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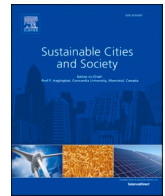
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Monitoring progress towards a circular economy in urban areas: An application of the European Union circular economy monitoring framework in Umeå municipality

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ABSTRACT

As cities worldwide implement strategies to accelerate the transition toward a circular economy (CE), there is an increasing need for tools to monitor progress. However, a standardised metric for CE monitoring in urban areas is lacking. This study examines the potential of the EU Circular Economy Monitoring Framework (CEMF), an established indicator-based framework for measuring national- and EU-level circularity performance, as a monitoring tool for urban areas. For this purpose, available data sources that can support the framework's application at the urban level are mapped, and data quality is assessed following the pedigree matrix approach. Next, the CEMF indicators are computed for the urban area of Umeå, Sweden. The mapping showed limited availability of urban-level data, necessitating the downscaling of national-level data using proxy factors. Most available urban-level data are of high quality, while the quality of national-level data is reduced when used to compute indicators at the urban level. The application of the CEMF in Umeå indicates that there are areas where the municipality performs well, though further improvements are needed. We conclude that the CEMF has potential as a monitoring tool for urban areas. However, improvements in CEMF...s scope and data availability are recommended.

1. Introduction

The circular economy (CE) is envisioned as an alternative to the unsustainable linear 'take-make-waste' model that has dominated the global economic system (Chizaryfard et al., 2020; Kristensen & Mosgaard, 2020; Reike et al., 2018). It is a concept that describes both an ideal and an instrumental economic development model that promotes the responsible and cyclical use of resources to maintain their value in the economy, minimise environmental pressures, and contribute to improved socio-economic welfare (Geisendorf & Pietrulla, 2018; Moraga et al., 2019; Petit-Boix & Leipold, 2018). According to Kirchherr et al. (2017), it can be implemented at three system levels; the micro level (products, consumers, companies), the meso level (eco-industrial parks) and the macro level (cities, regions, countries) with the ultimate aim to achieve sustainable development.

In the last years, the CE has been gaining particular momentum as a

model that, combined with concepts like the smart city and eco-city, could contribute to achieving sustainable urban development (Prendeville et al., 2018). Cities and urban settlements (henceforth urban areas) are complex spatial, socio-economic, and socio-technical systems with distinct metabolic processes and socio-economic functions. Under the current linear paradigm, the metabolism of most contemporary urban areas is predominately linear, characterized by vast input of natural resources and outputs of waste and emissions (Kennedy et al., 2011). Consequently, urban areas today are hotspots of resource consumption, greenhouse gas emissions, waste generation, and pollution, causing irreversible environmental changes (Campbell-Johnston et al., 2019). The CE is considered to have great potential to drive the transition from linear to circular urban metabolism, helping to address a range of sustainability challenges faced by urban areas (Sánchez Levoso et al., 2020; Tan et al., 2021). Recognizing this potential, local authorities and urban planners worldwide are implementing, or currently developing, policy

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Table 1

The CEMF and its indicators (adapted from EC 2018).

Thematic area	No	Indicators	No	Sub-indicators	Unit
Production and consumption	1	EU self-sufficiency for raw materials	–	–	%
	2	Green public procurement	–	–	–
	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, chain linked volumes (2010)
			3.3	Generation of waste excluding major mineral wastes per domestic material consumption	%
	4	Food waste	–	–	Million tonne
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	kg per capita
			6.6	Recovery rate of construction and demolition waste	%
Secondary raw materials	7	Contribution of recycled materials to raw materials demand	7.1	End-of-life recycling input rates (EOL-RIR)	%
			7.2	Circular material use rate	%
	8	Trade in recyclable raw materials	8.1	Imports from non-EU countries	tonne
			8.2	Exports to non-EU countries	tonne
Competitiveness and innovation.	9	Private investment, jobs and gross value added related to circular economy sectors	8.3	Intra EU trade	tonne
			9.1	Gross investment in tangible goods	% of GDP at current prices
			9.2	Persons employed	% of total employment
	10	Number of patents related to recycling and secondary materials	9.3	Value added at factor cost	% of GDP at current prices
			–	–	Number

and planning measures and strategies to accelerate the transition toward a more circular urban development model (OECD, 2020; Paiho et al., 2021; Vanhuysse et al., 2021).

In this context, urban planners and decision-makers need to continually monitor and assess the progress of the implemented measures and strategies to manage the transition toward a CE based on firm information (Paiho et al., 2020). Informed planning and decision-making are crucial to assure efficient use of resources and enable coordination between different stakeholders and various systems involved in the transition toward an urban development model based on CE principles. This requires the application of well-designed and effective metrics (e.g. indicators, indices and indicator-based frameworks) that clearly reflect CE principles and show to what extent a transition towards a CE can contribute to achieving sustainable development (Bianchi et al., 2022; Superti et al., 2021).

In the last years, numerous CE metrics have been proposed in the literature on all system levels of CE (Brändström & Eriksson, 2022; Saidani et al., 2019). In general, most of the proposed metrics often do not share common theoretical or methodological grounds and present contradictions in both content and form (Corona et al., 2019; Švarc et al., 2021). As a result, there is a lack of standard metrics on all system levels of CE, which impedes comparability and contributes to confusion in understanding the level of circularity performance (Švarc et al., 2021). At the urban level, there have been studies focusing on mono-dimensional metrics, such as indicators and indices, either by creating inventories with these metrics (Fusco Girard & Nocca, 2019; OECD, 2021), exploring their thematic connections (Superti et al., 2021), or exploring the use of a few single indicators (Sánchez Levoso et al., 2020). However, studies focusing on indicator-based frameworks (i.e. integrated systems of indicators) that can capture multiple aspects of the CE transition are scanty. Due to the above reasons, a widely accepted standardised indicator-based framework for monitoring CE development at the urban level is lacking.

A potential approach to address this gap could be to adapt existing regional- or national-level indicator-based frameworks to the urban

level (Paiho et al., 2020; Urban Agenda for the EU, 2019). The benefit of this approach is that it could bring consistency when measuring circularity performance, facilitating comparisons between different territorial scales. In a previous study, Papageorgiou et al. (2021) identified and assessed, based on defined criteria, several macro-level indicator-based frameworks that could be applied to monitor CE development in urban areas. One of the identified frameworks that fulfilled most assessment criteria is the European Commission's circular economy monitoring framework (CEMF) (EC, 2018a) (see Section 2). The CEMF is an established and well-recognized monitoring system that has been applied to monitor progress toward a CE in the EU and its member states. In two recent studies, Rincón-Moreno et al. (2021) adapted the CEMF and tested its applicability at the micro level (companies), while Bianchi et al. (2022) applied the framework to three European regional case studies. Paiho et al. (2020) and the Urban Agenda Partnership on CE (Urban Agenda for the EU, 2019) discussed the possibility of using the CEMF at the urban level. However, to our knowledge, no previous study has explored the potential of the CEMF as a monitoring tool for urban areas based on empirical evidence from its application to a specific urban area. This article aims to address this research gap by answering the following research question:

What is the potential of the CEMF as a monitoring tool for urban areas?

The specific objectives are to (1) map available data sources that can support the application of the CEMF at the urban level, (2) evaluate the quality of the identified data, and (3) test the applicability of the CEMF using the Umeå urban area in Sweden as a study setting. With this empirical work, we aim to contribute to forwarding the operationalisation of CE principles in urban areas by equipping decision-makers and practitioners with the evidence needed to establish processes and guidelines for consistent and effective monitoring and evaluation of progress towards a CE in the urban context.

The paper proceeds as follows. Section 2 provides an overview of the CEMF. Section 3 describes the methodological approach employed in this study. Section 4 presents the results, and Section 5 discusses the

Table 2The pedigree matrix used to assess data quality, modified from [Chen & Lee \(2021\)](#).

DQI Score	1	2	3	4	5
Reliability	Verified data produced following quality assurance procedures.	Verified data partly based on assumptions and calculations.	Non-verified data based on calculations or partly based on qualified estimates	Qualified estimates (e.g., expert judgements) or educated guesses	Non-qualified estimates or uneducated guesses or data compromised by inconsistencies
Completeness	Continuous data available for every year	Non-continuous data available for every second year	Non-continuous data available for every third year	Non-continuous data available for every fourth year	Non-continuous data available for every fifth (or more) year
Time representativeness	New data are disseminated within 1 year after the reference year.	New data are disseminated within 2 years after the reference year.	New data are disseminated within 3 years after the reference year.	New data are disseminated within 4 years after the reference year.	New data are disseminated within 5 or more years after the reference year.
Geographical representativeness	Data from the urban area under study	Average data from the region in which the urban area under study is included	Data from another urban area with similar conditions or average data from the country in which the urban area under study is included	Data from another urban area with slightly similar conditions	Data from another urban area with distinctly different conditions or from an unknown urban area

strengths and limitations of the CEMF as a monitoring tool for urban areas, provides recommendations and describes the research limitations. [Section 6](#) summarizes the main conclusions of the study.

2. The EU circular economy monitoring framework

The CEMF was introduced by the European Commission (EC) in January 2018 ([EC, 2018a](#)) as part of the EU Action Plan for the CE ([EC, 2015](#)) to provide a tool for measuring progress toward a CE in the EU and its member states. [Table 1](#) presents an overview of the CEMF. It consists of 10 key indicators and 23 secondary indicators classified into four thematic areas: (i) *Production and consumption*; (ii) *Waste management*; (iii) *Secondary raw materials*; iv) *Competitiveness and innovation*. The indicators are routinely updated based on available data from Eurostat and the European Patent Office (EPO) and published on a dedicated website ([Eurostat, 2022f](#)). Three indicators, the *EU Self-sufficiency for raw materials*, *End-of-life recycling input rates* and *Food waste*, are calculated only at the EU level, and the indicator *Green public procurement* is under development.

Although the CEMF was initially developed for application at the national or EU level, this study explores whether it is also applicable at the urban level. The motivation behind this choice is the following. First, the CEMF is an established monitoring system intended for broad adoption and better communication of monitoring results, allowing consistent multiscale comparisons of circularity performance. Second, its indicators were selected based on the RACER "Relevant, Acceptable, Credible, Easy, Robust" assessment criteria ([EC, 2018a](#)). Third, in a previous study ([Papageorgiou et al., 2021](#)), we assessed 15 criteria indicator-based frameworks that could be applied to measure circularity at the urban level based on the criteria; stakeholder engagement, effective communication, ability to track temporal changes, alignment with CE principles, transparency, applicability, validity and relevance to sustainable development, and we found that the CEMF fully or partially fulfils all the assessment criteria, apart from the criterion alignment with CE principles. Despite its merits, it has been discussed in the literature ([Paiho et al., 2020](#); [Urban Agenda for the EU, 2019](#)) that the low availability of urban-level data could impede its application at the urban level. Hence, a fourth justification for carrying out this research is to ascertain whether available data could support the application of the CEMF in urban areas.

3. Methods and data

This section describes the methodological approach of this study. [Section 3.1](#) presents amendments made to improve the comprehensiveness of the CEMF. [Section 3.2](#) describes the approach for mapping data

sources that could provide data for the application of the framework at the urban level, mainly in the Swedish context, and [Section 3.3](#) describes the approach for evaluating the quality of the identified data. [Section 3.4](#) provides a short description of the study setting, and [Section 3.5](#) provides an overview of how the CEMF indicators were calculated for Umeå.

3.1. Modified circular economy monitoring framework

[Table 3](#) presents the modified CEMF. In the modified framework, the wording of some indicators was changed to reflect their application at the urban level. Furthermore, two indicators of the original framework, indicator 2 *Green public procurement* and indicator 4 *Food waste* (see [Table 1](#)), were replaced by new ones, and an additional indicator was also included. Indicator 2, which is currently under development, was replaced by the indicator *CE/waste prevention criteria developed in guidelines for procurement*. This is a qualitative indicator (Yes/No) proposed by the Partnership on Circular Economy ([Urban Agenda for the EU, 2019](#)). It was included in the framework as it can provide a straightforward first appraisal of whether a municipality engages in efforts to include CE principles in its procurement practices. In case a municipality has established criteria, this qualitative indicator could be replaced by a quantitative one measuring the share of public procurement that includes CE/waste prevention criteria, provided that the municipality collects the necessary data. However, as most municipalities have not yet established these criteria, a qualitative indicator like the one suggested in this study can provide helpful information. Indicator 4 was replaced by the indicator *Generation of food waste per capita* (kg/capita) to monitor this waste stream, which is currently monitored only at the EU level. This indicator measures food waste from households, commercial kitchens, grocery stores, and similar activities, but not from the agri-food industry. As it is also important to gain insight into how this waste stream is managed, the indicator *Biologically treated food waste, including home composting* (%), was added to the *Waste management* thematic area. This indicator measures the percentage of food waste undergoing biological treatment (e.g., anaerobic digestion, composting).

3.2. Mapping data sources

The process for data source mapping was based on a desktop study. It also included personal communication with two officers of Umeå municipality (Öberg & Levisson, 2021, personal communication, 15 November), who are involved in developing Umeå's CE strategy and coordinating the municipality's analysis and statistics unit. For the data source mapping, the identification of bottom-up data (i.e. urban-level data from databases, published studies and surveys) was prioritised.

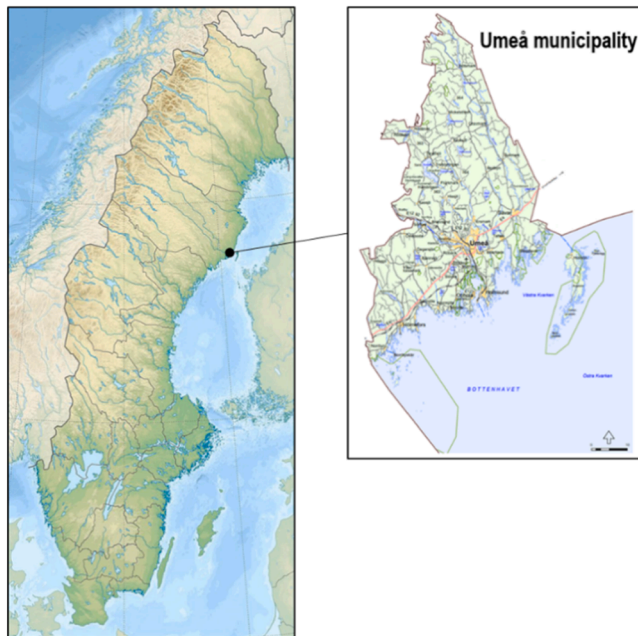


Fig. 1. The municipality of Umeå (adapted from Umeå municipality (2022b)).

However, as bottom-up data were not always available, regional- or national-level data that could be downscaled to the urban level with a top-down approach were sought.

3.3. Data quality evaluation

The quality of data from the identified sources was evaluated following the pedigree matrix approach proposed by Funtowicz & Ravetz (1990) to code descriptive information on qualitative aspects of an object of study into a numerical scale (Ciroth et al., 2013). The conceptual idea of the pedigree matrix was transferred to Life Cycle Assessment (LCA) by Weidema & Wesnæs (1996) and Weidema (1998) as an approach for data quality management and uncertainty assessment in life cycle inventories. The use of the pedigree matrix approach for identification and selection of good quality data was also proposed by Chen & Lee (2021). In the present study, the pedigree matrix approach is applied, as it can characterise data quality aspects in a structured way allowing the conversion of descriptive information into concrete numerical values.

The pedigree matrix described by Chen & Lee (2021) was modified for this study. The original matrix incorporates five data quality indicators (DQIs) (reliability, completeness, temporal representativeness, geographical representativeness and technological representativeness) and a rating scale from 1 to 5. The modified matrix (Table 2) incorporates four DQIs, instead of five. The criterion technological representativeness was not included, as it is more relevant for micro-level (i.e. product) data since it relates to technological production conditions. The rating scale of the matrix is again from 1 to 5, with 1 indicating very good, 2 good, 3 fair, 4 poor and 5 very poor data quality. The definitions of the qualitative aspects for each DQI concerning the rating scale are described in each matrix cell of Table 2.

The overall quality of each dataset was expressed as a single score, the Data Quality Rating (DQR), which was calculated using Eq. (1) (JRC, 2010):

$$DQR = \frac{R + C + T + G + 4 \cdot X_w}{i + 4}, \quad (1)$$

where R is Reliability, C Completeness, T Temporal representativeness, G Geographical representativeness, X_w is the weakest quality rating

obtained (i.e. highest numeric value) amongst the DQIs, and i is the number of applicable DQIs (not equal to 0). In Formula 1, the ratings for each of the DQIs are aggregated. The weakest quality rating amongst the DQIs is counted 5-fold since the weakest DQI weakens the overall quality of a data set. The sum is divided by the number of the applicable DQIs plus 4, as the weakest DQI is included five times.

3.4. Study setting: Umeå municipality

Umeå lies on the Gulf of Bothnia in northern Sweden (Fig. 1) and is the largest city in the Upper Norrland region, with 130,224 inhabitants in 2020 (SCB, 2022d). Umeå is a medium-sized but fast-growing city that is projected to host a population of 200,000 by 2050 (Umeå municipality, 2018). With two universities and over 39,000 students, Umeå is a centre for education, technical and medical research. The largest employers are municipal and regional authorities, academia, and the service sector (Kolada, 2022).

The Umeå urban area was selected as a study setting to apply the CEMF, since transitioning toward a CE is a political priority for the municipality, according to the Strategic Plan 2016–2028 (OECD, 2020; Umeå municipality, 2016). Moreover, the municipality promotes resource efficiency and reuse and recycling of materials through its current waste plan (Umeå region, 2020). It also supports non-profit organisations that encourage product sharing and local entrepreneurial communities engaged in the circular business model application (Circular Regions, 2022). Additionally, the municipality has been considering different circular and climate-smart public procurement practices, though it has not yet implemented them (OECD, 2020; Umeå municipality, 2022a).

3.5. Calculation of the CEMF indicators for Umeå

The geographical boundary for calculating the CEMF indicators coincides with the geographical boundaries of the Umeå municipality. The indicators were calculated with an annual resolution, except for indicators 3.2, 3.3, 5.2, 6.6, and 7.2 (see Table 3), for which data are only available biennially. The time frame of the calculation was set from 2014 to 2020 to use the most recent available data and offer an adequate range for potential trends to appear. The indicators were computed combining a bottom-up and top-down approach. With the former, indicators were calculated using available urban-level data specific to Umeå. With the latter, national-level data were downscaled to the urban level to compute indicators for which urban-level data were not available.

Next, sub-Section 3.5.1 describes the approach for downscaling the national-level data. Sub-Section 3.5.2 outlines the approach for estimating the domestic material consumption (DMC), which is necessary for computing indicators 3.3 *Generation of waste excluding major mineral wastes per domestic material consumption* and 7.2 *Circular material use (CMU) rate*. Sub-Section 3.5.3 describes the approach for computing indicator 10 *Number of patents related to recycling and secondary raw materials*.

3.5.1. Data downscaling

Proxy factors (i.e. ratios) based on the number of persons employed within different sectors in Umeå and Sweden or based on population were used to downscale the identified macro-scale data. This approach has been employed in urban metabolism studies (Browne et al., 2009, 2011; Niza et al., 2009; Rosado et al., 2014) and has been validated by Patrício et al. (2015) and Westin et al. (2020). The different proxy factors used in this study are described in Table A1 of Appendix A. Based on the proxy factors, the following macro-scale data were downscaled:

¹ The application of the formula proposed by JRC (2010) is flexible and can be done even if not every DQI is relevant.

Table 3

The modified CEMF, data sources that can be used for estimating its indicators at the urban level and their DQRs.

Thematic area	No	Indicator	No	Sub-indicator	Data source	Information	DQR	Downscaling
Production and consumption	1	Self-sufficiency for raw materials	–	–	–	–	–	–
	2	CE/waste prevention criteria developed in guidelines for procurement	–	–	Reports and webpages. Data source for Umeå: Umeå municipality (2022a)	Information about municipal procurement processes	–	–
	3	Waste generation	3.1	Generation of municipal waste per capita	Avfall Sverige (2022a)	Data on municipal waste generation in Swedish municipalities	1	–
			3.2	Generation of waste excluding major mineral wastes per GDP unit	a. Eurostat (2022d) b. SCB (2022c)	a. National-level data on total waste generation per sector b. Data on urban GDP per capita	a. 2.5 a b. 1.6	a. Using the number of workers per sector b. -
			3.3	Generation of waste excluding major mineral wastes per DMC	a. Eurostat (2022d) b. Westin et al. (2020)	a. National-level data on total waste generation per sector b. DMC of several Swedish cities in 2010, including Umeå in 2010	a. 2.5 b. 4.1	a. Same as 3.2 b. -
Waste management	4	Generation of food waste per capita	–	–	Same as 3.1	Estimated data based on information on food waste treatment in Swedish municipalities	2.3	–
			–	–	–	–	–	–
	5	Overall recycling rates	5.1	Recycling rate of municipal waste	Same as 3.1	Data on recycling rate of municipal waste in Swedish municipalities	1	–
			5.2	Recycling rate of all waste excluding major mineral waste	Eurostat (2022e)	National-level data on management of waste excluding major mineral waste, by waste management operations	2.5	Using the number of recycling workers
	6	Recycling rates for specific waste streams	6.1	Recycling rate of overall packaging	Eurostat (2022 h)	National-level data on recycling rate of overall packaging	2.4	Same as 5.2
			6.2	Recycling rate of plastic packaging	Same as 6.1	National-level data on recycling rate of plastic packaging	2.4	Same as 5.2
			6.3	Recycling rate of wooden packaging	Same as 6.1	National-level data on recycling rate of wooden packaging	2.4	Same as 5.2
			6.4	Recycling rate of e-waste	Eurostat (2022g)	National-level data on recycling rate of e-waste	2.4	Same as 5.2
			6.5	Recycling of biowaste in municipal waste	Same as 3.1	Data on recycling rate of biowaste within municipal waste in Swedish municipalities	1	–
			6.6	Recovery rate of construction and demolition waste	Eurostat (2022e)	National-level data on recovery rate of construction and demolition waste.	2.5	Using the number of workers in the construction sector.
			6.7	Biologically treated food waste (including home composting)	Same as 3.1	Data on biologically treated food waste from households in Swedish municipalities.	1	–
Secondary raw materials	7	Contribution of recycled materials to raw materials demand	7.1	End-of-life recycling input rates (EOL-RIR)	–	–	–	–
			7.2	Circular material use rate	a. Eurostat (2022j) and SCB (2022e) (for 2020) b. Eurostat (2022c) c. Westin et al. (2020)	a. National-level data on treatment of waste by waste category, hazardousness and waste management operations b. National-level data on trade in waste destined for recycling. c. DMC of Swedish cities, including Umeå.	a. 2.5 b. 2.3 c. 4.1	a. Using the number of recycling workers b. Using the number of recycling workers and the number of workers in the manufacturing sector c. -
			–	–	–	–	–	–
	8	Trade in recyclable raw materials	8.1	Imports to the urban area from non-EU countries	Eurostat (2021i)	National-level data on imports of recyclable raw materials from non-EU countries to Sweden.	2.3	Using the number of persons employed in sectors where the
			–	–	–	–	–	–

(continued on next page)

Table 3 (continued)

Thematic area	No	Indicator	No	Sub-indicator	Data source	Information	DQR	Downscaling
Competitiveness and innovation			8.2	Exports from the urban area to non-EU countries	Same as 8.1	National-level data on exports of recyclable raw materials from EU countries to Sweden.	2.3	recyclables could be used as raw materials Same as 5.2.
			8.3	Imports to the urban area from EU countries	Same as 8.1	National-level data on imports of recyclable raw materials from EU countries to Sweden.	2.3	Same as 8.1
			9.1	Gross investment in tangible goods	Eurostat (2022a)	Annual detailed enterprise statistics for Sweden.	2.4	Using the number of persons employed in CE sectors.
	9	Private investment, jobs and gross value added related to circular economy sectors	9.2	Persons employed	a. SCB. Not publicly accessible data.	a. Number of persons employed per economic activity (4th level of the NACE Rev.2 classification) at the urban-level.	a. 1.6	a. -
					b. Eurostat (2022a)	b. Number of persons employed per economic activity (4th level of the NACE Rev.2 classification) at the country-level.	b. 1.6	b. -
			9.3	Value added at factor cost	Same as 9.1	Same as indicator 9.1.	2.4	Same as 9.1
	10	Number of patents related to recycling and secondary materials	–	–	EPO (2022)	Number of patents related to CE developed within the urban area.	3.9	–

1 *Generation of total waste excluding major mineral wastes.* These data are only available at the national level (Eurostat, 2022d) and reported per economic activity, according to the NACE Rev. 2 classification of economic activities in the European community (Eurostat, 2008). The NACE classification structure is hierarchical with four levels of detail. Data on total waste generation in Eurostat are reported based on the first (most aggregated) classification level. To downscale the data to the urban level, the ratios of the number of persons employed within each of these economic activities were calculated using data from Statistics Sweden (SCB) (SCB, 2022a)² (see Eq. (A1) in Appendix A). This approach assumes that waste generation from economic activities is correlated to the number of persons employed in them, as tested and confirmed by Patricio et al. (2020). The Eurostat dataset also contains data on total waste from households. This data was downscaled using the ratio of the total population in Umeå to the total population in Sweden (see Eq. (A2) in Appendix A).

2 *Recycling rates of total waste and specific waste streams.* These data are reported by Eurostat, (2022e, 2022g, 2022h, 2022j) only at the national level. To downscale data on recycling rates of all waste, e-waste, and overall, plastic and wooden packaging, the share of all employees working as recycling workers was calculated for Umeå and Sweden based on data from SCB (2022b). Next, the ratio of these two shares was calculated and used as a proxy factor to downscale the national data assuming that the number of recycling workers reflects recycling rates (see Eq. (A3) in Appendix A). To downscale data on the recovery rate of construction and demolition waste, the numbers of persons employed in the construction sector in Umeå and Sweden were used (SCB, 2022a) (see Eq. (A4) in Appendix A). This is based on the assumption that a large share of the recovery activities (e.g. back-filling) in this sector is performed on-site by construction workers.

3 *Trade in recyclable raw materials.* Data on imported and exported amounts of recyclable raw materials are available at the national

level (Eurostat, 2021i). Export data were downscaled using the ratio of the number of recycling workers in Umeå to the total number of recycling workers in Sweden (see Eq. (A5) in Appendix A). This approach assumes that the number of recycling workers determines the amount of recyclable materials recovered for export. Import data were downscaled using the ratio of persons employed in economic activities that could use the recyclables as raw materials (see Eq. (A6) in Appendix A). For the application of the CEMF at the national or EU level, a detailed list of recyclable raw materials has been defined based on Combined Nomenclature (CN) codes used in international trade in goods statistics (EC, 2018a). The materials on the list are classified into five main classes: (i) plastics; (ii) paper and cardboard; (iii) precious metal; (iv) iron and steel; (v) copper, aluminium and nickel. It was assumed that these materials could be used as raw materials in three NACE activities: (i) C17 Manufacture of paper and paper products; (ii) C22 Manufacture of rubber and plastic products; (iii) C24 Manufacture of basic metals. The ratios of the numbers of persons employed in these three sectors in Umeå to those in Sweden were calculated using data from SCB (2022a).

4 *Trade in waste destined for recycling and waste recycled in domestic recovery plants.* Data on the trade of waste destined for recycling is available only in national statistics on the trade of goods (Eurostat, 2022c). The data were downscaled following the above-described approach for downscaling data on trade in recyclable raw materials (see Eqs. (A7) and (A8) in Appendix A). The only difference is that data on imported waste destined for recycling was downscaled using the ratio of persons employed in the whole manufacturing sector instead of specific economic activities, as the list of CN-codes approximating traded waste (Eurostat, 2018) is broader and includes waste that various manufacturing activities could use. National-level data on waste recycled in domestic recovery plants are available by Eurostat (2022j) and (SCB, 2022e) (for 2020). They were downscaled using the ratio of recycling workers in Umeå and Sweden (see Eq. (A9) in Appendix A).

5 *Private investment and value-added related to CE sectors.* In the context of the CEMF, the CE sectors are approximated by the recycling and repair and reuse sectors (EC, 2018a). These two sectors are defined based on specific economic activities of the fourth level of the NACE

² The data in the SCB datasets is reported according to the SNI 2007 (SCB, 2007) classification, which is the Swedish equivalent of the NACE Rev.2 classification.

classification described by EC (2018a). Data on private investment and value-added at the fourth level of the NACE are only available at the national level. The data were downscaled to the Umeå level using the ratios of the numbers of persons employed within these specific economic activities in Umeå to those in Sweden, which were calculated based on data from SCB (2022a)³ (see Eq. (A10) in Appendix A).

3.5.2. Domestic material consumption

The calculation of indicators 3.3 and 7.2 requires the estimation of the DMC. The DMC in Umeå was taken from Westin et al. (2020), who estimated the DMC of several Swedish cities in 2010. The DMC from 2010 to 2020 was then estimated, assuming that the trend of DMC in Umeå is the same as in Sweden. Therefore, the annual change of the DMC in Sweden from 2010 to 2020 was calculated based on data from Eurostat (2022b) and then used to interpolate the DMC in Umeå (see Appendix B).

3.5.3. Circular material use rate

Indicator 7.2 CMU rate is defined by Eq. (2) as the ratio of the circular use of materials (U) to the overall material use (M) (Eurostat, 2018):

$$CMU = \frac{U}{M} = \frac{R - Im + Ex}{DMC + U} \quad (2)$$

where U is defined as the amount of waste recycled in domestic recovery plants (R), minus imported waste destined for recovery (Im), plus exported waste destined for recovery abroad (Ex), and M as the aggregate of DMC and U . The DMC was estimated based on the approach described in 3.5.3 and R , Im and Ex were calculated by downscaling national data, as described in 3.5.1.

3.5.4. Number of patents

The indicator *Number of patents related to recycling and secondary raw materials* was computed based on EPO's Worldwide Patent Statistical Database (PATSTAT) (EPO, 2022). The database contains bibliographical and legal status data from patent offices of leading industrialised and developing countries worldwide (EPO, 2022), including address information from patent applications filed at the EPO and other smaller patent offices (de Rassenfosse et al., 2019). Hence, it is possible to identify patents originating from a specific city. The identification of the number of patents related to recycling and secondary raw materials originating from Umeå was done through queries in the PATSTAT 2022 spring edition using the Structured Query Language (SQL) (for a guide, consult EPO 2020). For this purpose, the recommended by the EC (EC, 2018) codes of the Cooperative Patent Classification (CPC) were applied following guidelines suggested by the Joint Research Centre (JRC) (Fiorini et al., 2017).

4. Results

4.1. Available data sources

The identified data sources are summarised in Table 3. The urban-level data are available for eight indicators (2, 3.1, 3.3, 5.1, 6.5, 6.7, 9.2 and 10). For indicator 2, reports, guidelines or webpages can be used to find information on municipal procurement processes. For indicators 3.1, 3.3, 5.1, 6.5 and 6.7, waste statistics for Swedish municipalities published annually by the Swedish Waste Management Association (SWMA) (Avfall Sverige, 2022a) can be used. For indicator 9.2, data on the number of persons employed per economic activity at the fourth level of the NACE classification are needed, as the CE sectors in the CEMF are defined based on this classification level. SCB collects data at

this level of detail at the national and urban levels. The national-level data are reported by Eurostat (2022a). The urban-level data are not publicly accessible, though municipalities in Sweden have access to them (Öberg & Levisson 2021, Personal Communication, 15 November 2021). For indicator 10, data on patent statistics can be found in the PATSTAT database. There are no available urban-level data for the other indicators of the modified CEMF. To bridge this gap, existing national-level Eurostat and SCB data can be downscaled to the urban level using proxy factors (see 3.5.1).

4.2. Data quality

The calculated DQRs of the identified datasets are shown in Table 3 and explained in Appendix C. Note that for indicator 2, the DQR was not estimated, as it is a qualitative indicator based on information about municipal procurement processes.

For most indicators that can be computed with a bottom-up approach, the quality of urban-level data is generally high. Indicators 3.1, 5.1, 6.5 and 6.7 can be computed using municipal waste statistics produced by the SWMA based on direct inputs from the municipalities (Avfall Sverige, 2022b). The quality of these data is "very good" (DQR = 1), as they are verified data produced based on specific guidance for interpretation of definitions and input descriptions (Avfall Sverige, 2020), they are continuous, they are disseminated in less than one year, and they are available at the urban level. For indicator 4.1, verified data are not directly provided in the SWMA reports. However, data on food waste generation can be estimated based on information about food waste management in Swedish municipalities provided in these reports. As these data are estimated and not verified, their DQR is 2.3, which indicates data quality between "good" and "fair". For indicator 9.2, data on the number of persons employed per economic activity at the urban and national levels is collected by SCB and reported by Eurostat. The reliability of the data is very good, owing to the SCB's quality policy and the fact that predominately administrative data are used, thereby minimising sampling errors (Eurostat, 2022). Moreover, they are continuous and available at the urban level. However, they are disseminated within 2 years after the reference year, and because of this, the DQR is 1.6, indicating data quality between "very good" and "good".

For indicator 10, which can also be computed with a bottom-up approach, the PATSTAT database is a readily available data source. However, there is a variation in the quality of data extracted from the database due to inconsistencies in the provision of address information or other relevant information (Fiorini et al., 2017). For this reason, data from PATSTAT used to compute the indicator at the national or EU level undergo harmonisation checks by JRC based on algorithms and own assessments (ibid.). However, the algorithms are not publicly available and a similar harmonisation to improve the quality of data at the urban level is not feasible. Another shortcoming with data from PATSTAT is that there is a delay of at least 3.5 years in their dissemination. Consequently, the DQR for the PATSTAT data is 3.9, indicating data quality between "fair" and "poor".

All the other indicators of the CEMF can be computed using down-scaled national-level data. The degree of geographical representativeness of these data is low, as they reflect national conditions instead of local conditions. Hence, their rating in the DQI *geographical representativeness* is 3, which reduces the overall quality of these datasets. Apart from this common shortcoming, the quality of the national-level datasets varies, as they have different qualitative characteristics. National-level data on the generation and recycling of waste excluding major mineral wastes (Eurostat, 2022d, 2022e), recovery rate of construction and demolition waste (Eurostat, 2022e), and recycling of all waste (Eurostat, 2022j), which can be used for computing indicators 3.2, 3.3, 5.2, 6.6 and 7.2, are verified and produced following quality assurance procedures. However, they are discontinuous (available only every second year) and become available within 2 years after the reference year. Consequently, the DQR of these datasets is 2.5, indicating data

³ Note that data from SCB on the number of persons employed in Umeå at the fourth level of the NACE classification is not publicly accessible.

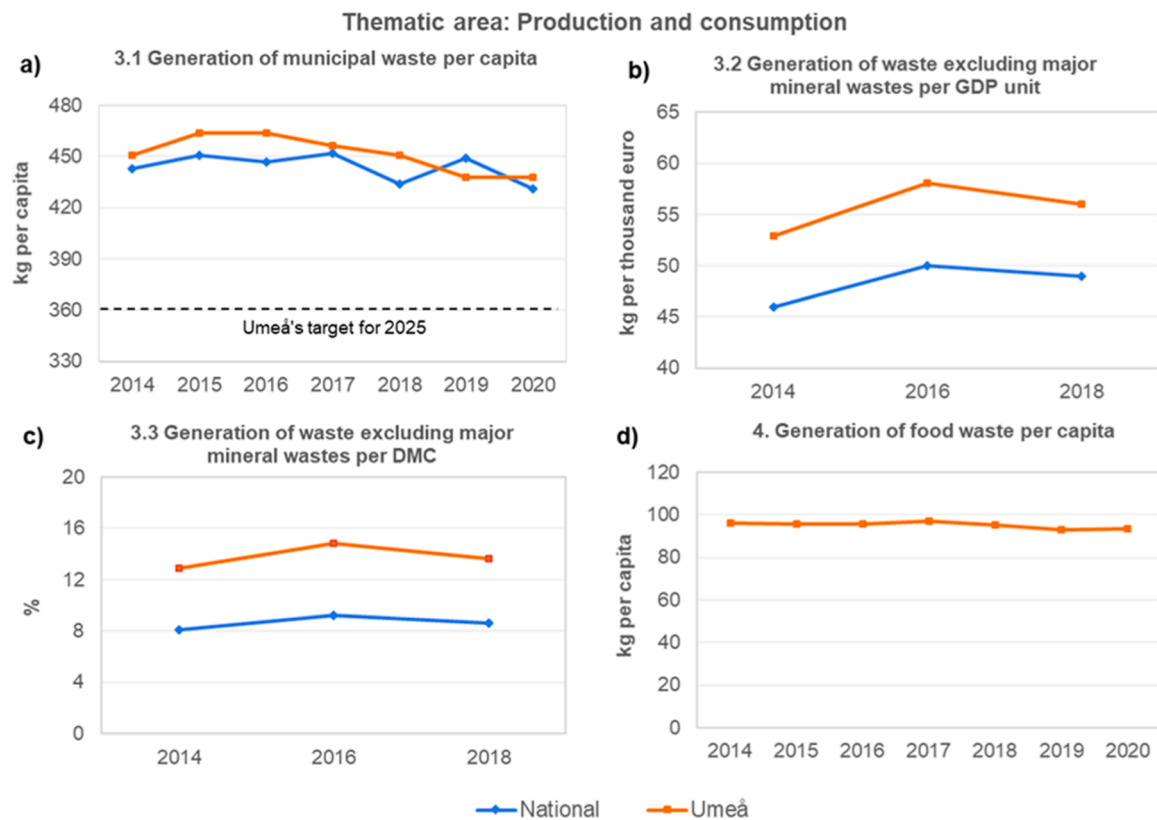


Fig. 2. Indicators of the *Production and consumption* thematic area for Umeå and Sweden.

quality between "good" and "fair". For data on the recycling rate of overall, plastic and wooden packaging (Eurostat, 2022h) and e-waste (Eurostat, 2022g), which can be used for computing indicators 6.1, 6.2, 6.3 and 6.4, the dissemination is also done within two years. Nonetheless, these data are continuous; thus, their DQR is slightly lower (2.4), indicating better quality. For the same reasons, the DQR of data from annual detailed enterprise statistics (Eurostat, 2022a), which can be used for calculating indicators 9.1 and 9.3, is 2.4. Regarding data on trade in recyclable raw materials (Eurostat, 2021i), which can be used for calculating indicators 8.1, 8.2 and 8.3, and data on trade in waste destined for recycling (Eurostat, 2022c), which can be used for calculating indicator 7.2, the DQR is even better (2.3), as they are continuous and disseminated within one year.

For the computation of indicator 3.2, data on GDP per capita in the urban area from SCB (2022c) are needed. These data are verified, continuous and available at the urban level. However, they are disseminated within 2 years after the reference year. Due to this, the DQR is 1.6 instead of 1, indicating data quality between "very good" and "good". Moreover, for indicator 3.3, data on the DMC in the urban area are required. The DMC for various Swedish urban areas, including Umeå, was estimated by Westin et al. (2020) using the Urban Metabolism Analyst model (Rosado et al., 2014). These data are not verified, and they are not complete, as they are only available for one year (2010). Consequently, the calculated DQR⁴ is 4.1, indicating data quality between "poor" and "very poor".

4.3. Results from the application of the CEMF to Umeå

The calculated values of the CEMF indicators for Umeå are

⁴ The DQI time representativeness was not included as the data on DMC were produced for one specific case study without any intention to update them and disseminate them periodically.

summarised in Table D1 of Appendix D. Their plots are shown in Figs. 2–5 and are presented per thematic area in the following sections. In general, the coverage for the monitoring period 2014–2020 varies amongst the indicators of the framework due to differences in data availability and quality. For indicators that there are available national-level data on the dedicated website of the CEMF (Eurostat, 2022f), the graphs of indicator values in Sweden were also plotted in the figures.

4.3.1. Production and consumption

Fig. 2a shows that municipal waste generation per capita in Umeå is comparable to the national average and that there was a downward trend in municipal waste generation in Umeå from 2015 to 2020. Nonetheless, further reduction needs to be achieved in the short term. In the most recent waste plan for the Umeå region⁵ (Umeå region, 2020), the Umeå municipality has set a target to reduce municipal waste generation to 360 kg/cap by 2025, which requires a considerable reduction of approximately 80 kg/cap within a five-year timeframe. Fig. 2b shows that food waste generation was roughly steady at approximately 95 kg/cap from 2014 to 2019. According to the municipality's targets in the plan mentioned above, the collected amounts of food waste and residual waste together have to be 25% lower in 2025 than in 2015, highlighting the necessity for further reductions in both waste streams. Fig. 2c and d show that overall waste generation per GDP unit or per DMC were higher in Umeå than in Sweden. These two graphs also show that the lack of continuous data does not permit a detailed depiction of trends. For qualitative indicator 2, no graph was plotted. For this indicator, it was found that no CE or waste prevention criteria have been established in Umeå's procurement processes. However, circular procurement models for the municipality are currently under consideration (Umeå Municipality, 2022a).

⁵ Umeå region consists of the municipalities of Bjurholm, Nordmaling, Robbtsfors, Umeå, Vindeln and Vännäs.

Thematic area: Waste management

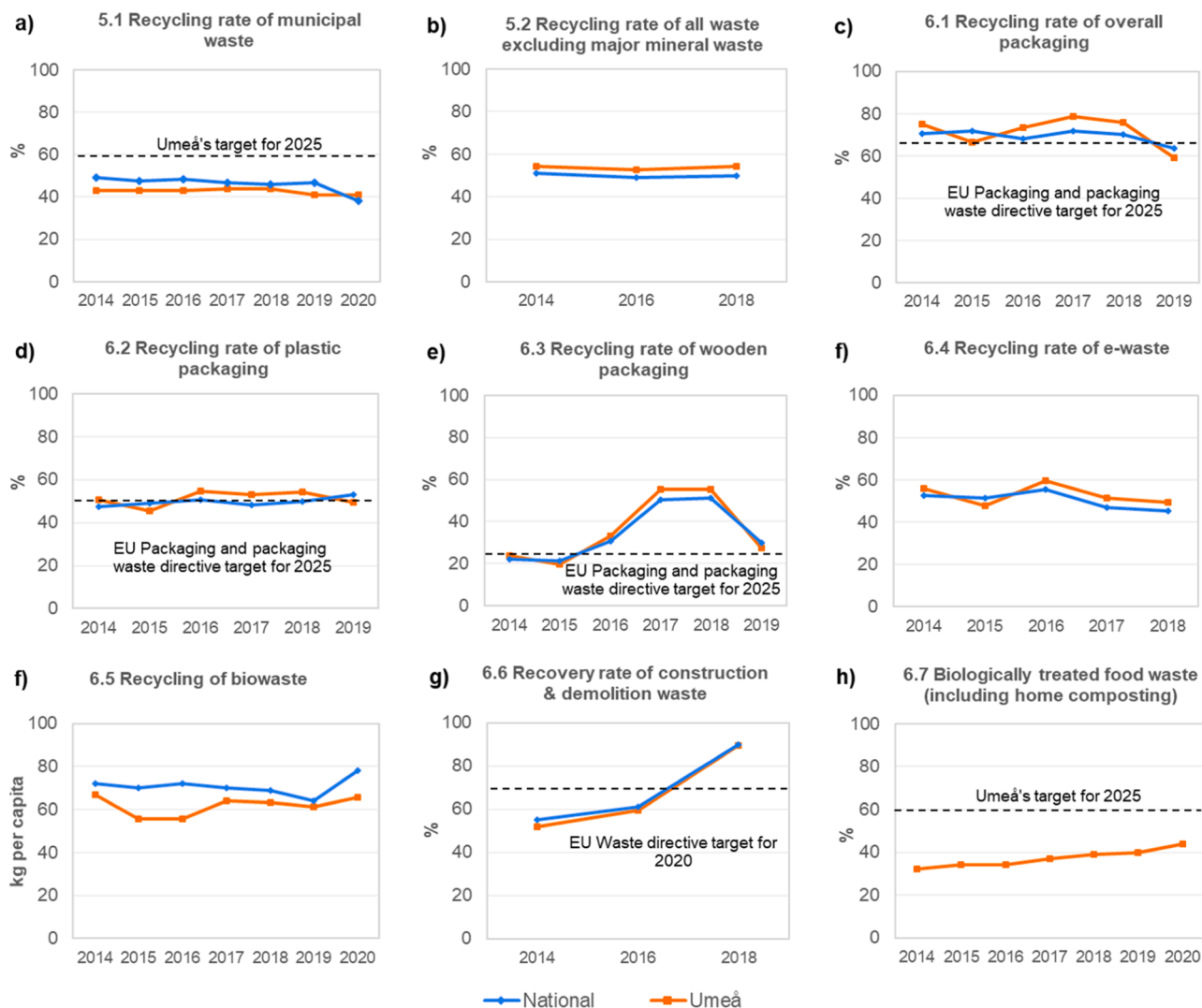


Fig. 3. Indicators of the *Waste management* thematic area for Umeå and Sweden. Fig. 3a and 3h show the targets for municipal waste recycling and biological treatment of food waste as defined in the regional waste plan (Umeå region, 2020). Fig. 3c, 3d and 3e show the recycling rate targets for overall, plastic and wooden packaging according to the EU Packaging and packaging waste directive (2018/852) (EC, 2018b). Fig. 3g shows the recovery rate target for construction and demolition waste according to the EU Waste directive (2008/98/EC) (EC, 2008).

Thematic area: Secondary raw materials

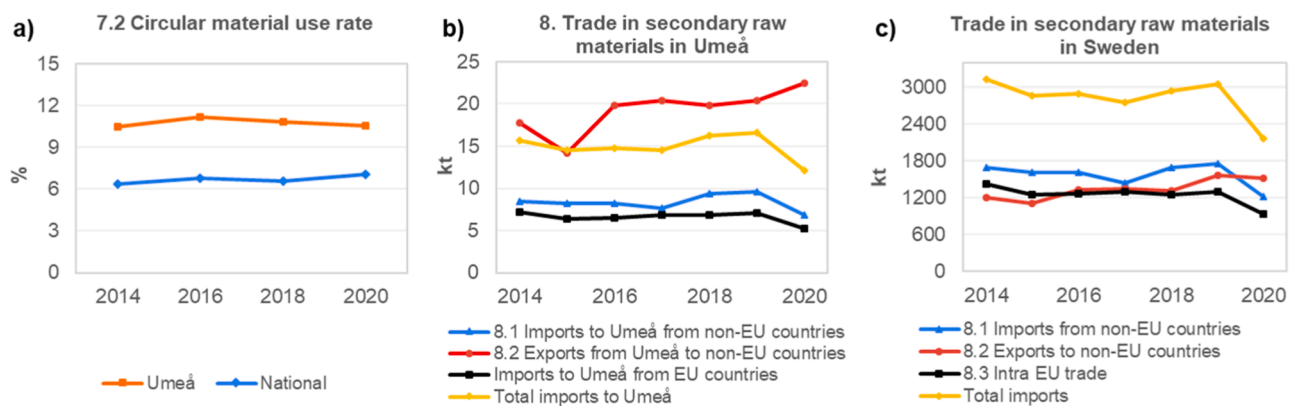


Fig. 4. Indicators of the *Secondary raw materials* thematic area for Umeå and Sweden.

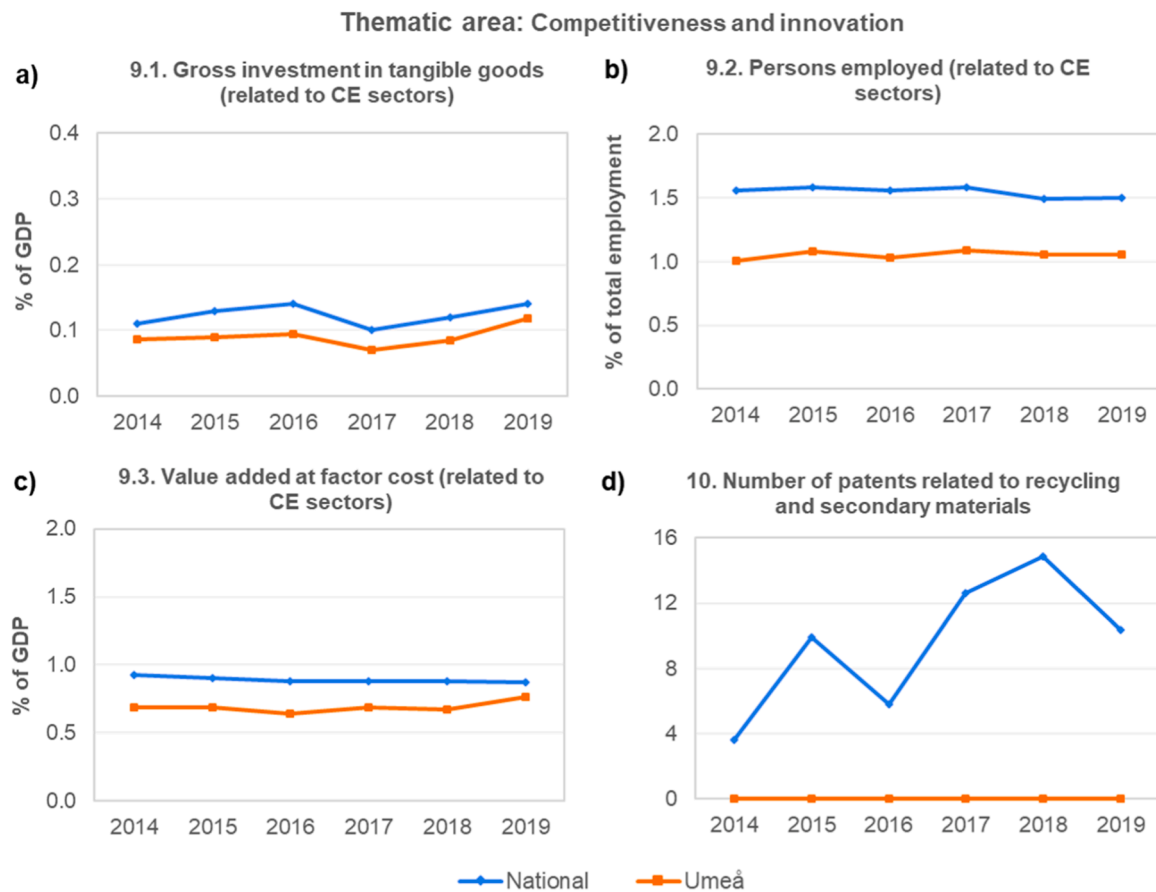


Fig. 5. Indicators for Competitiveness and Innovation thematic area for Umeå and Sweden.

4.3.2. Waste management

Fig. 3 shows the graphs of the indicators of the thematic area of *Waste management*. Some graphs also show targets from the regional waste plan (Umeå Region, 2020) or from EU directives. Overall, the recycling rates for different waste streams in Umeå are comparable to the national ones. For municipal waste, the recycling rate in Umeå became higher than the national one in 2020. However, this rate should further increase by almost 20% by 2025 to reach the targets of the aforementioned waste plan. The recycling rates for overall, plastic and wooden packaging were usually higher than the EU targets during the monitoring period, both in Umeå and Sweden. For the recycling rate of overall packaging, there was a noticeable decrease from 2018 to 2019, which may be correlated to the decrease in the recycling rate of wooden packaging in the same period. This reduction could be because the EU target (25%) has been reached since 2015, which might have reduced recycling efforts for wooden packaging and promoted its use as biomass fuel. For e-waste, the recycling rates in Umeå and Sweden were lower than the EU targets, which were set for different types of e-waste in the EU Waste electrical and electronic equipment (WEEE) directive (2012/19/EU) (EC, 2012) and range from 55% to 80%. This indicates that more recycling efforts for this waste stream are needed. For biowaste, the recycled amount per capita in Umeå in 2020 was lower than in Sweden by almost 12 kg/cap indicating that there is perhaps a need to promote further biowaste recycling in Umeå. For the recovery rate of construction and demolition waste, there was a significant increase for Umeå and Sweden from 2014 to 2018, which could be driven by the demand to reach the EU target (70%) (EC, 2008). Finally, Fig. 3h shows an upward trend in food waste going for biological treatment in Umeå, though this value should increase by almost 20% by 2025 to reach the target of the waste plan. Note also that Fig. 3h does not show national values, as indicator 6.7 is not included in the original CEMF.

4.3.3. Secondary raw materials

Fig. 4a shows the graph of indicator 7.2 for Umeå and Sweden. As anticipated, the values of the indicator for Umeå were higher than in Sweden since the calculated DMC in Umeå is lower than in Sweden (see Appendix B). The main reason is that the DMC values largely depend on the values of domestic extraction (for more details, see Eurostat (2001)), which for most materials (e.g., metal ores, biomass) takes place outside urban areas. Due to the variation in the estimation of the DMC because of differences in system boundary definition, the direct comparison of the values of the CMU rates between Umeå and Sweden may not be relevant. However, comparing trends to detect similarities and differences could be useful. For example, Fig. 4a shows that the CMU rate remained almost steady from 2014 to 2020 in Umeå and Sweden.

Fig. 4b and 4c show that the trade in secondary raw materials differs between Umeå and Sweden. In Umeå, the amount of exported secondary raw materials was higher than that of imported materials, while in Sweden, the amount of imported materials was higher. Both in Umeå and Sweden, an increase in exports from 2016 to 2020 is noticeable, while for imports a considerable decrease is noticed in 2020.

4.3.4. Competitiveness and innovation

Fig. 5 presents the graphs for the four indicators of the thematic area *Competitiveness and innovation*. For indicators 9.1, 9.2 and 9.3, the values in Umeå were lower than the national values, indicating a potential need for additional investments and job creation in CE sectors in Umeå. Regarding indicator 10, it was found that no patents related to recycling and secondary materials were developed in Umeå from 2014 to 2019.

5. Discussion

5.1. Strengths and limitations of the CEMF as a monitoring tool for urban areas

The CEMF is a well-structured thematic framework with indicators in four thematic areas. Applying the CEMF can reveal trends informing decision-makers about baseline conditions in these areas. For Umeå, the framework's application indicated varying trends in the different thematic areas. In the thematic area *Production and consumption*, there was a downward trend in municipal waste generation, indicating some progress in this area. *Food waste generation* remained relatively unchanged from 2014 to 2020, while there were no prevailing trends for waste generation excluding major mineral wastes per GDP or per DMC. In the thematic area of *Waste management*, there were upward trends for the recovery rate of construction and demolition waste and biologically treated food waste. In contrast, the recycling rates of the other waste streams remained relatively steady or show slightly downward trends. In the thematic area of *Secondary raw materials*, the CMU rate was almost steady from 2014 to 2020, and the imports and exports of secondary raw materials were relatively stable from 2015 to 2020, when a considerable increase in exports and decrease in imports was noticed. Likewise, in the thematic area of *Competitiveness and innovation*, there were no significant variations in private investment, jobs, gross value added, and the number of patents from 2014 to 2019, indicating no significant progress in this area.

Moreover, the CEMF can be used for target-setting and tracking progress toward defined targets. As shown in the context of the Umeå case, the indicators *Generation of municipal waste per capita*, *Recycling rate of municipal waste* and *Biologically treated food waste* were associated with specific targets of the local waste plan, revealing that further progress is needed in these areas to achieve these targets. Nonetheless, it is noteworthy that only 3 out of the 24 indicators of the framework could be associated with specific targets from existing municipal strategies and plans. This highlights a need to set additional CE targets for Umeå, which could be done using the CEMF indicators as a basis.

Another strength of the CEMF is that it allows multiscale comparisons. In the Umeå case, the computed indicators were compared against those for Sweden. The comparison indicated that municipal waste generation in Umeå was comparable to that in Sweden, and that the generation of waste excluding major mineral wastes per GDP unit or per DMC was higher in Umeå over the monitoring period. It also showed that the recycling rates of the different waste streams in Umeå are similar to the national averages. The comparison of the values of the CMU rate in Umeå against that in Sweden is not relevant, as the two rates are estimated using different system boundaries (see 4.2.3). However, the comparison of the trends of the CMU rate revealed they were almost steady in Umeå and Sweden during the monitoring period. Furthermore, the comparison of trends in trade of secondary raw materials between Umeå and Sweden showed that, contrary to Sweden, the exports are higher than the imports in Umeå. Finally, all the indicators of the thematic area of Competitiveness and innovation have lower values in Umeå compared to Sweden, which indicates that more attention is needed in this area.

Nonetheless, the CEMF has limitations as a monitoring tool for urban areas. A significant limitation is the low availability of good quality urban-level data. The data source mapping showed that there are available urban-level data only for 8 out of the 24 indicators of the modified CEMF, at least in the Swedish context. Most of these data are generally of high quality, except for data on the number of patents. For the other indicators, national-level data need to be downscaled to the urban level. However, the geographical representativeness of the national-level data is low, and thus their quality is reduced. Furthermore, there are additional problems with the quality of some national-level data, as some datasets are discontinuous and are disseminated with a delay of 2 or more years. The lack of continuous data is a significant shortcoming. It does not permit a detailed depiction of trends for

a specific monitoring period, as demonstrated in the Umeå case, where some indicators of the CEMF could not be computed for every year of the monitoring period (see Table D1). Overall, the top-down approach to calculating CEMF indicators generates uncertainty in the results, highlighting the need to improve data availability and quality at the urban level.

In addition, the CEMF lacks a systems perspective, as its structure is not based on an explicit system definition. Consequently, the relationships between the different indicators of the framework are not clearly established, which creates risks for conducting incoherent assessments. Furthermore, due to a lack of systems perspective, the application of the CEMF cannot demonstrate linkages between different resources, wastes, sectors and functions when applied to an urban area. Furthermore, it cannot show how CE strategies developed at the urban level interact with national or regional strategies or policies, making it challenging to understand whether these urban strategies can contribute to the broader CE.

Another limitation of the CEMF is that it predominately focuses on solid material resources and waste (mainly recycling). A potential explanation lies in the availability of reliable data on waste (EESC, 2018), as also demonstrated in this study. Another potential factor for this narrow focus is that the CEMF draws upon two other indicator-based frameworks, the Resource Efficiency scoreboard (EC, 2016a) and the Raw Materials scoreboard (EC, 2016b), which have several well-established indicators focusing on material resources and waste. Due to its narrow focus, the CEMF overlooks important aspects of CE, such as longevity, reuse, industrial symbiosis, eco-design, and disregards other resources (e.g., water, energy and land) (Pacurariu et al., 2021; Paiho et al., 2020). Furthermore, the CEMF does not include indicators that can measure potential environmental effects (e.g. climate change, pollution, biodiversity loss) from a transition to a CE and has only a few indicators (9.1, 9.2 and 9.3) that can capture the socio-economic effects of this transition. It is also noteworthy that the CEMF overlooks potential links between the CE and sharing economy. This is evident in indicators 9.1, 9.2 and 9.3, which are computed taking into account only the recycling and repair and reuse sectors (EC, 2018a), disregarding sectors relevant to sharing economy, such as the ones described by EC (2018c).

Furthermore, another limitation of the CEMF, when considered as a monitoring tool for urban areas, is that certain indicators may not be relevant in an urban context. For example, the indicator *Number of patents related to recycling and secondary materials* is focused on a specific technological domain, i.e., recycling and reuse technologies, and its application to an urban area would probably provide a limited view of the innovation activity in this domain, in relation to the national context. This was demonstrated clearly in this study, where the indicator was zero for Umeå for every year of the monitoring period.

5.2. Recommendations for CE monitoring at the urban level

This section provides recommendations that could improve existing CE monitoring approaches and systems, including the CEMF, and potentially guide the development of new ones.

5.2.1. Taking a systems perspective

The importance of taking a systems perspective when monitoring CE development at any level (i.e. micro-, meso- or macro-level) has been previously discussed in the literature (Helander et al., 2019; Pauliuk, 2018). Pauliuk (2018) concluded that the lack of systems perspective could lead to developing monitoring systems containing incoherent CE indicators that would fail to provide comprehensive and credible assessments. Helander et al. (2019) highlighted the need to adopt a comprehensive systems perspective when monitoring progress toward an environmentally sustainable CE at the company or national level to include all sections of the studied socio-economic system and capture all key environmental flows. We concur with these suggestions and recommend adopting a systems perspective when monitoring CE progress at the urban level.

For this purpose, applying an urban metabolism (UM) approach could be particularly beneficial. The urban metabolism approach considers an urban area as an organism that metabolises material and energy into products and wastes and takes a systems perspective to describe and model the urban system (Kennedy et al., 2011; Pincetl et al., 2012). Applying an UM approach can provide insight into how the urban system is structured and its sub-systems function and interact and can help define its system boundaries explicitly. This explicit system definition could function as a structure for developing a new indicator-based framework or amending the structure of existing ones. Furthermore, Material Flow Analysis (MFA), one of the most common UM assessment methods, can map and quantify the most significant flows and stocks of materials and energy in urban areas. Hence, applying the MFA could create a quantitative basis for calculating indicators and potentially inspire the development of new ones.

5.2.2. Monitor multiple dimensions

As we discussed in Section 5.1, a limitation of the CEMF is its narrow scope. This is a common limitation of most existing indicator-based CE monitoring frameworks (Papageorgiou et al., 2021). Nonetheless, the transition to a CE is a multi-dimensional process (Cairns & Patel, 2020) that requires the consideration of multiple dimensions when monitoring progress toward a CE. Three dimensions generally overlooked by most CE monitoring frameworks are the environmental, energy and institutional dimension (Papageorgiou et al., 2021).

Integrating the *environmental dimension* in monitoring CE development in urban areas is essential for evaluating whether CE strategies and activities can contribute to environmental sustainability. Conceptually, the CE model recognises that environmental pressures mainly derive from materials overuse and that increased material use efficiency and closed material loops can decrease these pressures (Helander et al., 2019). Based on this notion, most existing CE monitoring frameworks, including the CEMF, contain indicators focused on resource efficiency and recycling, implicitly assuming that improved performance in these indicators reflects environmental benefits. However, CE activities can create trade-offs and synergies in the complex nexus between resources, climate and biodiversity (Calisto Friant et al., 2021) and may result in unintended rebound effects that can ultimately undermine environmental sustainability, such as increased production and consumption levels because of increased resource efficiency (Chen, 2021; Helander et al., 2019). Hence, a holistic approach based on a life cycle perspective and integrating multiple environmental aspects is needed to fully assess potential environmental impacts, trade-offs, and synergies from CE activities. Previous studies (Corona et al., 2019; Rigamonti & Mancini, 2021; Saadé et al., 2022) have shown that the LCA methodology and the associated Life Cycle Impact Assessment indicators have high potential in assessing multiple environmental aspects related to the CE and constitute an area of research that could contribute to incorporating the environmental dimension into CE monitoring.

Regarding the *energy dimension*, in most established CE conceptualizations, the transition to a CE model is supported by renewable non-fossil fuel-based energy (Kirchherr et al., 2017; Kiviranta et al., 2020). The perception of the energy and energy sector in the CE model is primarily focused on the quality of electric and thermal power supply, which implies reducing fossil fuels in the energy mix, increasing the share of renewables, and increasing energy efficiency. A potential approach to monitor and assess these aspects could be mapping and quantifying energy flows throughout the urban system by applying a UM approach and then calculating relevant indicators. Additionally, several indicator sets have been developed to evaluate the sustainability of energy systems covering a wide range of indicators on the quality of supply, energy efficiency and productive use, energy dependency and energy security (Gunnarsdóttir et al., 2020; Ligus & Peternek, 2021). These indicator sets are predominately intended for energy systems at the national level. However, they are also scalable to the urban level and could potentially be used to monitor CE's energy-related aspects.

The *institutional dimension* refers to formal or informal rules, such as regulatory instruments (e.g. laws), cultural values, social norms, traditions and habits, that both influence and are influenced by social practices and policy-making (Schulz et al., 2019). Aspects related to the institutional dimension may include stakeholder participation in managing and steering decisions and political processes, ownership models (Moreau et al., 2017), policies and regulations (Schulz et al., 2019) and local skill base (Kabeyi & Olanrewaju, 2022). To include an institutional perspective when monitoring progress towards a CE at the urban level, indicators that can measure performance or reflect changes connected to interventions related to the abovementioned aspects are needed. For this purpose, relevant indicators need to be developed or identified in other frameworks. For example, Berisha et al. (2022) proposed to assess the institutional dimension of urban systems performance concerning Sustainable Development Goal 11 on sustainable cities using procedural indicators that monitor formal cooperation, functional relations and goal-orientated coordination. Such indicators could be relevant to CE, and their applicability for measuring urban circularity could be further explored.

Additional dimensions that have been discussed in the literature include the *social dimension*, which encompasses aspects related to well-being, social justice and equity (Calisto Friant et al., 2021), the *cultural dimension*, which includes aspects associated with cultural impacts of the CE transition (Vanhuysse et al., 2021), the *behavioural dimension*, which covers aspects related to activism, commitment and leadership (Rios et al., 2022), and the *technological dimension*, which incorporates aspects related to technological solutions for CE implementation (Pomponi & Moncaster, 2017).

The consideration of multiple dimensions in monitoring systems for CE, such as the CEMF, could support more comprehensive and holistic assessments of CE progress in urban areas. At the same time, such monitoring systems would require numerous indicators and significant data inputs. Existing urban sustainability and smart city assessment frameworks could function as pools for both indicators and data. For example, several smart city assessment tools contain environmental indicators (e.g. waste, water and energy indicators) (Sharifi, 2019), which could also be relevant for CE monitoring. However, the selection of such indicators should be carefully done, taking into account specific CE principles, such as the R-principles (Potting et al., 2017) or the seven operational principles of CE (Suárez-Eiroa et al., 2019), to ensure that the selected indicators are relevant to the CE context.

5.2.3. Improve the availability and quality of data

Applying reliable metrics for tracking CE progress is only possible if appropriate data are available at the municipal level. Uptake and novel application of data-driven smart solutions in urban management and planning are expected to change how cities implement sustainable solutions (Bibri, 2021). To lead the digital transformation, municipalities need to establish data collection systems along with systems and guidelines to govern the management and use of generated data (Johnson et al., 2022). By investing in better data collection and management systems, municipalities will be able to simultaneously address local data gaps and contribute to enhanced national data quality. Furthermore, community and citizen science initiatives can support urban data systems by engaging various societal actors, such as citizens, scientists, private companies and non-governmental organisations, in collecting and sharing data (Moreno Pires et al., 2017; Rathnayake et al., 2020). For example, smart meters in households can provide high-resolution data on energy consumption within an urban area, and organisations that collect, sort and treat waste can provide data on the quantities of materials they collect and divert for reuse, repair and recycling. These alternative data sources can play an important role in the urban data landscape, but they do not come without challenges and costs. In particular, systems for validation and verification are necessary to ensure the comparability and legitimacy of supplied data.

5.3. Research limitations

A limitation of this study is that the pedigree matrix approach necessarily involves subjective judgments from the applicants, and the DQR should be considered a representation of subjective judgments of data quality (Weidema, 1998). Nonetheless, this limitation does not undermine the utility of the pedigree matrix as a tool for data quality assessment, as it can represent the varying quality of different data sources in a comprehensive and structured manner. A second limitation is that the top-down approach to downscale national-level data is inherently uncertain. Testing various downscaling methods, such as the ones presented by Horta & Keirstead (2017), combined with uncertainty assessment methods, such as the one presented by Patrício et al. (2015), could help alleviate this limitation. Such an approach was not deemed suitable for this study, as its main purpose was to demonstrate the use of the CEMF as a potential monitoring tool for urban areas. Another limitation is that the top-down approach cannot capture local conditions and initiatives. As a result, indicators calculated based on downscaled data would probably measure similar performance for urban areas of similar size in the same country. This is a recognized limitation of this approach (Dijst et al., 2018), which is why the use of bottom-up data was prioritized in this study. Nonetheless, the availability of bottom-up data is still low, as demonstrated in this study, which necessitated the use of alternative data sources and approaches. A fourth limitation is that the identified available data sources mainly reflect Swedish urban contexts. Nevertheless, in terms of generalizability, our findings, and primarily our methodological approach, could also be relevant for urban areas within the EU, as the CEMF is a framework that has already been applied in EU member states and is expected to be developed and applied further. Outside the EU, it is too early to say if the CEMF can be applicable or compatible with local data management systems in other regions, as this study has not considered the application of the framework outside of the EU context.

6. Conclusions

This study demonstrates how an indicator-based framework, the CEMF, initially developed for monitoring progress toward a CE at a national or regional level, can be applied at the urban level. For this purpose, we amend the framework with new indicators deemed suitable for the urban context. Next, we map available data sources that could support its application and assess the quality of the identified data. By calculating the indicators of the amended framework, we test its applicability as a monitoring tool for urban areas in the specific context of the Umeå municipality in Sweden. Based on this empirical exercise, we evaluate the strengths and limitations of the CEMF as a CE monitoring tool for urban areas and provide recommendations for improving the framework and CE monitoring, in general, at the urban level. To our knowledge, this is the first study that applies this framework in an urban setting and one of the few studies that provide empirical evidence on how indicator-based frameworks can and should be used for CE monitoring at the urban level.

Overall, the CEMF is a well-structured thematic assessment framework based on a limited number of practical and easy-to-interpret indicators, which can reveal trends in different thematic areas, thereby helping to track progress, as demonstrated by its application to Umeå in this study. Furthermore, the fact that the CEMF has already been applied at the national or EU level allows for multiscale comparisons, which is essential for establishing benchmarks. For example, in this study, the computed CEMF indicators for Umeå were compared against those for Sweden. The indicators of the CEMF could also form the basis for developing specific CE targets, helping formulate CE strategies.

Additionally, the CEMF could function as a tool to enhance and coordinate communication amongst urban stakeholders and guide establishing protocols for gathering and sharing data and formalising circularity assessment.

However, we have identified limitations of CEMF that should not be overlooked. First, the CEMF lacks a system perspective, which creates risks of conducting incoherent assessments unsuitable for informed decision-making. Furthermore, the CEMF is predominately focused on solid material resources and waste, disregarding other resources (e.g. energy, water), and cannot fully capture the multiple dimensions of the CE transition, such as the environmental, energy, institutional and social dimensions. On a more practical level, the low availability of urban level data for calculating the indicators necessitates using downscaled macro-scale data following a top-down approach. This methodological approach, combined with the limited quality of certain datasets, generates uncertainty, reducing the assessment's credibility.

Despite the limitations of the CEMF uncovered in this study, the application of the framework at the urban level has potential. Its limitations could be addressed, to a certain extent, by applying a systems perspective (see Section 5.2.1), integrating additional dimensions with corresponding indicators (see Section 5.2.2), and developing appropriate systems, tools, and routines for data collection and management at the urban level (see 5.2.3). These recommendations are applicable to the CEMF and other existing monitoring systems, which have similar limitations.

Our research makes several contributions. First, it contributes to the ongoing discussion of how progress toward a CE can and should be monitored and assessed at the urban level based on indicators by testing the usefulness of the CEMF as a monitoring tool for urban areas. The empirical evidence from this application can advance the understanding of decision-makers, urban planners and researchers on the strengths and limitations of using these types of monitoring tools at the urban level. Second, it provides a detailed mapping of available data sources that could support CE monitoring in urban areas, mainly in the Swedish context. Third, it demonstrates a specific methodological approach for evaluating data quality, which could be replicated in different contexts. Fourth, it makes recommendations that could improve existing monitoring tools, including the CEMF, and guide the development of new ones.

Given that this study is limited to a single application of the CEMF in a specific study setting, further applications of the framework could be conducted for urban areas of different scales, both in Sweden and the EU, to validate our findings. Further research is also needed to explore how multiple dimensions can be considered when monitoring CE development in urban areas. Moreover, a potential future research area could be focused on applying the UM approach for improving existing or developing new indicator-based frameworks for urban areas.

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Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Appendix A. Equations for downscaling national-level data

(Table A1)

Table A1

Explanation of the downscaling process of macro-scale data based on proxy factors (ratios).

Description	Equation
1. Equation for downscaling national data on generation of total waste excluding major mineral wastes	$Tw_{n,U} = Tw_{n,S} * \frac{\text{the number of persons employed in sector } n \text{ in Ume\ddot{a}}}{\text{the number of persons employed in sector } n \text{ in Sweden}} \quad (A1)$ <p>where: $Tw_{n,U}$: Total waste excluding major mineral wastes produced by sector n in Umeå $Tw_{n,S}$: Total waste excluding major mineral wastes produced by sector n in Sweden</p>
2. Equation for downscaling national data on household waste	$Hw_U = Hw_S * \frac{\text{total population in Ume\ddot{a}}}{\text{total population in Sweden}} \quad (A2)$ <p>where: Hw_U: Household waste produced in Umeå Hw_S: Household waste produced in Sweden</p>
3. Equation for downscaling national data on the recycling rates of all waste, e-waste and overall, plastic, and wooden packaging	$R_{f,U} = R_{f,S} * \frac{\text{share of all employees in Ume\ddot{a}} \text{ working as recycling workers}}{\text{share of all employees in Sweden working as recycling workers}} \quad (A3)$ <p>where: $R_{f,U}$: Recycling rate of the waste fraction f in Umeå $R_{f,S}$: Recycling rate of the waste fraction f in Sweden</p>
4. Equation for downscaling national data on the recovery rate of construction and demolition waste	$r_U = r_{f,S} * \frac{\text{share of all persons employed in Ume\ddot{a}} \text{ working in the construction sector}}{\text{share of all persons employed in Sweden working in the construction sector}} \quad (A4)$ <p>where: r_U: Recovery rate of construction and demolition waste in Umeå r_S: Recovery rate of construction and demolition waste in Sweden</p>
5. Equation for downscaling national data on exports of recyclable raw materials	$Expr_U = Expr_S * \frac{\text{number of recycling workers in Ume\ddot{a}}}{\text{number of recycling workers in Sweden}} \quad (A5)$ <p>where: $Expr_U$: Exports of recyclable raw materials from Umeå $Expr_S$: Exports of recyclable raw materials from Sweden</p>
6. Equation for downscaling national data on imports of recyclable raw materials	$Impr_U = Impr_S * \frac{\text{persons employed in sectors in Ume\ddot{a}} \text{ that can use the recyclables}}{\text{persons employed in sectors in Sweden that can use the recyclables}} \quad (A6)$ <p>where: $Impr_U$: Imports of recyclable raw materials to Umeå $Impr_S$: Imports of recyclable raw materials to Sweden</p>
7. Equation for downscaling national data on exports of waste destined for recycling	$Expw_U = Expw_S * \frac{\text{number of recycling workers in Ume\ddot{a}}}{\text{number of recycling workers in Sweden}} \quad (A7)$ <p>where: $Expw_U$: Exports of waste destined for recycling from Umeå $Expw_S$: Exports of waste destined for recycling from Sweden</p>
8. Equation for downscaling national data on imports of waste destined for recycling	$Impw_{m,U} = Impw_{m,S} * \frac{\text{persons employed in the manufacturing sector in Ume\ddot{a}}}{\text{persons employed in the manufacturing sector in Sweden}} \quad (A8)$ <p>where: $Impw_U$: Imports of waste destined for recycling to Umeå $Impw_S$: Imports of waste destined for recycling to Sweden</p>
9. Equation for downscaling national data on the amount of waste recycled in domestic recovery plants	$Rw_U = Rw_S * \frac{\text{number of recycling workers in Ume\ddot{a}}}{\text{number of recycling workers in Sweden}} \quad (A9)$ <p>where: Rw_U: the amount of waste recycled in recovery plants in Umeå Rw_S: the amount of waste recycled in domestic recovery plants</p>
10. Equation for downscaling national data on private investment and value-added related to CE sectors	$x_U = x_S * \frac{\text{persons employed within CE economic activities in Ume\ddot{a}}}{\text{persons employed within CE economic activities in Sweden}} \quad (A10)$ <p>where: x_U: private investment or value-added related to CE sectors in Umeå x_S: private investment or value-added related to CE sectors in Sweden</p>

Appendix B. Domestic Material Consumption

(Table B1)

Table B.1

The DMC values for Sweden and Umeå.

	2014	2015	2016	2017	2018	2019	2020	Source
DMC in Sweden (t/cap)	23.5	23	23.2	24.1	24.6	25.8	25	Eurostat (2021i)
DMC in Umeå (t/cap)	16.2	15.9	16	16.7	17	17.8	17.2	Estimated based on Westin et al. (2020)

Appendix C. Calculation of Data Quality Ratings

(Table C1)

Table C.1

The calculation of the DQRs of the identified data sources of the CEMF indicators (R: Reliability, C: Completeness, T: Time representativeness, Geographical representativeness).

No	Indicator/Sub-indicator	Data source	R	C	T	G	DQR
1	Self-sufficiency for raw materials	–	–	–	–	–	–
2	CE/waste prevention criteria developed in guidelines for procurement	Reports and webpages. Data source for Umeå: (Umeå municipality, 2022a)	–	–	–	–	n.a
3.1	Generation of municipal waste per capita	(Avfall Sverige, 2022a)	1	1	1	1	1
3.2	Generation of waste excluding major mineral wastes per GDP unit	a. (Eurostat, 2022d)	1	2	2	3	a. 2.5 a
		b. (SCB, 2022c)	1	1	2	1	b. 1.6
3.3	Generation of waste excluding major mineral wastes per DMC	a. (Eurostat, 2022d)	1	2	2	3	a. 2.5
		b. Westin et al. (2020)	3	5	–	1	b. 4.1
4	Generation of food waste per capita	Same as 3.1	3	1	1	1	2.3
5.1	Recycling rate of municipal waste	Same as 3.1	1	1	1	1	1
5.2	Recycling rate of all waste excluding major mineral waste	(Eurostat, 2022e)	1	2	2	3	2.5
6.1	Recycling rate of overall packaging	(Eurostat, 2022h)	1	1	2	3	2.4
6.2	Recycling rate of plastic packaging	Same as 6.1	1	1	2	3	2.4
6.3	Recycling rate of wooden packaging	Same as 6.1	1	1	2	3	2.4
6.4	Recycling rate of e-waste	(Eurostat, 2022 g)	1	1	2	3	2.4
6.5	Recycling of biowaste in municipal waste	Same as 3.1	1	1	1	1	1
6.6	Recovery rate of construction and demolition waste	(Eurostat, 2022e)	1	2	2	3	2.5
6.7	Biologically treated food waste (including home composting)	Same as 3.1	1	1	1	1	1
7.1	End-of-life recycling input rates	–	–	–	–	–	–
7.2	Circular material use rate	a. (Eurostat, 2022j)	1	2	2	3	a. 2.5
		b. (Eurostat, 2022c)	1	1	1	3	b. 2.3
		c. Westin et al. (2020)	3	5	–	1	c. 4.1
8.1	Imports to the urban area from non-EU countries	(Eurostat, 2021i)	1	1	1	3	2.3
8.2	Exports from the urban area to non-EU countries	Same as 8.1	1	1	1	3	2.3
8.3	Imports to the urban area from EU countries	Same as 8.1	1	1	1	3	2.3
9.1	Gross investment in tangible goods	(Eurostat, 2022a)	1	1	2	3	2.4
9.2	Persons employed	a. SCB. Not publicly accessible data.	1	1	2	1	1.6
		b. (Eurostat, 2022a)	1	1	2	1	1.6
9.3	Value added at factor cost	Same as 9.1	1	1	2	3	2.4
10	Number of patents related to recycling and secondary materials	(EPO, 2022)	5	1	4	1	3.9

Appendix D. Indicator values for Umeå

(Table D1)

Table D1

The values of the indicators of the adjusted 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 excluding major mineral wastes per GDP unit	53.8	N/A	59	N/A	56.9	N/A	–	kg/k€
	3.3	Generation of waste excluding major mineral wastes per domestic material consumption	12.9	N/A	14.8	N/A	13.6	N/A	–	%
Waste management	4	Generation of food waste per capita	96.3	95.6	95.6	97	95.4	93	93.6	kg/cap
	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	–	%
Secondary raw materials	6.7	Biologically treated food waste, including home comp.	32	34	34	37	39	40	44	%
	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	ktonne
	8.2	Exports from Umeå non-EU countries	17.8	14.2	19.9	20.4	19.9	20.5	22.5	ktonne
Competitiveness and innovation	8.3	Imports to Umeå from EU countries	7.2	6.3	6.5	6.9	6.9	7.1	5.3	ktonne
	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 employment
	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	–	

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