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The Urban Circularity Assessment Framework (UCAF): a Framework for Planning, Monitoring, Evaluation, and Learning from CE Transitions in Cities

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Abstract
While several studies have been undertaken to understand the circular economy (CE) in cities, there needs to be a comprehensive framework acknowledging why certain decisions related to the CE have been taken. This paper proposes a framework building on literature reviews on circular cities and engagements with cities. Our research objectives are to improve how the CE is understood at the city level; and support the planning, monitoring, evaluation, and learning on the CE at the city level. Our framework locates urban CE strategies and visions, biophysical and socio-economic urban stocks and flows, and institutional arrangements within the triple bottom line concept and conceptualises how they interact. Our case studies with two cities provide insight into the strengths and weaknesses of the cities' CE approaches. It can help identify priority interventions.

Keywords Circular economy · Circular cities · Framework · Indicators · Measurement

Abbreviations

CE	Circular economy
CO_2-e	Carbon dioxide equivalent
MEL	Monitoring, evaluation, and learning
NACE	Nomenclature of Economic Activities
SDG	Sustainable Development Goal
UCAF	Urban Circularity Assessment Framework

Highlights • As many cities embark on a circular economy (CE) transition, designing solid CE approaches is essential. The Theory of Change (ToC) methodology could be a valuable tool as it makes explicit the anticipated transition trajectory and provides clarity over assumptions.
• In this paper, we present the Urban Circularity Assessment Framework (UCAF), building on the ToC methodology to support cities with a practical tool visualising how they approach the CE. It consists of five components: (1) the vision related to the CE in the city; (2) the institutional arrangements and participation in the CE processes; (3) the CE strategies selected; (4) urban stocks and flows; and (5) societal impacts, measured through the triple bottom line.
• Our case studies in the cities of Umeå and Stockholm point to the framework's robustness and can assist municipalities in reflecting, learning, and improving their CE approach.

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Introduction

Globally, more than a hundred cities are adopting the circular economy (CE) to achieve planning goals of climate change mitigation, resource management, and societal welfare [1, 2]. The CE is an "economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes" [3, p. 229]. It focuses on "designing out waste and pollution, keeping products and materials in use, and regenerating natural systems" [4]. A common visualisation includes the butterfly diagram [5], which displays both a technical and biological cycle, with different methods to improve the material flows within society and reduce environmental impacts. Aside from the environmental benefits, the CE could contribute substantially to the economy in terms of job creation and lower costs for industry [6, 7].

The CE is a model for cities that can decouple urban development from resource consumption, thereby integrating economic welfare priorities with eradicating environmental pressures while addressing cities' socio-economic challenges [8–11]. Notably, the CE can capitalise on the spatial and economic proximity between stakeholders and resources to close material loops at the city level [12].

Yet, while some have argued that the CE has significant sustainability potential [9, 13–15], others suggest that the link between the current interpretation and practice of the CE model results in weak sustainability practices making its contribution to the realisation of Agenda 2030 goals negligible [16]. For many decision-makers, understanding how policies and strategies contribute to creating more sustainable societies is paramount [17, 18], including policies related to the CE. Indeed, even if a circular model–based intervention is deliberately designed to achieve strong sustainability, greater circularity does not necessarily entail direct environmental and socio-economic benefits across multiple systems [19]. Scholars call for caution when advocating "circularity for circularity's sake" when potential environmental and social trade-offs and rebound effects are not considered [12, 20, 21].

Therefore, to enhance overall circularity performance, there is a need to evaluate circular solutions, practices, and strategies to advance monitoring and governance of a complex transition towards a more CE [22, 23]. One methodology to do so is the Theory of Change (ToC), which "explains how a given intervention, or set of interventions, are expected to lead to a specific development change, drawing on a causal analysis based on available evidence" [24, p. 3]. It is widely used in the development sector, with aid agencies using it to clarify how change occurs and assumptions made. It describes how changes are expected to occur (ex ante) or how changes have occurred (ex post), allowing decision-makers to plan better and monitor and evaluate interventions [25]. Unlike the logical framework approach, ToCs are non-linear, with different pathways leading to impact; causal (explaining why a particular activity will cause a consequence); and explanatory in nature [26]. They entail understanding the organisation and the external environment and are strategic management tools. ToCs aim to improve learning, enhance accountability to local communities and funders, and clarify results and impacts [27].

This paper presents a framework to support the planning, monitoring, evaluation, and learning within cities on the CE. Our research objectives are to (1) improve how the CE is understood at the city level and (2) support the planning, monitoring, evaluation, and learning on the CE at the city level. Our research questions are:

- RQ1) What components should a CE framework cover to assist the planning, monitoring, evaluation, and learning of the CE at the city level?

- RQ2) What learnings arise from applying this framework in different contexts?

We do so as we have identified several knowledge gaps.

First, little research has managed to explain the causal links between the CE vision, stakeholder participation, strategies, urban stocks and flows, and the impacts of the CE on society. Current methods to measure the CE at the city level, such as urban metabolism (see, e.g. [28] for an application), have been found too narrow in scope, often focusing only on resource input and waste outputs [29]. The doughnut economy model [30], in turn, has been said to be too normative and not follow economic theory [31–33]. Our framework provides a systems perspective of the CE at the city level, linking with economy drivers and moving beyond materials and energy flows to understand the complexity of cities [34]. It moves beyond the waste and wastewater industry and recycling and recovering strategies to other sectors and R-strategies [1] and incorporates environmental impacts and socio-economic assessments [35–37]. Through the use of the ToC methodology (see, for instance, [38], who used it to evaluate circular business models), our framework allows to monitor the impacts of and link the CE to broader sustainability agendas and efforts [2, 23, 39].

Second, as noted by Carrière et al. [40], there are insufficient robust case studies on the CE at the city level. Basing our framework on the ToC implies an ability to use it for planning, monitoring, evaluation, and learning. Our case studies have provided learnings to the two cities in our sample but can also inform other practitioners and academia on how to design the CE within cities. To that end, a checklist was developed (see Supplementary material). It supports the challenge identified by several scholars in applying context-specific CE strategies [2, 35, 41, 42]. Our framework also provides insights into the data necessary to measure the CE at the city level [23, 39].

Our paper is structured as follows. The "Methods and Materials" section presents the methodology and materials used to arrive at our framework. Then, in the "The UCAF" section, we set out the framework and describe its components. The results of our analysis of the CE plans of the cities of Umeå and Stockholm against this framework are presented in the "Application of the UCAF to the Cities of Umeå and Stockholm, Sweden" section. The "Discussion" section contains a discussion, followed by a conclusion in the "Conclusion" section.

Materials and Methods

Our Urban Circularity Assessment Framework (UCAF) was developed iteratively over 3 years in the Urban Circularity Assessment Framework (UCAF) project.[1] Our research consortium involved two academic partners, two government actors (a municipal government and a municipally owned water and waste company), and two private sector companies. Below, we describe the methodology used to develop the UCAF, answering our first research question on the components of a CE framework to assist the planning, monitoring, evaluation, and learning of the CE at the city level. Then, we detail the aim and methods used in the case studies to capture the learnings from applying the UCAF in different contexts.

The UCAF design was based on several literature studies and engagement with our project consortium. First, we catalogued scientific and grey literature on circular cities published between 2010 and 2020 using the systematic mapping methodology [43]. As a result, we

[1] The UCAF project: https://www.sei.org/projects/urban-circularity-assessment-framework/.

mapped how 103 cities in 45 countries envisioned the CE, the sectors they focus on, and the strategies that have been applied [1]. We also used this systematic map to verify how the societal consequences of the CE had been understood [36], using the International Association of Impact Assessment's Social Impact Assessment methodology [44]. Furthermore, we reviewed the validity of indicators and frameworks to measure the CE at the city level [23]. Throughout this literature review process, we engaged with our consortium partners to ensure the usability and completeness of the framework. During several workshops (June 2020, December 2020, May 2021, April 2022, and October 2022), we discussed different components, visualisations, and connections between the other components of our UCAF. For example, the first workshop in June 2020 focused on co-defining the scope and boundaries of the framework. This was facilitated through open discussions in break-out groups on the status of ongoing work, data availability, and essential aspects and features of the framework. In a third workshop in May 2021, preliminary visualisations of different frameworks were presented, followed by ranking and prioritisation of the relevance of other indicators. In a fourth workshop in April 2022, the UCAF (Fig. 1) was introduced and finalised. A supplementary literature review was conducted in July 2022 to capture recently published papers on circular cities (2021–2022) that provide evidence for the UCAF. Finally, the UCAF was presented at several conferences to get insight from academia and other conference participants into the framework's robustness. This includes the European Cities and Regions Conference and the Circularity versus Sustainability Research Symposium, hosted by Greenhouse at the University of Stavanger, in collaboration with Stavanger Chamber of Commerce, Nordic Edge, and Grønn By in October 2022, and the UN's High-Level Political Forum side event on circular cities, organised by the Stockholm Environment Institute and GiZ in July 2023.

To test the framework, we carried out case studies, one with the city of Umeå in Northern Sweden and one with the city of Stockholm, the capital of Sweden. From June 2021 to April 2022, we ran case studies with the city of Umeå, one focusing on the level of CE in the city and the other on how social impacts had been considered in the

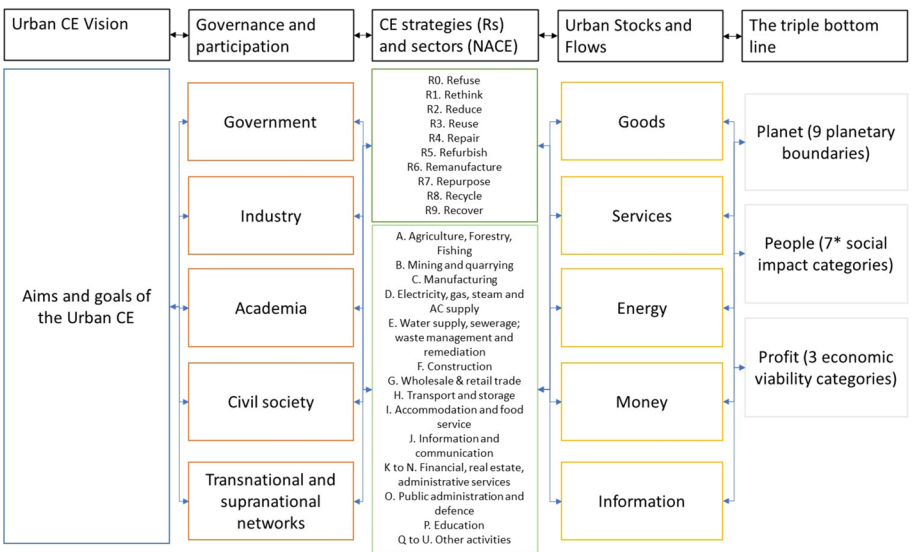

Fig. 1 The Urban Circularity Assessment Framework (UCAF)

plans. Those studies' data collection and analysis are detailed in [37, 45]. This research was supplemented with documents from the cities and initiatives they were involved in [46–53]. The document analysis was done inductively and iteratively [54]. All documents were read through several times, followed by a data extraction, organised according to the different components of the framework. Between April 2022 and October 2022, both case study cities confirmed the data extraction and analysis. In the next step, the case studies were compared against one another, allowing the addition of an evaluative element to the research using colour coding. A darker colour in the visualisation of the case study results indicated a stronger focus and better embeddedness of the component within the city's CE approach. This final assessment and colour coding was presented at the last workshop in October 2022 for the consortium to sign off on the learnings from the case study applications. In addition, the checklist (see Supplementary material) was shared with a researcher working on the CE. She filled it in with a city in Norway and subsequently provided feedback on the checklist. As we did not collect further data from the Norwegian city, we did not include the assessment in this study.

The UCAF

Overall, we identified five components to analyse and evaluate the city-level CE. These components are connected, whereby the status of one component or how it has been perceived influences the other components. The UCAF involves connections with the ToC methodology, which entails visioning, impact, and strategies [55]. According to Forti [56], good ToCs should cover (1) the target population; (2) results; (3) the period; (4) activities, strategies, and resources; (5) context; and (6) assumptions. We also embedded a process component that allows to understand how the CE strategy came into effect. In the below, we describe each component. In the Supplementary material, we provide a checklist that can guide the application of the UCAF to other case studies. The checklist contains an overview of each component, guiding questions, some selected indicators for each component, and means of verification, which can show cities in filling in the framework. On the UCAF project website, an interactive web tool is available describing these components, with links to relevant publications and guidance on best practices.

The UCAF components are interconnected and can be read from left to right, right to left, or even starting in the middle (see Fig. 1). They each influence and are influenced by the components to their left and right. Below, we describe the components from left to right. For example, the stakeholders that are invited to design the CE strategy (component two) can strongly weigh in on the vision the city puts forward for the CE (component one), as well as shape the strategy that the city utilises for the CE (component three). Similarly, the urban stocks and flows (component four) are a result of the CE strategies that have been selected (component three) and direct the impacts under the triple bottom line (component five). The guiding questions for assessing each component (see at the end of each component and in our checklist in Supplementary material) evidence this interconnectedness.

The City's Circular Vision

Our first component is the vision, which sets the scene for the CE at the city level [41, 57, 58]. It aims to assess the ambition level in the city related to the CE.

According to [57], there are four types of CE visions, depending on the stance on technological innovation and ecological collapse (sceptical or optimistic) and the approach to social, economic, environmental, and political considerations (holistic or segmented). Circular societies (reformist and transformational) take holistic approaches, considering the social and political environment integral, whereas the CE (technocentric and fortress) entertains only techno-economic aspects. Transformational circular societies and fortress CE do not consider eco-economic decoupling feasible and assume a break from capitalism. In contrast, reformist circular societies and technocentric CE deem technological innovations will suffice to solve the environmental and economic challenges [57]. The EU, for example, aligns with the technocentric reformist circular society due to its holistic vision yet limited social and political analysis [59]. Another typology of the CE vision is into two categories: (1) strong CE, which encompasses a shared responsibility of the state and producers, also incorporating social considerations and "fairness within planetary limits" [58, p. 1], whereas the (2) weak CE assumes the market will resolve the current challenges [58].

Guiding questions for assessing the CE vision component include is the CE strategy heavily focused on technology? Is it described as a win for the environment, the economy, and the people? Does it entail the whole city, or is it focusing on specific sectors? Who wrote and supported the CE vision?

The City's CE Governance and Participation

Our second component is related to institutional arrangements, mapping how different departments within the municipalities, supraordinate government agencies, and non-municipal actors, organised along the quadruple helix model (i.e. industry, academia, civil society — see [60]) supplemented with transnational and supranational organisations, participate in the design, implementation, monitoring, evaluation, and learning along the CE transition.

It aims to assess the capability (i.e. resource allocation and competence) and level of horizontal (social-technical and social-ecological) and vertical integration (top-down and bottom-up) of the CE within the city [61, 62]. This is particularly important as ample evidence shows that including the wrong or excluding the right stakeholders can lead to failed transitions, including CE transitions [63–66]. More specifically, transitioning to the CE at the city level can be classified as an "unstructured" problem, as there is low certainty around knowledge and low consensus around norms and values [67].

Guiding questions to understand the governance and participation in the CE process in the city, building on [68], include which organisations participate at which stage in the CE process (design, implementation, monitoring, evaluation, learning)? How representative are these stakeholders compared to the local context? What competencies do these stakeholders have, including about the CE? What resources do these stakeholders have to participate in the CE process? What impact and influence do they have over the CE approach? How are local stakeholders (from the different stakeholder categories) getting involved (informed, advocacy, decision-making)? What barriers do the local stakeholders face to governance and participation, and how have these been addressed?

Answers to these questions can be allocated according to the "ladder of participation" [69], ranging from non-participation (manipulation and therapy) to tokenism (informing, consultation, and placation) to citizen power (partnership, delegated authority, and citizen control). Another method of organising answers is by assessing whether the processes are just, i.e. in terms of distributional, procedural, and recognition justice [63, 70, 71].

The City's Circular Strategies

The third component, i.e. the CE strategies, with accompanying work plans and budgets, is embedded within institutional arrangements (component two) and details how the CE vision at the city level (component one) will be carried out while capturing the anticipated impact on urban stocks and flows (component four). It aims to understand how holistic the CE has been designed through understanding which sectors and R-strategies it covers. We use the NACE classification system [72] for sectors, which organises industries into manufacturing, construction, energy, and waste categories. The R-strategies range from zero to nine, with the lowest being the highest environmental value (R0 refusing consumption) to R4 repairing, R6 remanufacturing, R8 recycling, and R9 recovery (waste to energy) [73].

The main instruments a municipal government can deploy CE strategies include public procurement, zoning laws, capacity building, and knowledge exchange [74]. The link with component two (institutional arrangements) is such that those designing the CE strategy will determine the primary focus. For example, municipal environment departments mainly focus on strategies related to waste management and maintenance of parks and green zones. In contrast, social welfare departments focus on strategies related to specialised disability and elderly care. Specific strategies, concentrating solely on CE, can also be developed across institutional arrangements, touching on, for example, procurement policies within the municipal government while sharing economic policies and information campaigns on recycling.

Guiding questions to understand component three are: what sectors are covered by the CE strategy? How representative are these sectors for the local context? What are vital facts and figures for these sectors? Are the connections between the different sectors understood? What R-strategies are in focus?

Urban "Stocks and Flows"

Our fourth component focuses on urban stocks and flows. It aims to holistically showcase the planning and policy implications of the CE strategies (component three) before moving into the broader societal implications for the planet, people, and profit (component five).

When assessing circularity at the city level, most studies focus primarily on material flows [75–79], energy flows [80], or a combination of both [81–84]. Most non-academic research on circular cities also uses material flow analysis as the departing point for the CE assessment in the city (see, for instance, [85–87]).

However, aside from material flows (goods and products including waste and water) and energy, a city's other stocks and flows interact with one another, which needs to be considered when designing CE strategies. These include information flows (see, for instance [88, 89]), showing who has (and has not) been privy to information and processes (linking here with component 2 — institutional and governance arrangements), monetary flows [90–92], and services (transportation and storage), as consequences of, for example, the sharing economy, as in [93–95].

Therefore, our fourth component incorporates five urban stocks and flows that must be considered and assessed simultaneously (Table 1).

Guiding questions relate to the kind and type of stocks and flows considered. What data is being collected on these different stocks and flows? What methods are being used to measure and monitor these stocks and flows? To what extent are connections between different stocks and flows understood and made explicit? What policies have been

Table 1 Urban stocks and flows and some intrinsic components

Stocks and flows	Intrinsic components and sectors for consideration (linking with framework component 3)
Materials (goods and products including waste and water)	Covering, among others, the sectors of agriculture, forestry, and fishing; mining and quarrying; manufacturing; water supply, sewerage, waste management and remediation; construction; wholesale and retail trade
Services	Including transportation and storage — linked to, among others, the sharing economy; products as a service; mobility as a service
Energy	Covering, among others, the electricity, gas, steam, and air-conditioning supply sectors
Money	Financial flows; banking; procurement
Information	Knowledge and awareness; education and training; digital services

designed to support the CE transition across these five stocks and flows? The latter questions aim at understanding the level of embeddedness of the thinking around stocks and flows in the strategies and their connection to the triple bottom line, or component five.

Societal Consequences for the Planet, People, and Profit

Our framework's fifth and final component provides structure surrounding societal impacts, particularly organised along the triple bottom line of people, planet, and profit [96]. It displays the ultimate effect the CE approach will or could have. With this framing, we move beyond the environmental impact and incorporate the social and economic consequences, which have been overlooked in the discourse [36, 97].

Table 2 provides some indicators for measuring these societal impacts, building on a review of urban sustainability metrics [98]. For the planet, we adhere to the doughnut economy model [30] and use the nine planetary boundaries [99], some of which can be applied at the city level [100–103]. For people, we use the International Association for Impact Assessment's Social Impact Guidance, which breaks down social impacts into eight categories [44]. The fifth social impact category relates to people's environment and is omitted as this is covered within the planetary bottom line. We utilise economic performance indicators for the profit section, such as GDP growth and innovation, as other scholars use [14, 91, 104–107].

Guiding questions here focus on what types of impacts are being considered. How extensive are these impacts covered in the CE approach? How much thought is there for negative, at times unintended consequences of transition processes? How differentiated are the implications for different societal groups?

Summary

Practitioners, decision-makers, and academia can use the UCAF to visualise the approach to the CE at the city level, as shown in the next section. Through the application of the UCAF, the robustness of the CE approach in the city should become easier to understand,

Table 2 Sustainability parameters relating to planetary boundaries and social and economic impacts, including the respective indicators

Bottom line	Category	Description/indicator
Planet	Climate change	Atmospheric CO_2 concentration (ppm); energy imbalance at the top-of-atmosphere (W m^{-2})
	Novel entities	Not yet quantified
	Stratospheric ozone depletion	Stratospheric O_3 concentration (Dobson units (DU))
	Atmospheric aerosol loading	Aerosol optical depth (AOD)
	Ocean acidification	Carbonate ion concentration, average global surface ocean saturation state concerning aragonite
	Biogeochemical flows (P and N cycles)	Phosphorus flows from freshwater systems into the ocean Phosphorus flow from fertilisers to erodible soils Industrial and intentional biological fixation of nitrogen Atmospheric and solute losses of nitrogen
	Freshwater use	Maximum amount of consumptive blue water use (km^3yr^{-1}); blue water withdrawal as % of mean monthly river flow
	Land-system change	Area of forested land as % of original forest cover and as % of potential forest
	Change in biosphere integrity	BII — Biodiversity Intactness Index; E/MSY — extinction per million species per year
People	People's way of life (category 1)	How people live, work, play, and interact with one another on a day-to-day basis
	People's culture (category 2)	Shared beliefs, customs, values, and language or dialect
	People's community (category 3)	Cohesion, stability, character, services, and facilities of the community
	Political systems (category 4)	The extent to which people can participate in decisions that affect their lives, the level of democratisation that is taking place, and the resources provided for this purpose
	People's health and well-being (category 6)	The state of complete physical, mental, social, and spiritual well-being and not merely the absence of disease or infirmity
	People's personal and property rights (category 7)	Whether people are economically affected or experience personal disadvantages, which may include a violation of their civil liberties
	People's fears and aspirations (category 8)	People's perceptions about their safety, their fears about the future of their community, and their aspirations for their future and the future of their children

Table 2 (continued)

Bottom line	Category	Description/indicator
Profit	CE economic growth	Contribution of the CE companies to GDP
	CE business	Share of CE companies over total companies, the number of CE bankruptcies over total CE companies, comparison of the number of CE bankruptcies compared to total companies Financial performance of CE initiatives: liquidity, solvency, and profitability ratios (including levels of investments, capital flows, and interest rates for CE companies)
	CE innovation	Number of applications for patents and patent intensity in the municipality related to the CE
	CE business infrastructure and attractiveness	Herfindahl Index (measuring the level of competition); percentage of vacant offices and retail space; days to obtain a license (business or construction)

Source: based on [14, 28, 44, 91, 96, 98–112]

as it makes explicit assumptions, visualises gaps in the CE approach (across the five components), and shows whether the interconnectedness of the different components is well understood with the city (Table 3).

Application of the UCAF to the Cities of Umeå and Stockholm, Sweden

To test the usefulness of the UCAF, we applied it to two case studies: the city of Umeå and the city of Stockholm. Umeå city is located in Northern Sweden, with a population of 130,997 [113]. It has a university which has close to 38,000 students [114], and on average, its population is highly educated, and unemployment is low (less than 5%) [115]. Most people work in industry (close to 38,000), and about 20,000 work for either the municipal or regional government [115]. About one in six citizens have low economic standards, defined as having a disposable income that is less than 60% of the median income in Umeå [116]. Yet, 45% are younger than 25 years old [116]. Sweden's capital, Stockholm, has a population of 978,770 [113]. It has several universities, research centres (e.g. Stockholm University, the Royal Institute of Technology KTH, Karolinska Institute), and an extensive service industry, including banking [113]. It also has the second largest port in Sweden after Gothenburg and is a logistics hub [113]. In Stockholm, 12% of the population is classified as having low economic standards, with 34% of them younger than 25 years old [116].

Our analysis of the CE approach in Umeå and Stockholm using the UCAF shows different priorities and nuances (Fig. 2). In the Supplementary material, we provided more detail on each city for each component.

Both cities appear to adhere to an optimistic viewpoint of the CE, relying on technological innovation to achieve the CE. In both cities, we note challenges around the involvement of civil society in the process (component two), a narrow focus on the reduction of consumption and recycling of materials to reduce overall waste (component three), and limited societal consequence analysis around the impacts on people and the economy (component five). As both cities recently started their CE journey, it is understandable that there are gaps in their plans. Indeed, research has shown that civil society and social impacts have been little considered [10, 36, 66, 97, 117–119]. Similarly, most cities' circular economy strategies cover mainly construction, waste, energy, recycling, and the incineration of waste for power [1].

Contrary to studies on CE approaches in other cities, Umeå and Stockholm have a strong CE vision and political will (component one), which could help overcome barriers related to institutional capacity and regulatory obstacles [42]. In its survey on circular cities, the OECD [47] reported that over two-thirds of its survey respondents found a holistic CE vision "a major obstacle …, often due to poor leadership and coordination, and the lack of political will". Quite a few cities lack personnel skills and have a fragmented management structure, leading to difficulties in carrying out the circular city vision [47, 120, 121]. This does not seem to be the case in Umeå or Stockholm.

Therefore, to ensure solid CE transition approaches, recommendations include (1) a mapping of the local ecosystem within each city and their power, interest, and capability to inform a stakeholder engagement strategy (component two); (2) a more thorough assessment of the urban stocks and flows, including the funds needed to support these CE initiatives, and information campaigns to motivate and regulate households and businesses to

Table 3 The UCAF checklist

Component	Answers	Guiding questions	Some Indicators	Some means of Verification
Vision	The extent to which a strong (society-wide) or weak (market) viewpoint is taken towards the CE in cities, as in [58]; alternatively, whether socio-political aspects are incorporated in the CE vision, and the level of reliance on technological innovation to ensure eco-environmental decoupling, as in [57]	What are the city's ambitions for the CE? Why? What are the linkages to sustainability targets such as Agenda2030, the EU Green Deal, and others? Why? Is the CE strategy heavily focused on technology? Is it described as a win for the environment, the economy, and the people? Does it entail the whole city, or is it focusing on specific sectors? Who wrote and supported the CE vision?	• Number of actors (size, type) that (actively) support the CE vision • Number of actors (size, type) that know about the city's CE vision	• Vision statements • Strategy documents • Number of information campaigns on the CE
Governance and participation	The extent to which stakeholders from the quadruple helix model (government, industry, academia, and civil society) have participated in the planning, monitoring, and evaluation of the CE strategy in the city, and the departments responsible for the CE vision, strategy, and implementation within the municipal government	Which organisations participate at which stage in the CE process (design, implementation, monitoring, evaluation, learning)? How representative are these stakeholders compared to the local context? What competencies do these stakeholders have, including about the CE? What resources do these stakeholders have to participate in the CE process? What impact and influence do they have over the CE approach? How are local stakeholders (from the different stakeholder categories) getting involved (informed, advocacy, decision-making)? What barriers do the local stakeholders face to governance and participation, and how have these been addressed?	• Number of actors involved in the design, implementation, monitoring, evaluation and learning processes (type, size) compared to all actors in the local ecosystem • Level of participation of different actors in the various processes • Capability (capacity and skills) of different actors • Number of strategies designed to ensure active participation of all relevant stakeholders in the process	• Minutes of meetings • Budget allocations
Circular strategies and sectors	The extent to which the strategies take a system perspective, touching upon the various sectors (see, e.g., [72] and R-strategies [73])	What sectors are covered by the CE strategy? How representative are these sectors for the local context? What are the key facts and figures for these sectors? Are the connections between the different sectors understood? What R-strategies are in focus?	The comprehensiveness of the CE strategy: • Number of sectors that have a CE strategy • Level of R strategy in each sector • Level of interconnectedness of the CE strategies across sectors	• Strategy documents • Statistical data on the local industry

Table 3 (continued)

Component	Answers	Guiding questions	Some Indicators	Some means of Verification
Urban stocks and flows	The extent to which socio-economic and biophysical stocks and flows within the city have been considered	What kind and type of stocks and flows are being considered? What socio-economic constellation (jobs, unemployment, education level, safety, cohesion) is there in the city? What data is being collected on these different stocks and flows? What methods are being used to measure and monitor these stocks and flows? To what extent are connections between different stocks and flows understood and made explicit? What kind of information is being shared about the CE in the city? How? Why? What kind of business models are being developed for the CE? Why? What are their main advantages and disadvantages? What policy instruments (regulatory, economic, voluntary) are being deployed to support the transition to a CE in the city? What kind of funding is foreseen to support the CE in the city?	• Material flow data • Energy consumption data • Number of CE initiatives in the city (e.g., sharing initiatives, libraries, second-hand stores, waste collection points) • Mobility data – public and active transport • Number of information campaigns on the CE • Number and size of procurement with a CE element compared to total procurement	• Statistical data on urban stocks and flows • Policy documents and instruments • Spatial plans • Municipal financial accounts

Table 3 (continued)

Component	Answers	Guiding questions	Some Indicators	Some means of Verification
Societal consequences – the Triple bottom line	The extent to which the CE strategies impact the triple bottom line: planet (planetary boundaries), people (social impacts), profit (financial performance indicators)	Which impacts under each category of the triple bottom line have been considered? What types of impacts are being considered? What problems will the CE solve? Why? How extensive are these impacts covered in the CE approach? How much thought is there for negative, at times unintended consequences of transition processes? How differentiated are the impacts for different societal groups? What level of intersectionality analysis is done?	Nine planetary boundaries • Climate change: Atmospheric CO_2 concentration (ppm); energy imbalance at the top-of-atmosphere (W m^{-2}) • Novel entities: TBC • Stratospheric ozone depletion: stratospheric O_3 concentration (Dobson Units (DU)) • Atmospheric Aerosol Loading: Aerosol optical depth (AOD) • Ocean Acidification: Carbonate ion concentration, average global surface ocean saturation state concerning aragonite • Biogeochemical flows (P and N cycles): Phosphorus flows from freshwater systems into the ocean; Phosphorus flows from fertilisers to erodible soils; Industrial and intentional biological fixation of Nitrogen; Atmospheric and solute losses of Nitrogen • Freshwater Use: Maximum amount of consumptive blue water use (km^3yr^{-1}); Bluewater withdrawal as % of mean monthly river flow • Land-system change: Area of forested land as % of original forest cover and as % of potential forest • Change in Biosphere integrity: BII—Biodiversity Intactness Index; E/MSY – Extinction per million species per year Seven social impact categories: • People's way of life: number of jobs in the CE; quality of employment • Culture: level of integration of different perspectives in the CE • Community: level of social cohesion within the city; number of participants in community events on the CE • Political systems: level of participation • Health and wellbeing: level of illness, mental health challenges • Personal and property rights: housing prices; people's ability to purchase assets; • Fears and aspirations: number of citizens that support the CE Four economic impact categories: • CE economic growth: Contribution of the CE companies to GDP • CE business: Share of CE companies over total companies; the number of CE bankruptcies over total CE companies; comparison of the number of CE bankruptcies compared to total companies • Financial performance of CE initiatives: liquidity, solvency and profitability ratios (including levels of investments, capital flows and interest rates for CE companies) • CE innovation: Number of applications for patents and patent intensity in the municipality related to the CE • CE business infrastructure and attractiveness: Herfindahl Index (measuring the level of competition); percentage of vacant offices and retail space; days to obtain a license (business or construction)	• Statistical data on the planetary boundaries and socio-economic indicators

adhere to the CE strategies (component four); and (3) a more systematic coverage around the stance on the CE in the city, by embedding impact assessments and critical reflections on who wins and who loses from a transition to the CE (component five). The urban stocks and flows assessment should improve the CE's spatial planning [122–125]. Some of the questions described in the checklist (see Supplementary material) could help improve the planning, monitoring, evaluation, and learning of the CE approach.

Discussion

In this paper, we aimed to answer two research questions: RQ1) What components should a CE framework cover to assist the planning, monitoring, evaluation, and learning of the CE at the city level? And RQ2) what learnings arise from applying this framework in different contexts?

The five components in our framework allow us to understand the bigger picture in which the CE is approached by the cities [55]. The structure of the framework seems logical, and the interconnection between the different components sensible: the case studies showed that the vision influenced who participated in the design of the CE strategy, leading to a focus on a few sectors and strategies, material flows and energy flows, and climate change mitigation in terms of environmental impact. Our framework also allowed us to make explicit the stance that both cities hold towards the CE, classifying them as weak CE [58, 59]. Compared to other frameworks, it goes beyond resource management [29] but views cities as complex systems [34, 62].

Applying the UCAF to two case studies and presenting it at multiple conferences provided insight into the framework's applicability. We noted it was easy to engage quickly to make a first draft, and a great conversation started around whether the CE approach in the city was comprehensive. Some of the challenges and learnings from [55] resonate, including tensions around the focus and core of the CE transition [126], fulfilling both service and science roles [55, referring to [127–129]. However, it is essential that the UCAF, like other ToCs, are not used as a tick-box exercise [130].

Further work on the UCAF could entail selecting indicators for each component and putting forward more comprehensive means of verification to assess the components [23]. It is also necessary to clarify the relationship between various urban flows, their environmental footprints, and socio-economic impacts to understand the overall circularity performance and to aid decision-makers in designing interventions considering their interactions and potential rebound effects [12, 28, 131].

A limitation is that both cities are at the start of their CE transition journey, and hence, we have yet to be able to test the robustness of the framework over time. A reflection on the case studies is also that we must ask why specific approaches were chosen. This would have allowed us to embed our findings within the local context and deepen our understanding of the planning and learning processes around the CE in both cities. To understand how learning on the CE occurs, the UCAF case study could be carried out again in the future, thereby shedding light on whether changes have been made to the CE approach in the cities, what they have learned during the CE transition, and whether the UCAF supported this reflection and learning journey.

Conclusion

With this paper, we have put forward an urban circularity assessment framework which will allow city governments and other stakeholders to develop a CE strategy that bridges all scales, from local to global levels of concern. It builds on a comprehensive hierarchical approach with a strategic CE vision and sustainability targets at the top, which lead to institutional arrangements, CE strategies, urban stocks and flows, and links to the triple bottom line. Our framework is based on extensive literature reviews, case studies, and discussions with CE experts and practitioners in Sweden and elsewhere.

Our case studies signal the comprehensiveness of the framework. It has been found easy to understand and fill in. It also has proven to be a conversation starter around the strengths and weaknesses of the CE approaches in cities. It can stimulate different stakeholders to get involved in the CE transition.

Details on the UCAF Application for the City of Umeå and Stockholm

The Circular City Vision

The vision of Umeå is to be "a leader in circular economy" [46, p. 4]. Umeå sees CE as "a means to achieve its goal to be fossil fuel-free by 2040 while enhancing innovation and creating the enabling environment for new business models. Transitioning towards a CE has been a political priority for the city since the Strategic Plan 2016–28" [46, p. 4]. Stockholm's vision centres on becoming resource-smart within the solid and liquid waste and energy sectors [51].

Governance and Participation Municipal governments carry out various functions related to urban planning and housing, social welfare and health care, education, environmental services, transportation, and economic development activities [132]. For Sweden, for example, the mandatory functions include social services, childcare and preschool, primary and secondary education, care for older people, support for the physically and intellectually disabled, primary healthcare, environmental protection, urban planning, refuse collection and waste disposal, rescue and emergency services, water supply, and sewerage and road maintenance [132, p. 77]. Optional functions include culture, housing, energy supply, employment, and industrial and commercial services [132, p. 78]. In addition, city governments have functions linked with governance and fiscal and financial compliance (the "enablers" in the urban sustainability framework [133]).

In Umeå, the CE work in Umeå is led by the Department of Strategic Business Development, supported by the Departments of Environment and Waste Management and Urban Planning [48]. It designed its CE strategy after consultation with eight government entities such as the municipal government of Umeå and Lycksele, the regional government of Västerbotten, the Swedish Public Transport Authority, and the Swedish Agency for Economic and Regional Growth (35 people in total); 6 academic institutions (18 people); 2 civil society organisations (2 persons); and 31 industry partners (44 people) [47, pp. 81–83]. Civil society indicated limited involvement in setting the CE strategy in the city [134].

In Stockholm, designing the CE is a shared responsibility between, among others, the city's Environmental Management Department and the Department for Strategic City

Development, supported by, among others, the water and waste company Stockholm Vatten och Avfall and waste sorting and treatment depots. There are also connections with the city's back-office functions related to green procurement. The city has an internal recycling centre (Stocket) that refurbishes, among other items, office furniture for reuse [51].

Circular Strategies In Umeå, while the CE strategy is in its early stages, it focuses on promoting circularity among businesses and start-ups, collaborations with universities, and implementing green public procurement [46]. Sectors that are targeted in Umeå are waste management (NACE code E), retail trade (NACE code G), and restaurants (NACE code I), the latter two entailing support for small businesses to tackle food waste, sustainable mobility, and the sharing economy. Umeå will develop a plan for circular construction by 2025 [53].

For Stockholm, the CE strategies entail minimising the use of resources and waste production (e.g. food waste and support for the sharing economy) and increasing material recycling before it ends up being incinerated in the district heating plant (e.g. plastics, textiles, and food waste); and increasing resource efficiency in construction. The sectors targeted in Stockholm are heat generation (NACE code D), waste management (NACE Code E), construction (NACE code F), and household consumption and production of waste (allocated to NACE Code G, wholesale and retail trade given reduced purchasing). Aside from its overarching resource-smart strategy [51], the city has a specific plan for plastics and one to increase the CE in the construction sector [50, 52].

Each city also plans to increase the CE in their operations by assessing procurement practises, reducing waste, and purchasing second-hand furniture (in 2025 in Umeå [53]).

Urban Stocks and Flows There needs to be more description of the urban stocks and flows in the strategies of both cities. Yet, given the selected strategies, we infer that goods, services, and energy flows are the key stocks and flows under consideration. The Swedish Statistical Agency collects data on some indicators related to stocks and flows (such as material flow accounts [135]). Yet, most data is not downscaled to the urban level, as also discussed in our case study on Umeå [45].

Societal Consequences Both cities are part of the Strategic Innovation Programme Viable Cities [136] and the EU Mission for Climate Neutral and Smart Cities [137], which entail developing climate action plans that will lead to climate-neutral cities by 2030. However, targets set by both cities differ somewhat, with Umeå aiming for 2 tonnes of CO_2-e per capita by 2040 [53] and Stockholm city for 1.5 tonnes of CO_2-e per capita [51]. In addition, the plan of Stockholm also entails targets for reductions in phosphorus effluent and freshwater use [51].

Assessments of the social and economic consequences of transitioning to the CE in both cities need to be documented. However, our research indicated a positive view of how the CE would impact people and businesses [37].

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Data Availability The data used for this paper is available on the UCAF project website: https://www.sei.org/projects/urban-circularity-assessment-framework/.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication The author consents to publication.

Competing Interests The author declares no competing interests.

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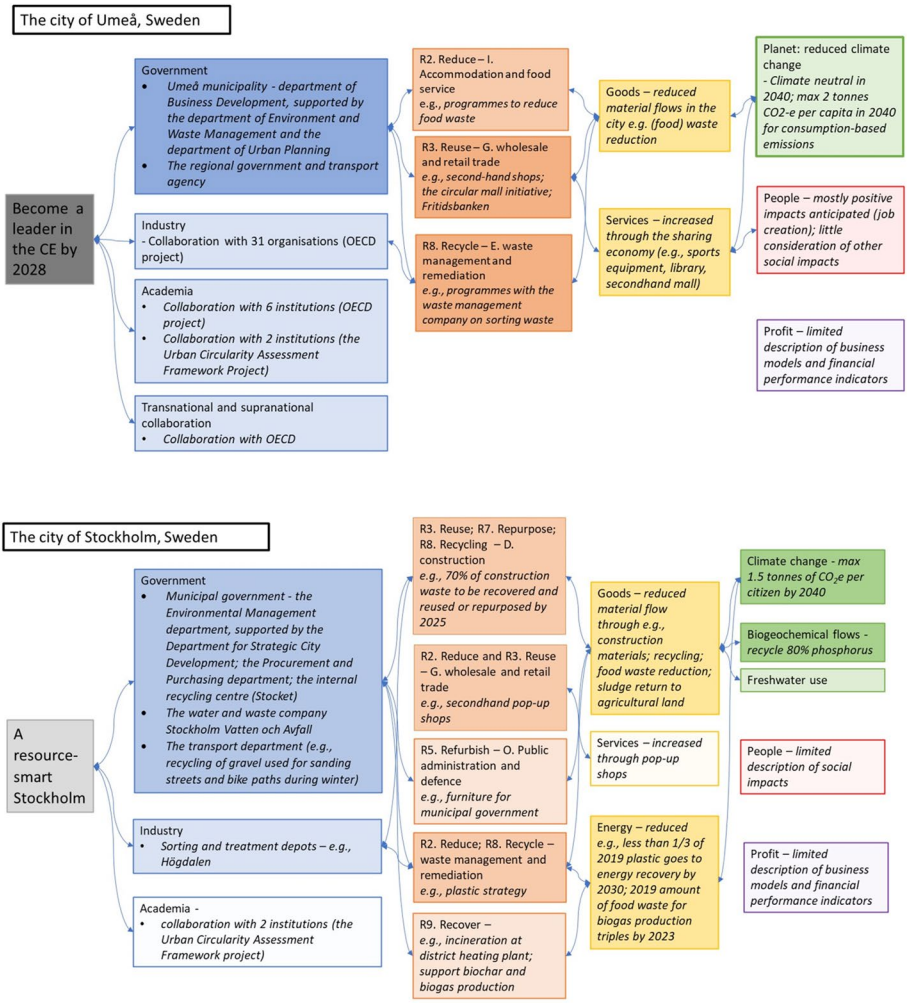

Fig. 2 Analysis of the CE vision, governance, strategies, stocks, and flows and impacts for the cities of Umeå and Stockholm, Sweden. Legend: the darker the colour, the more vital a component is addressed in the city

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