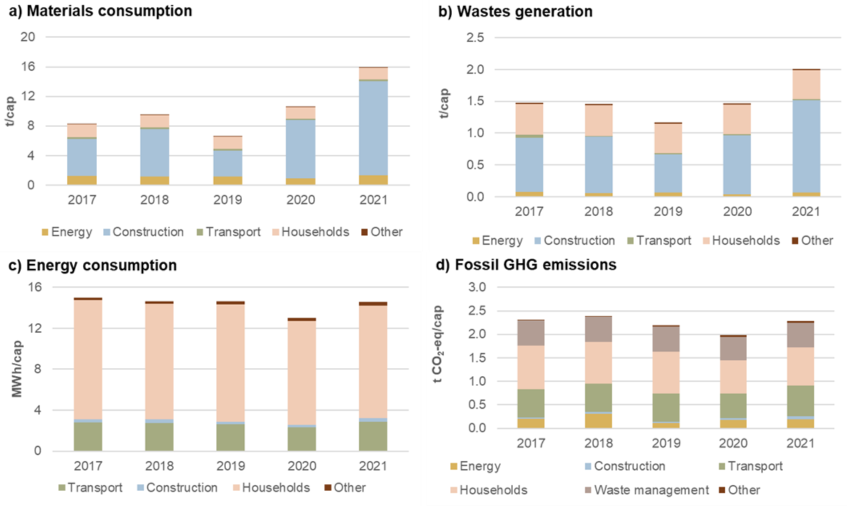


Figure 5: The contributions of the urban sectors to materials use (a), waste generation (b), energy use (c), and fossil GHG emissions (d). Note that (b) does not include the waste management sector, as this sector receives waste from other sectors and (c) does not include the energy sector, as this sector supplies energy to the other sectors (Source: **Paper III**).

Furthermore, quantitative data derived from MEFA facilitated the visualization of main waste flows and processes within the waste management sector through a Sankey diagram (Figure 6). The diagram revealed that most of the municipal solid waste (MSW) in Umeå was either sorted for recycling or incinerated for energy recovery, with only a small portion being landfilled. It also showed that about three quarters of CDW were sorted for recycling or used for recovery operations at the landfill (for covering and construction), together with compost, stabilized sludge from the wastewater treatment plant, and non-hazardous combustion ash from the incinerator.

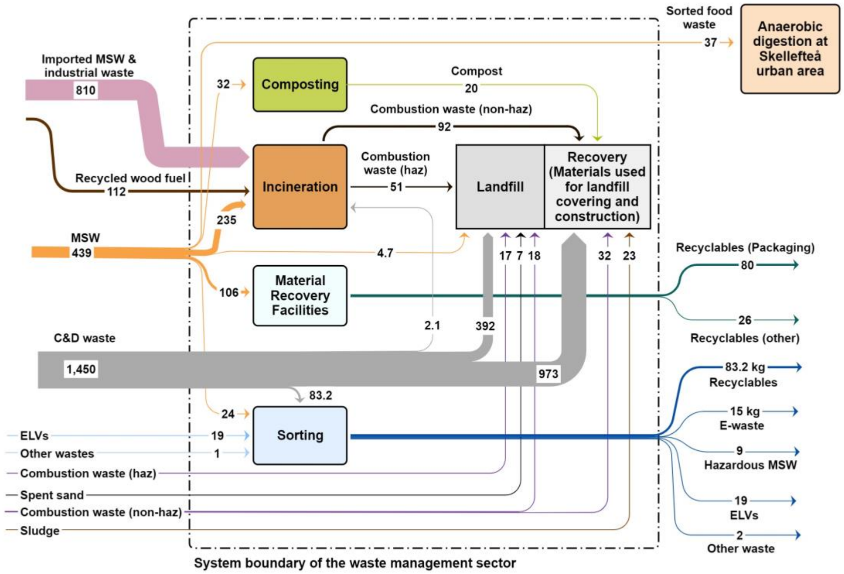


Figure 6: A Sankey diagram depicting the waste management sector in Umeå in 2021, with flows measured in kg/cap (Source: **Paper III**).

This ability to provide detailed quantitative information on urban metabolic flows is a key strength of MEFA, making it particularly useful in designing urban-level circular strategies. Such information could enable decision makers to identify and prioritize key sectors and flows within the urban system, facilitating the design of circular strategies with material- and sector-specific targets and measures. This approach aligns with the EC's Circular Economy Action Plan (EC, 2020), which also prioritizes specific sectors and materials. Moreover, detailed information about waste processes and flows can support decision-makers in driving improvements in the waste management sector. For instance, in Umeå, where over half of MSW is incinerated for energy recovery, a circular strategy could set specific measures and targets to redirect recyclables, from incineration to recycling or reuse, adhering to the 4Rs (reduce, reuse, recycle, and recover) principle of the CE (see Section 2.2.1). The strategy could also encourage recycling options for CDW, which is currently directed to recovery operations at the local landfill.

Additionally, MEFA has great potential to support the monitoring of implemented circular strategies. As illustrated in the Umeå case, applying MEFA over a multi-year period allows for tracking temporal shifts in resource consumption, waste generation and emissions. This information can assist decision makers in assessing the effectiveness of implemented circular strategies in improving the UM of an urban area. Furthermore, quantitative data obtained from MEFA can form the basis for developing and calculating CE indicators. Importantly, MEFA offers a systems perspective of the studied urban system, facilitating the connection of the developed indicators to specific processes and flows of the system.

While the application of MEFA to Umeå demonstrated its utility as a decision-support tool in the CE context, it also emphasized several limitations. A major limitation is its strong reliance on the availability of urban-level data, which is often limited for certain sectors. In the Umeå case, the scarcity of readily available data for the manufacturing, service, and agriculture, forestry, and fishing sectors resulted in their exclusion from the assessment. Another limitation is the absence of a standardized classification system for material and energy flows in MEFA applications. To contribute to addressing this limitation, **Paper III** proposed a comprehensive classification system for use in UM studies. Additionally, MEFA's scope is confined to a territorial perspective, without considering the global hinterland of the urban system. Lastly, MEFA assesses flows solely based on their mass and energy content, without considering environmental impacts associated with these flows, a limitation previously highlighted in the literature (Giljum & Hubacek, 2009; Goldstein et al., 2013; Stephan et al., 2020). To address the last limitation, **Paper III** suggested combining MEFA with LCA, an idea further developed in **Paper IV**.

Paper IV applied the UM-LCA approach to retrospectively assess the environmental performance of Umeå in 2021 and to prospectively assess potential environmental impacts of different future circular strategies. Through this application, the paper aimed to examine the potential of UM-LCA to inform the design and monitoring of circular strategies for urban areas.

The retrospective application of UM-LCA complemented the findings of MEFA in **Paper III**, providing a more comprehensive understanding of Umeå's environmental performance. The rLCA highlighted that, although households consumed significantly less materials than the construction sector, they were the primary drivers of environmental impacts in Umeå, as they were the largest contributors to all impact categories, except for OD, for which the waste management sector was the main contributor (see Figure 7). As regards the construction sector, which MEFA identified as a key sector in terms of material use and waste generation, it contributed to most impact categories, though to a lesser extent than households, or waste management in OD. These findings emphasized the importance of considering environmental impacts alongside resource consumption and waste generation when analyzing urban systems. This comprehensive perspective helps to identify not only sectors where resource consumption and waste generation can be reduced (e.g., the construction sector), but also sectors that offer opportunities to significantly lower environmental impacts (e.g. households). Thus, it can more effectively guide the design of f impactful and well-targeted circular strategies.

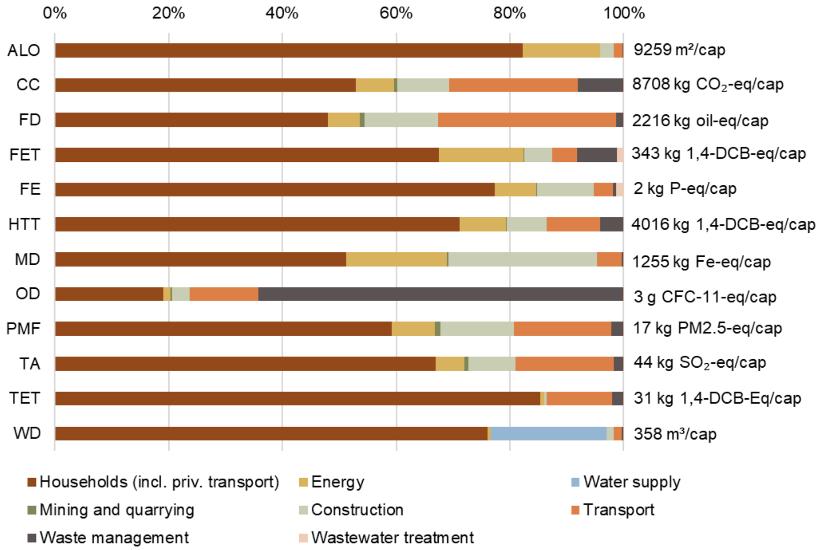
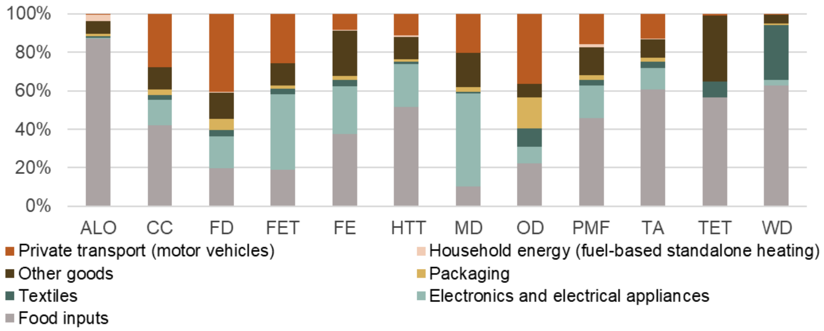


Figure 7: Contributions of sectors to Umeå's environmental impacts (ALO – agricultural land occupation; CC - climate change; FD - Fossil depletion; FET - freshwater ecotoxicity; FE - freshwater eutrophication; HT - human toxicity; MD – Metal depletion; OD - ozone depletion; PMF - particulate matter formation; TA - terrestrial acidification; TET - terrestrial ecotoxicity; WD - water depletion). (Source: **Paper IV**).

Moreover, the rLCA provided valuable insights into which metabolic flows contribute the most to the environmental pressures exerted by the urban system. It revealed that food products consumed by households were the largest contributors to eight environmental impact categories (see Figure 8a), with animal-based products (e.g., meat and dairy) being the primary sources of impact in most categories (see Figure 8b). It also highlighted that fossil fuels used for private transport, as well as smaller material inputs into households like textiles, electrical appliances and electronics, contribute considerably to environmental impacts (see Figure 8a). Therefore, reducing the consumption of these materials should be a key priority in a circular strategy, as it can substantially improve Umeå's overall environmental performance

a) Households



b) Food inputs in households

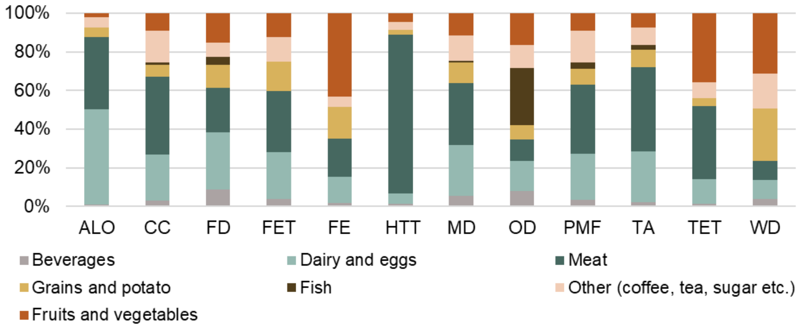


Figure 8: Distribution of environmental impacts caused by households (a), and distribution of environmental impacts from food inputs to households (b) (ALO – agricultural land occupation; CC - climate change; FD - Fossil depletion; FET - freshwater ecotoxicity; FE - freshwater eutrophication; HT - human toxicity; MD – Metal depletion; OD - ozone depletion; PMF - particulate matter formation; TA - terrestrial acidification; TET - terrestrial ecotoxicity; WD - water depletion). (Source: **Paper IV**).

At the same time, the pLCA demonstrated that a circular strategy prioritizing measures to reduce material use in households and the construction sector could (FS2) offers greater environmental benefits compared to a strategy focused solely on recycling (FS3) (see Figure 9). Notably, the analysis also revealed that increased recycling in FS3 could even lead to slightly higher impacts in Terrestrial Ecotoxicity than the baseline scenario (FS1), highlighting the potential of LCA to capture such trade-offs. In addition, the pLCA emphasized the importance of considering future developments in the background system, as they significantly influenced the performance of the FSs. As shown in Figure 9, the environmental impacts across the three FSs were lower in all but three impact categories (ALO, TET and WD) under the optimistic BS2, which, unlike the baseline BS1, encompasses ambitious climate change mitigation policies (see Figure 3).

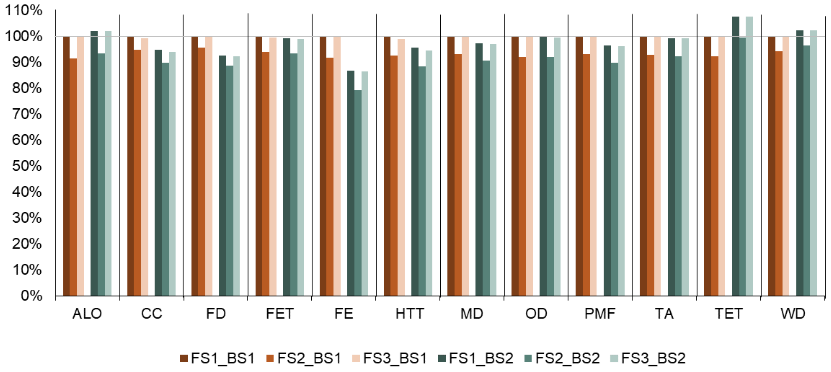


Figure 9: The environmental impacts of the assessed scenario combinations normalized to FS1_BS1 scenario (FS1_BS1 = 100%) (ALO – agricultural land occupation; CC - climate change; FD - Fossil depletion; FET - freshwater ecotoxicity; FE - freshwater eutrophication; HT - human toxicity; MD – Metal depletion; OD - ozone depletion; PMF - particulate matter formation; TA - terrestrial acidification; TET - terrestrial ecotoxicity; WD - water depletion). (Source: **Paper IV**).

Overall, applying the UM-LCA approach to Umeå demonstrated its significant potential as a decision-support tool in the CE context. By conceptualizing the urban system from an UM perspective, it enables a systems perspective, facilitating its modeling as a network of multiple interacting sectors. This allows for a more in-depth analysis of the urban system, helping decision makers focus on critical sectors. Furthermore, the coupling of MEFA and LCA provides complementary information on material and energy flows along with environmental impacts associated with these flows. Such information facilitates the assessment of flows based not only on their mass and energy content, but also on their embodied environmental impacts. This, in turn, can help decision makers prioritize sectors and flows in a circular strategy, targeting those that offer the greatest opportunities for reducing environmental impacts.

Additionally, applying the UM-LCA prospectively based on different scenarios for both the foreground and background systems further enhances its utility as a decision support tool. As demonstrated in the Umeå case, the analysis of the FSs highlighted the importance of reducing material consumption to improve Umeå's future environmental performance. At the same time, the analysis of BSs revealed that Umeå's future environmental performance does not only depend on implementing circular strategies within the urban area, but also on broader developments in the background system. For instance, if the global socio-economic system develops according to the less optimistic BS1, the anticipated benefits of implementing a circular strategy promoting reduced consumption may not be fully realized, something that decision makers need to consider when setting the level of ambition for targets in a circular strategy.

It is also important that the coupling of MEFA with LCA in the UM-LCA approach creates opportunities for enhanced monitoring of the progress of implemented circular strategies. By combining MEFA and LCA, rather than using MEFA alone, it becomes possible to track changes in material and energy flows together with environmental impacts over time. In this way, the UM-LCA can provide more comprehensive information, allowing decision makers to better appraise the effectiveness of implemented strategies in reducing resource use, waste and environmental impacts.

Nevertheless, the UM-LCA approach also has limitations. Firstly, since it builds on MEFA, its applicability is largely dependent on the availability of urban-level data, which, as previously discussed, can be limited, especially for some sectors. Moreover, the process-based modelling approach of UM-LCA relies on representative LCI datasets to describe urban metabolic flows. However, given the extensive variety of metabolic flows in an urban system, it is practically impossible to use fully representative datasets for all of them, as such data are not always available in existing LCI databases like Ecoinvent. Consequently, proxy datasets need to be used, introducing uncertainty in the results.

Furthermore, although the integration of MEFA with LCA enables a life cycle perspective that accounts for environmental impacts beyond urban boundaries, it cannot fully describe the exact metabolic relationships between the urban system and its hinterlands. This limitation hinders the analysis of metabolic flows from a spatial perspective, which could be achieved using a multiregional input–output approach, as demonstrated by Bahers & Rosado (2023). Consequently, information from applying the UM-LCA approach are insufficient for guiding the development of targeted measures aimed at reducing environmental impacts in specific locations outside the urban boundaries.

Another limitation stems from the approach to normalize the gross annual environmental impacts on a per capita basis instead of using a traditional functional unit (see Section 3.2.4), which prevents the consideration of different socio-economic factors in the assessment. As a result, the assessment cannot capture differences in quality of life, income and lifestyle among the urban citizens (Albertí et al., 2019; Goldstein et al., 2013). This restricts the potential of the UM-LCA approach to reveal how these socio-economic factors influence the environmental pressures exerted by the urban system (Albertí et al., 2019; Goldstein et al., 2013), hindering the development of circular strategies with measures tailored to the socio-economic conditions of urban citizens.

Lastly, although the UM-LCA approach can provide valuable insights into metabolic flows and environmental impacts, it has limited potential to provide information on specific aspects of the CE. For example, it cannot provide information on waste management performance (e.g. recycling rates), resource efficiency, material reuse, and governance aspects. To obtain this type of information, the UM-LCA approach needs to be integrated with relevant CE indicators. This idea was further explored in **Paper V**.

4.3 A framework to assess UM and circularity

Paper V addressed the third research question of the thesis: *“How can the indicator-based and UM-LCA approaches be integrated to provide a comprehensive assessment of UM and circularity in urban areas, supporting decision-making within the context of the CE?”*

The paper introduced a novel framework that integrates the indicator-based and UM-LCA approaches to assess the UM and circularity of urban areas to inform decision-making in the CE context. The framework is depicted in Figure 10. It comprises the following five phases:

> **Phase 1 – Overall aim definition:** In this initial phase, the overall aim of the assessment is defined, specifying the reasons for carrying out the assessment, the intended use of the results and the target audience.
>
> **Phase 2 – Retrospective UM-LCA:** In the second phase, the UM-LCA approach is applied retrospectively to analyze the urban system, offering insights into how it metabolizes resources and causes environmental impacts. This phase consists of two sub-phases: rMEFA and rLCA. The rMEFA is conducted following the methodology by Brunner and Rechberger (2017) and using the conceptual model in Fig. 2 to define the relevant flows, stocks, and processes of the urban system. The rLCA follows the four-step procedure described in ISO 14040 (ISO, 2006).
>
> **Phase 3 – Circularity assessment (CA):** In the third phase, the level of circularity of the urban system is assessed across five CE pillars: 1) *Sustainable inputs*, 2) *Extension of useful life*, 3) *Increase of the intensity of use*, 4) *End-of-life*, and 5) *Governance*. The assessment is carried out by calculating the indicators of the dashboard presented in Table 10.
>
> **Phase 4 – Prospective UM-LCA:** This phase is optional. It is conducted if the goal is to assess the environmental impacts of various future circular strategies to identify which ones can lead to most environmental benefits. Phase 4 is carried out by applying the UM-LCA approach prospectively, using future scenarios for both the foreground and background systems. It includes two sub-phases: pMEFA and pLCA. The pMEFA is conducted to quantify metabolic flows in the urban system as described by the foreground scenarios. The pLCA is performed to assess environmental impacts from the implementation of circular strategies in the urban system (foreground system), while also accounting for changes in the background system.
>
> **Phase 5 – Interpretation:** In the final phase, the results from the rUM-LCA, pUM-LCA and CA are interpreted in relation to the overall aim and specific goals of the assessment, leading to conclusions and recommendations. As part of the interpretation process, data quality checks, sensitivity analyses, and uncertainty analyses (either qualitative or quantitative) can be performed to evaluate the robustness of the assessment.

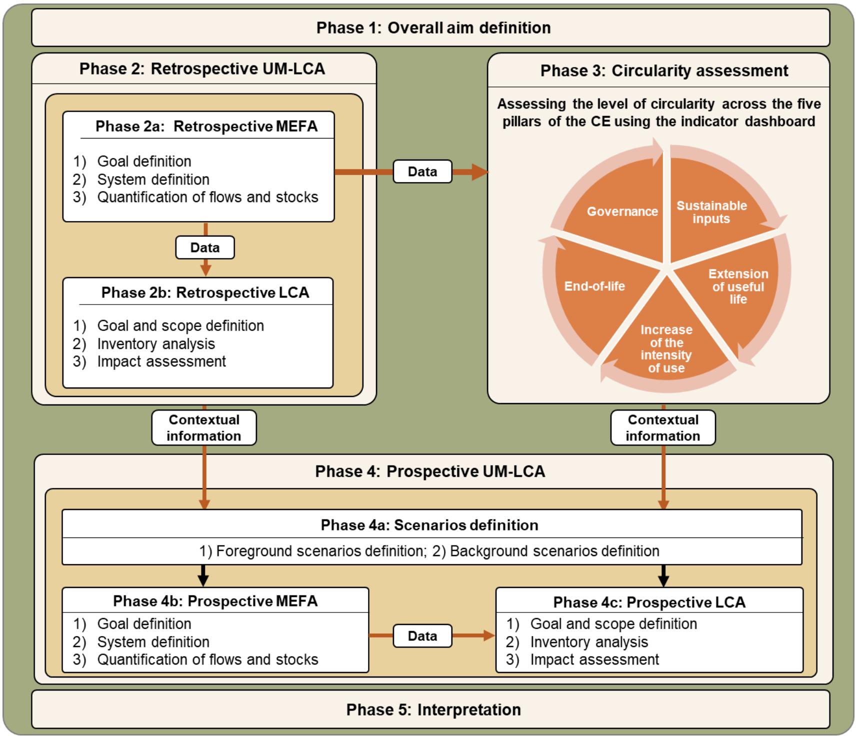


Figure 10: The proposed framework and its five main phases (rMEFA: retrospective MEFA, rLCA: retrospective LCA, pMEFA: prospective MEFA, pLCA: prospective LCA).

The applicability and utility of the proposed framework were demonstrated through its application to Umeå. The overall aim of the assessment, as defined in Phase 1, was to inform the development of a new circular strategy for Umeå by retrospectively analyzing its UM and circularity and by prospectively assessing the environmental impacts of potential future circular strategies. The primary target audience included local policy makers and urban planners. The rUM-LCA in Phase 2 was carried out building on the results obtained from the application of rMEFA and rLCA in **Papers III** and **IV**. To simplify the demonstration of the framework, the rUM-LCA was limited to a single year (2021), since applying the rLCA with a muti-year time frame would have been a very data-intensive process. The CA assessment in Phase 3 was performed by computing the indicators of the dashboard for a five-year period (2017-2021) using urban-level data. In Phase 4, the pUM-LCA was conducted based on the foreground and background scenarios of **Paper IV** (see Fig. 3) and the respective results of pMEFA and pLCA.

The interpretation of the results was done in Phase 5. Only the results of the CA (Phase 3) are discussed here, as the main findings of the rUM-LCA (Phase 2) and pUM-LCA (Phase 4) were already covered in Section 4.2. The CA, based on the indicators outlined in Table 10, revealed varying levels of progress across the five CE pillars. On the one hand, Umeå has made considerable progress in minimizing landfilling of MSW, attaining relatively high recovery and recycling rates for CDW and MSW, and decarbonizing its energy system, which mainly relies on renewable energy. On the other hand, there are areas that still require improvement, such as increasing the share of renewable energy in total energy consumption, mainly by reducing fossil fuel use in transportation, improving efficiency in water supply, maximizing collection rates of recyclables, increasing public transport use, and incorporating CE criteria into procurement guidelines.

The CA also revealed that certain indicator values changed only slightly during the study period, indicating marginal improvements or even declines in certain areas. A key issue is that, although electricity and district heating production are largely decarbonized (Indicators 1 and 2), the share of non-renewables in final energy consumption remained almost steady during the study period (Indicator 3). The main reason is that the transport sector is largely dependent on fossil fuels (Indicator 4), highlighting the need for systemic changes in this sector. At the same time, it is equally important to intensify efforts in areas where performance is already strong. For example, Indicators 10 and 11 show that, although the shares of CDW and MSW collected for recovery and recycling were relatively high, they remained almost steady during the study period, indicating that there is room for improvement.

Achieving further progress across the five CE pillars requires a systematic implementation of targeted measures, which could be part of a comprehensive circular strategy. Based on the findings of the CA, along with insights from the rUM-LCA and pUM-LCA, the following recommendations can be made to help shape such circular strategy:

1. Prioritize reductions in material consumption, particularly in households and the construction sector.
2. Focus on reducing the use of the most environmentally impactful materials, including food (especially animal-based products), fossil fuels, textiles, electrical appliances and electronics.
3. Increase the share of renewable energy in final energy consumption.
4. Optimize the utlilization of Umeå's public transport system, which has been fossil free since 2017.
5. Maximize the collection rates of all recyclables, ensuring that only non-recyclable materials are incinerated for energy recovery.
6. Improve efficiency in water supply by minimizing distribution losses.
7. Incorporate CE criteria into procurement processes.

Table 10 - The indicators of the dashboard calculated for Umeå.

No	Indicator name	Unit	2017	2018	2019	2020	2021
Sustainable inputs pillar							
1	Share of ren. energy in electricity production	%	96.5%	95.6%	96.8%	96.5%	96.9%
2	Share of ren. energy in district heat production	%	80.7%	77.9%	83.2%	81.3%	81.7%
3	Share of ren. energy in final energy consumption	%	58.2%	54.5%	59.6%	59.7%	57.7%
4	Share ren. energy in total energy use for transp.	%	11.1%	10.3%	9%	9.6%	9.4%
5	Energy intensity in water supply	kWh/m^3	0.83	0.84	0.87	0.82	0.88
6	Percentage of drinking water loss	%	17.8%	17.6%	17.3%	17%	16.7%
End-of-life pillar							
7	Generation of MSW	kg/cap	456.4	451.0	438.0	438.0	439.0
8	Generation of food waste	kg/cap	97.0	97.4	95.0	95.5	101.2
9	Generation of CDW	kg/cap	843	891	594	922	1 450
10	Recovery rate of CDW	%	70.5%	71.8%	70.3%	72.1%	72.8%
11	Share of MSW collected for recycling (including biological treatment)	%	42.9%	41%	41.3%	41.6%	45.6%
12	Share of MSW incinerated for energy recovery	%	55.4%	54.3%	54.1%	53.2%	53.5%
13	Share of MSW disposed in landfills	%	1%	1%	1%	5.5%	1.1%
14	Share of biologically treated food waste (including home composting)	%	37%	39%	40%	44%	41%
15	Share of sewage sludge treated for energy or nutrients recovery	%	100%	100%	100%	100%	100%
Extension of useful life pillar							
16	Materials collected and diverted for reuse	kg/cap	n/a	4.3	4.7	3.0	4.5
17	Number of second-hand shops in the urban area	Number	12	11	11	13	14
18	Employment in repair and reuse activities	% of total employm.	0.8%	0.8%	0.8%	0.8%	0.8%
Increase of the intensity of use pillar							
19	Number of bike sharing platforms available within the urban area	Number	1	1	1	1	1
20	Number of car sharing platforms available within the urban area	Number	5	5	5	4	4
21	Number of donation and sharing spaces within the urban area	Number	1	1	1	1	1
22	Collective transport on total passenger transport	% of pkm	n/a	15%	16%	14.1%	12.4%
Governance pillar							
23	CE criteria included in procurement guidelines	Yes/No	No	No	No	No	No
24	Availability of a CE strategy at city level	Yes/No	No	No	No	No	No
25	Availability of a municipal web platform for information on the CE	Yes/No	No	No	No	No	No
26	Number of projects initiated by the municipality to develop territorial synergies between economic actors	Number	0	0	0	0	0
27	Participation in international networks for CE	Number	1	1	1	2	2

Overall, the application of the framework to Umeå emphasized its primary strength: the potential to provide comprehensive information on metabolic flows, environmental impacts, and circularity of the urban system. Another strength is its flexibility, as the framework can be adapted to suit specific user needs. Depending on data availability, it could be applied to specific sectors or areas (e.g., districts) within the urban area or with varying time resolution (e.g., monthly). Moreover, the interpretation process can be tailored to meet the goals of users and the needs of the target audience, while the pUM-LCA in Phase 4 can be applied selectively, only where there is a need to assess future strategies.

These strengths make the framework particularly valuable as a decision-support tool in various contexts. As demonstrated in the Umeå case, the framework can be applied at the early-design phase of a new circular strategy to inform the development of the strategy. Another potential application is for monitoring the progress of strategies already in place. Specifically, the framework can be systematically applied (e.g., annually) to identify temporal changes in metabolic flows and environmental impacts, and track progress across the five CE pillars, allowing for the evaluation of a strategy's effectiveness in improving the UM, environmental performance and circularity of the urban system.

However, the application of the framework also revealed some of its weaknesses. A key weakness is that its application is a rather laborious process, as the combined application of the UM-LCA approach with the indicator dashboard requires extensive data, which, as demonstrated in **Papers II, III** and **IV**, are not always readily available. Another weakness is its complexity, largely because of the UM-LCA approach, which requires expertise in applying MEFA and LCA. This complexity is further amplified by the prospective application of UM-LCA in Phase 4, which requires additional expertise in tools for building prospective LCIs, such as the *premise* tool.

Furthermore, there are weaknesses associated with the indicator dashboard included in the framework. One weakness is the dashboard's limited capacity to capture socio-economic aspects (e.g., affordability and accessibility of CE services, changes in consumer behavior), due to the small number of relevant indicators. Moreover, although the dashboard draws on existing frameworks and indicators, it does not significantly contribute to standardization in the field, as its indicators do not fully align with those of any other dashboards. Another weakness is that the dashboard mainly reflects the context of urban areas in Sweden or other developed countries. This may limit its applicability to other urban areas, with different socio-economic, environmental and regulatory conditions, or where local authorities have limited resources (e.g., inadequate data collection and management systems, lack of expertise). Addressing the weaknesses of the dashboard as well as of the entire framework requires further research, as discussed in Section 5.4.

5. Discussion

The first section of this chapter (Section 5.1) critically discusses how CE assessment at the urban level can be advanced, drawing on the key findings of this thesis. The subsequent sections present the main contributions of this thesis (Section 5.2), discuss key limitations of the research (Section 5.3), and suggest potential directions for future research (Section 5.4).

5.1 How to advance CE assessment at the urban level?

The CE has been described as an 'irreversible, global megatrend' (EC, 2019), steadily gaining traction among academics, policy makers and businesses worldwide. For urban areas, it is widely seen as a promising approach to address the pressing challenges of unsustainable urbanization, with numerous local governments actively working to develop and implement circular strategies. In this context, this thesis aims to advance knowledge on approaches to monitor and assess CE progress at the urban level to support informed decision-making, particularly in the design and implementation of circular strategies.

Papers I and **II** provided valuable insights into the indicator-based approach to monitoring and assessing CE progress, with a particular focus on indicator-based frameworks. **Paper I** identified 15 frameworks in the literature that could be applied at the urban level (Section 4.1). The study revealed significant variability among these frameworks in terms of structure, scope, and attributes, indicating a lack of standardization. It also highlighted that their scopes are generally not comprehensive enough to capture multiple aspects related to the CE and the four pillars of sustainable development (environmental, economic, social and governance). Notably, some frameworks included several contextual indicators describing aspects less related to the CE, suggesting that these indicators may have been selected solely for their ease of measurement, rather than their relevance. This issue, previously identified in municipal indicators for monitoring progress on the SDGs (Zinkernagel et al., 2018), raises the risk of adopting incoherent frameworks that focus on aspects unrelated to the CE.

Paper II provided a more in-depth exploration of the indicator-based approach by applying the CEMF to Umeå (Section 4.1). This empirical exercise illustrated that the CEMF provides a structured approach to monitor and assess CE progress in urban areas based on relatively easy-to-interpret indicators. It also highlighted the framework's ability to support multi-scale comparisons (e.g., evaluating urban progress compared to national trends), which could contribute to standardizing practices in the field. However, the study also highlighted limitations of the CEMF as an assessment tool for urban areas. It revealed that it lacks a systems perspective, focuses mostly on material and waste flows, and its applicability heavily relies on the availability of urban-level data. This reliance poses significant practical challenges, as such data are often not accessible, an issue that is not unique to the CEMF, as it affects the applicability of most urban-level indicator-based tools (Kopp et al., 2024).

Overall, the findings of **Papers I** and **II** suggest that indicator-based frameworks can be useful tools in monitoring and assessing CE progress at the urban level, largely due to their ability to structure and effectively convey complex information. Nevertheless, the two papers also highlighted limitations of available indicator-based frameworks, particularly in relation to data constraints and their rather limited scopes. Consequently, relying solely on indicator-based frameworks cannot provide all the necessary information for decision-making in the CE context. This echoes the views of scholars (Kopp et al., 2024; Purvis & Genovese, 2023; Walzberg et al., 2021) who suggested combining the indicator-based approach with other assessment approaches, including UM assessment methods.

The idea of using UM assessment methods to monitor and assess CE progress at the urban level is not new. However, previous studies (Kalmykova & Rosado, 2015; Kopp et al., 2024; Lucertini & Musco, 2020; Petit-Boix et al., 2022) have discussed this idea from a conceptual point of view, without demonstrating the applicability and utility of these methods through empirical applications. **Papers III** and **IV** addressed this lack of empirical work by applying two UM assessment methods, MEFA and UM-LCA, to Umeå.

Paper III highlighted that MEFA can serve as a useful decision-support tool in the CE context (Section 4.2). Its application with a bottom-up approach enables an in-depth quantitative analysis of urban metabolic flows from a systems perspective, offering insights that indicators alone cannot provide. More specifically, it can reveal critical sectors in terms of resource use and waste generation within the urban system and identify the most significant flows by magnitude. These insights can be valuable in designing circular strategies with targeted measures for specific sectors and flows. Additionally, its application with a multi-year timeframe provides quantitative data that can reveal trends in metabolic flows, facilitating the evaluation of the effectiveness of implemented circular strategies in improving the urban system's metabolism.

However, **Paper III** also revealed significant challenges and limitations associated with MEFA. It highlighted that applying MEFA following a bottom-up approach is a challenging and time-consuming task due to high data demands. It also emphasized that MEFA is limited to assessing metabolic flows solely based on their mass and energy content, disregarding associated environmental impacts. Thus, using only MEFA to analyze UM cannot fully support decision-making when designing and monitoring circular strategies, as it cannot identify critical sectors and flows in terms of environmental impacts.

As demonstrated in **Paper IV**, the limited capacity of MEFA to account for environmental burdens can be addressed by applying a life cycle perspective through the UM-LCA approach (Section 4.2). By integrating MEFA with LCA, UM-LCA enables a comprehensive assessment that also includes environmental impacts embedded in urban metabolic flows. This integration makes UM-LCA a powerful tool in supporting the design and monitoring of circular strategies. Additionally, as shown in **Paper IV**, the application of UM-LCA with a prospective approach enhances its utility as a decision support tool by enabling the evaluation of the environmental impacts of future circular strategies, thereby helping to identify those that offer the greatest environmental benefits.

Nevertheless, **Paper IV** also emphasized that the coupling of MEFA with LCA significantly increases data requirements, as it necessitates the use of multiple LCI datasets in addition to material and energy flow data. These extensive data demands make the application of UM-LCA challenging, potentially limiting its broader applicability. Furthermore, the UM-LCA approach has limited potential to address specific aspects of the CE, such as resource efficiency, recycling rates, and governance aspects, due to the lack of relevant indicators. Thus, employing the UM-LCA approach without using appropriate CE indicators cannot fully support decision-making within the CE context.

In summary, **Papers I-IV** suggest that using the UM-LCA and indicator-based approaches in isolation can only provide fragmented and incomplete insights, which cannot fully support decision-making in the CE context. To adderess this fragmentation and advance CE assessment at the urban level, it is essential to integrate these two approaches. For this purpose, **Paper V** introduced a novel framework (Section 4.3) that combines the UM-LCA approach (applied both retrospectively and prospectively) with a dashboard of indicators structured around five CE pillars: 1) *Sustainable inputs*, 2) *Extension of useful life*, 3) *Increase of the intensity of use*, 4) *End-of-life*, and 5) *Governance*. By integrating these two approaches, the framework leverages the strengths of both, enabling a comprehensive assessment of UM and urban circularity. As demonstrated by its application, this assessment approach offers detailed insights into metabolic flows, environmental impacts and circularity, providing valuable information for informed decision-making in the CE context.

The framework, however, also has weaknesses, including its complexity, limited capacity to evaluate socio-economic aspects, and extensive data requirements. Among these, the high data demands pose a significant challenge to its applicability. As emphasized in this thesis, the data needed to calculate CE indicators and apply the UM-LCA approach are not always available or easily accessible at the urban level, and their quality is often questionable.

For MEFA especially, the bottom-up approach requires detailed data on material and energy flow and stocks, which are not systematically collected at the urban level by municipalities or statistical agencies. In Sweden, for instance, while open-access databases like Kolada (2025) and Opendata Umeå (2025) provide a broad range of urban-level data, they lack detailed material and energy flow data, aside from MSW. This complicated the application of MEFA to Umeå, as it required a laborious data collection process to gather the required data from multiple sources (for details see Section 3.2.3 and **Paper III**). Even with these efforts, significant data gaps remained, preventing the inclusion of certain sectors in MEFA and, by extension, in UM-LCA, while also necessitating assumptions and simplifications that introduced uncertainties.

This difficulty in accessing detailed, high-quality urban-level data, especially on material and energy flows and stocks, is one of the principal challenges in UM research (Athanassiadis, 2020; Neves et al., 2023). According to Kennedy & Hoornweg (2012), addressing this challenge is crucial for mainstreaming UM. This requires substantial efforts by municipalities, both in Sweden and worldwide, to establish effective and standardized systems for urban-level data collection and management, leveraging advancements in digital technologies and big data approaches (Creutzig et al., 2019; Geremicca & Bilec, 2024).

At the same time, it is equally important to develop specialized databases with standardized generic UM data for use when primary data are unavailable. Such databases could include, for example, standard emission factors, material weights, material intensity coefficients, and transformation rates for various processes within urban systems. A prominent initiative in this direction is the online, open-access platform Metabolism of Cities Data Hub (Metabolism of Cities, 2020), which aims to centralize diverse UM data from urban areas worldwide. Nevertheless, this platform has, for the moment, limited coverage of material and energy flows and stocks, as such data are often unavailable for certain urban areas or highly aggregated (e.g., total material consumption for an entire urban system). Consequently, despite the potential of this initiative, an established database with comprehensive flow and stock data is still lacking, complicating the application of MEFA and other UM assessment methods.

In light of the above, the key question that arises is *How to advance CE assessment at the urban level?* Addressing this multifaceted issue is not simple, as it requires advancement across various areas. This thesis identifies two critical areas for progress: 1) the integration of multiple assessment approaches and 2) the improvement of data availability and accessibility at the urban level. The framework proposed in **Paper V** contributes to progress in the first area by integrating the indicator-based and UM-LCA approaches. However, this framework should not be seen as a 'silver bullet' for CE assessment at the urban level, but rather as a foundational step for further development in this area. Further progress, though, can only be achieved if significant improvements are made in the availability, accessibility, and quality of urban-level data.

5.2 Contributions of the thesis

5.2.1 New insights and data

This thesis provides valuable insights into different approaches to monitor and assess progress toward the CE at the urban level. **Papers I** and **II** specifically focus on indicator-based frameworks. **Paper I** presents a comprehensive review of available frameworks, which could serve as a practical guide for policy makers, urban planners, researchers, and practitioners in identifying suitable frameworks based on their specific needs and objectives. **Paper II** provides empirical insights from the first-ever application of the CEMF in an urban setting, increasing understanding of its applicability, strengths and limitations as a tool for monitoring and assessing urban circularity while identifying opportunities for improving the framework and developing new tools.

Papers III and **IV** focus on UM assessment methods, offering empirical evidence on the applicability and utility of two core IE methods, MEFA and UM-LCA, in designing and evaluating urban-level circular strategies. By doing so, the two papers expand the range of methods available as decision-support tools in the CE context, going beyond the mainstream indicator-based approach. In this way, they contribute to fostering methodological pluralism in this area, as suggested by recent studies (Purvis & Genovese, 2023; Walzberg et al., 2021).

Beyond providing insights, this thesis also contributes valuable data. **Paper I** provides an extensive inventory of 305 CE indicators derived from the identified indicator-based frameworks, which could serve as a foundation for enhancing existing frameworks or developing new ones. **Paper II** offers a comprehensive mapping of available data sources that can support the application of various indicator-based frameworks for monitoring and assessing urban circularity, primarily within the Swedish context. Additionally, **Paper III** provides a thorough description of the data sources used for the MEFA of Umeå, which could guide and inspire similar applications, especially in Sweden.

5.2.2 Methodological and applied analytical advances

This thesis contributes to methodology development through the assessment framework introduced in **Paper V**. The framework offers a structured approach to integrating the UM-LCA and indicator-based approaches to assess the UM and circularity of urban areas. In its current form, it could support policy makers, urban planners, practitioners, and researchers in assessing UM and circularity in various urban settings. Furthermore, the proposed framework, along with insights from its application, lays the foundation for further research aimed at developing a user-friendly, digital tool.

Another important contribution is the advancement of the UM-LCA approach by demonstrating its application with a future-oriented perspective in **Papers IV** and **V**. To the author's knowledge, this is the first prospective application of the UM-LCA approach in the literature. By applying the UM-LCA prospectively, this thesis presents a powerful approach to assess the future environmental performance of urban systems, which can provide valuable insights for decision-making not only within the context of the CE but also in the broader context of sustainable urban development.

5.3 Research limitations

To address the research questions of this thesis, a combination of qualitative and quantitative methods was employed. While the limitations of each method are discussed in the appended papers and Sections 4.1–4.3 and 5.1 of this cover essay, this section highlights two key overarching research limitations.

One key limitation is that the research presented in Papers **II-V** is based on a single study area, making it difficult to generalize some of the results to other urban contexts. Umeå is a representative Swedish urban area, characterized by population growth, economic development, and high levels of resource use (see Sections 3.1.1 and 4.2). Consequently, the results of the assessments in **Papers II–V** are mainly relevant to urban areas with similar characteristics, primarily in Sweden. For example, the results of **Paper IV**, which identify households in Umeå as main contributors to environmental impacts (see Section 4.2), are most likely applicable to other urban areas in Sweden or other developed countries where residents have similar consumption habits. Likewise, the results of **Papers III** and **IV**, which indicate that the energy system does not significantly contribute to overall GHG emissions despite increased heating demands due to cold climate (see Section 4.2), are mostly relevant to other Swedish urban areas with largely decarbonised district heating systems like that in Umeå.

Furthermore, the governance context in Umeå is mainly representative of urban areas in Sweden and other developed countries, rather than developing countries. In Umeå, the local government is committed and actively working to promoting the CE model (see Section 3.1.1). As in many developed countries, this commitment is likely driven by aspirations to shift away from the prevailing linear paradigm to achieve environmental, social and economic benefits (Haswell et al., 2024). In contrast, in developing countries, local governments often play a less active role in promoting the CE, with initiatives primarily led by the private sector and civil society (Ddiba et al., 2020), usually due to resource scarcities, inadequate waste management and needs for job creation and income generation (Haswell et al., 2024). Thus, applying assessment approaches to support the design and implementation of circular strategies, as in the case of Umeå, may not be as relevant to urban areas in developing countries, where local governments often lack the motivation and capacity to drive CE initiatives.

Nevertheless, it should be emphasized that the aim of this thesis was not to analyse the UM and circularity of a specific urban area but to provide insights into the applicability, utility, strengths and limitations of the examined methods and approaches. While these insights can be influenced by the local context (e.g., availability of urban-level data), they have broader relevance beyond the specific case of Umeå. Specifically, they can be valuable to policy makers, urban planners, practitioners, and researchers worldwide, by offering a deeper understanding of how the indicator-based approach and UM assessment methods can be used to support decision making within the CE context. Thus, even though not all assessment methods and approaches explored in this thesis may be directly applicable to every urban setting, the insights gained could guide their application in certain contexts and inspire further research to improve their effectiveness and applicability.

The second limitation of the thesis is its predominant emphasis on the environmental pillar of sustainable development, with relatively less attention given to the social and economic pillars. This emphasis on the environmental pillar is particularly evident in **Papers III** and **IV**, which explore the use of UM assessment methods to evaluate environmental aspects. It is also reflected in the framework proposed in **Paper V**, which, in its current form, has limited capacity to address social and economic aspects, as it lacks relevant indicators and methods to evaluate such aspects. However, it should be highlighted that the proposed framework should not be viewed as a final solution but as a starting point for further research aimed at advancing CE assessment at the urban level.

5.4 Recommendations for further research

This thesis demonstrates the significant potential of integrating the indicator-based and UM-LCA approaches through the framework presented in **Paper V**. However, further development of the framework is required to strengthen its capacity to evaluate socio-economic aspects. A promising direction for further exploration is the integration of social LCA (sLCA) and Life Cycle Costing (LCC) in the framework to enable holistic assessments of the sustainability impacts of both existing and future circular strategies. Achieving this integration requires additional work to incorporate sLCA and LCC into the UM-LCA approach, creating an enhanced version of UM-LCA that could support decision-making across multiple contexts.

Furthermore, since this thesis is limited to a single study setting, additional applications of the proposed framework could be carried out to different urban areas, both in developed and developing countries. Such applications would provide a better understanding of the broader applicability and utility of the framework as a decision support tool in diverse urban settings, highlighting potential areas for improvement. Moroever, they could help determine which indicators in the dashboard are relevant across multiple contexts, providing ideas for refining the dashboard to become a standardized tool for urban areas.

Another avenue for future research is to investigate how the framework can be developed into a software application. As discussed in this thesis, implementing the framework in its current form is a complex task requiring expertise in applying various approaches and methods. The primary challenge stems from the use of the UM-LCA approach, as no existing tool integrates MEFA with LCA under an UM perspective. Thus, developing a digital tool to facilitate the application of the UM-LCA approach, both retrospectively and prospectively, is paramount. This tool could then be complemented with a digital version of the indicator dashboard, facilitating the full application of the framework.

Lastly, a key area for further research is improving the availability, accessibility and quality of urban-level data. This is essential not only for applying the framework proposed in this thesis, but also for facilitating the application of other methods and approaches to assess urban sustainability. Achieving this requires efforts in several key directions, including developing standardized practices for municipal data collection and management, leveraging digitization opportunities, advancing urban data science, fostering collaborative data-sharing initiatives, and creating specialized databases with comprehensive generic UM data.

6. Conclusions

The aim of this thesis was to advance knowledge on approaches to monitor and assess CE progress at the urban level to support informed decision-making within the context of the CE. This was achieved by investigating how the indicator-based approach and two UM assessment methods, MEFA and UM-LCA, can be used to assess circularity and guide the design and implementation of circular strategies at the urban level. The key conclusions of the thesis are summarized below in relation to the three RQs.

> *RQ1: What is* the *availability of indicator-based frameworks for assessing and monitoring CE progress at the urban level, and what are their strengths and limitations?*

The literature review in **Paper I** identified 15 macro-scale indicator-based frameworks that can be applied to monitor and evaluate progress towards the CE at the urban level. The assessment of these frameworks against specific criteria revealed significant variations in their structures, scopes, and attributes, indicating a lack of standardization in the field. It also revealed that all identified frameworks have limitations, particularly regarding their scopes, as they all lack sufficient indicators to comprehensively capture multiple aspects related to the CE and the four pillars of sustainable development (environmental, social, economic and governance). Nonetheless, certain frameworks, including the CEMF, performed relatively well in the assessment by meeting most of the criteria to a fair extent, suggesting that they have greater potential for monitoring and evaluating CE progress in urban areas.

The potential of the CEMF as a monitoring tool for urban areas was further explored by applying it to Umeå in **Paper II**. The study showed that the CEMF is a well-structured framework comprising a manageable number of relatively easy-to-interpret indicators that facilitate multiscale comparisons. However, it also has limitations, as it mostly focuses on material and waste flows, lacks a systems perspective, and its applicability is constrained by the limited availability of high-quality urban-level data.

Based on the findings of **Papers I** and **II,** it can be concluded that, although indicator-based frameworks are useful in monitoring and assessing CE progress at the urban level, they are insufficient on their own to provide all the necessary information for decision-making in the CE context due to their limitations.

> *RQ2: What is the applicability and utility of MEFA and UM-LCA in supporting the design and monitoring of urban-level circular strategies?*

Paper III demonstrated that MEFA has the potential to support the design and monitoring of urban-level circular strategies, as it can provide an in-depth quantitative analysis of material and energy flows from a systems perspective, providing detailed insights into the UM of urban systems. Nevertheless, the paper also emphasized that the applicability and comprehensiveness of MEFA are highly dependent on the availability of urban-level data, which can be often limited. It also highlighted that MEFA is limited to assessing metabolic flows solely based on their mass and energy content, without considering embedded environmental impacts.

Paper IV illustrated that the coupling of MEFA with LCA in the UM-LCA approach can address the limitation of MEFA to overlook environmental burdens, by providing a comprehensive assessment of environmental impacts embedded in material and energy flows from a life cycle perspective. This coupling makes the UM-LCA approach a powerful tool for supporting the design and monitoring of circular strategies by offering valuable insights into environmental pressures exerted by urban systems. Additionally, as shown in **Paper IV**, applying the UM-LCA prospectively strengthens its utility as a decision support tool by enabling the assessment of future circular strategies, helping to identify the most environmentally beneficial ones. However, the coupling of MEFA with LCA, especially with a prospective scope, increases complexity and data demands, making the application of UM-LCA challenging. Moreover, the UM-LCA approach has limited potential to address specific aspects of the CE, as it lacks suitable indicators. Thus, applying the UM-LCA approach in isolation, without employing appropriate indicators, cannot fully support decision-making within the CE context.

> *RQ3: How can the indicator-based and UM-LCA approaches be integrated to provide a comprehensive assessment of UM and circularity in urban areas, supporting decision-making within the context of the CE?*

Paper V emphasized the importance of integrating the UM-LCA and indicator-based approaches to support decision-making within the context of the CE. The paper introduced a novel framework that integrates the UM-LCA approach with an indicator-based framework comprising 27 indicators, which assess the level of progress across five CE pillars: 1) *Sustainable inputs*, 2) *Extension of useful life*, 3) *Increase of the intensity of use*, 4) *End-of-life*, and 5) *Governance*. By integrating the indicator-based and UM-LCA approaches, the framework leverages the strengths of both, enabling a comprehensive assessment of urban circularity and UM.

The application of the framework demonstrated its great potential to provide detailed insights into metabolic flows, environmental impacts and urban circularity for informed decision-making in the CE context. Nevertheless, the proposed framework also inherits the weaknesses of its components, including complexity of application and substantial data requirements. Additionally, in its current form, it has limited capacity to assess socio-economic aspects. Further research could be directed towards addressing these limitations by turning the framework into a digital tool to improve its applicability, enhancing its scope, and improving the availability and accessibility of urban-level data.

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