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RESEARCH ARTICLE

A Life-cycle Assessment Framework to Estimate the Environmental Impacts of Regional and Urban Areas: Application to the Autonomous Province of Trento, Italy

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Abstract

Policies and strategies to improve environmental sustainability in cities and regions have often focused on a single sector, subsystem or impact category, or a small number of them, limiting their potential to effectively reduce overall environmental impacts. Comprehensive frameworks are needed to adequately assess environmental impacts and to identify hotspots, trade-offs and opportunities with substantial improvement potential. This article introduces a systematic framework to calculate the potential life-cycle environmental impacts of consumption at the regional and city levels. The framework is applied to the Autonomous Province of Trento and its capital city, Trento, in northern Italy. The framework draws on (i) a state-of-the-art methodology combining urban metabolism and life-cycle assessment, which estimates cradle-to-gate environmental impacts of urban consumption, and (ii) the EU Consumption Footprint methodology, which estimates cradle-to-grave environmental impacts of household consumption. First, we develop a material flow accounting model to estimate annual consumption of thousands of product types. Second, we select a set of representative product types based on their relative mass consumption shares and on their potential environmental impacts, as identified in existing research, to ensure relevant coverage across all consumption areas. Third, we develop a cradle-to-grave life-cycle model to assess the potential environmental impacts of consumption across a broad range of impact categories. Cradle-to-grave and cradle-to-gate results are compared, highlighting the importance of a cradle-to-grave perspective, including food, buildings and transport, which contribute significantly to the overall impacts associated with regional and urban areas. This comprehensive and systematic framework can support more effective and integrated decision-making by comprehensively addressing consumption-driven environmental impacts of cities and regions across the full life cycle.

Keywords Urban Metabolism · Life-cycle Assessment · Urban Consumption · Environmental Impacts · Consumption Footprint

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Highlights

- A framework to calculate annual life-cycle environmental impacts of cities or regions.
- The framework includes consumption of food, mobility, buildings and household goods.
- Application to the Autonomous Province of Trento and the city of Trento, Italy, 2019.
- Food and buildings accounted for 94% of modelled mass consumption.
- Impacts are dominated by food, mobility and buildings across most categories.

1. Introduction

The increasing concentration of population and economic activities in cities has been associated with significant environmental challenges related to resource consumption, climate change and biodiversity impacts, among others. Cities account for most of the global energy use and the associated greenhouse gas (GHG) emissions (IPCC, 2014). The European Green Deal established the goal of achieving carbon neutrality by 2050, which requires the decoupling of economic development from resource consumption. In this context, cities and EU initiatives such as the EU Covenant of Mayors for Climate and Energy, the EU mission 'Climate-neutral and smart cities' and the Green City Accord play a key role. Currently, research is needed to support effective and ambitious local action toward a climate-neutral and environmentally sustainable development (Bastos et al., 2026; Buylova et al. 2024; Booth & Giuntoli, 2026).

Policies and strategies tackling environmental sustainability in cities and regions have often focused on only one or very few sectors and/or subsystems, or on only one or very few environmental impact categories and/or indicators (Ravikumar et al. 2024; Buylova et al. 2024; Lah, 2025; Cohen et al. 2021). Sectoral-based interventions with the focus on a single environmental concern (e.g., climate change) may offer limited potential to significantly reduce overall environmental impacts associated with a geographical area, and these approaches may be associated with unintended burden shifts (Achakulwisut et al., 2022; Ipsen et al., 2019; Kouloumpis et al., 2015). Integrated and comprehensive environmental impact assessment frameworks at the regional and city levels that consider a holistic systems thinking approach – addressing cities and all their interlinked subsystems – are needed to identify sectors and activities associated with environmental hotspots or with significant improvement potential (Bastos et al., 2026; Genta et al., 2022; Lavers Westin et al., 2019; Booth et al. 2026). To support effective decision-making for environmentally sustainable urban and regional development, such frameworks should be comprehensive, consider a wide range of environmental impacts, have a life-cycle perspective and be comparable and replicable (Albertí et al., 2019; Genta et al., 2022; Mirabella et al., 2019).

Several methods and approaches have been applied in recent years to address this challenge. Input-output (IO) methods use monetary flows (transactions) drawing on the model developed by Leontief (1970), and include, for example, multi-regional (MRIO) and environmentally extended input-output (EEIO) methods (Druckman & Jackson, 2009; Hertwich & Peters, 2009; Tukker et al., 2006). Ecological and carbon footprint methods link impacts of consumption-based activities with a reference to regenerative capacity, e.g., using a land-based indicator, such as global hectares, for communicating relative impacts, or the 'number of planets' needed to sustain a given lifestyle (Baabou et al., 2017; Dawkins et al., 2024; Isman et al., 2018; Larsen & Hertwich, 2010; Pan et al., 2019; Wackernagel et al., 2006). Previous research has also highlighted the potential of approaches combining material flow analysis (MFA) and life-cycle assessment (LCA), which have been increasingly applied to specific sectors, such as buildings or waste management (Goldstein et al., 2013; Graedel, 2019; Withanage & Habib, 2021; Barkhausen et al., 2023; Sakai et al., 2017). However, integrated process-based assessments including a comprehensive set of consumption areas, sectors and systems in a city or region are limited. Advancing the application of MFA-LCA frameworks to these geographical levels to provide increasingly comprehensive assessments, while keeping a high level of detail, would be a valuable contribution to support integrated sustainable development policies (Barkhausen et al., 2023; Graedel, 2019; Bastos et al. 2026).

Several MFA-LCA frameworks have been developed at the city level in recent years. For example, Lavers Westin et al. (2019) presented a framework that used a state-of-the-art MFA model to estimate cradle-to-gate environmental impacts of urban consumption for a wide range of representative products, which covers the manufacturing or supply chain from raw material extraction to the 'factory gate'. Recently, a framework combining material and energy flow analysis and LCA was developed to evaluate circular economy strategies from a cradle-to-grave perspective describing the complete life cycle of a product, from raw material extraction to the end of life, across eight urban sectors (Papageorgiou et al., 2024, 2025): households, construction, mining and quarrying, energy supply, transport, water supply, wastewater treatment and waste management. The EU Consumption Footprint has also applied a cradle-to-grave LCA framework to estimate environmental impacts at the EU and national levels (Beylot et al., 2019; Nuss et al., 2023; Sala et al., 2019; Sanyé Mengual et al., 2023), and Genta et al. (2022) presented the first application of the Consumption Footprint framework at the city level. In this framework, consumption and its environmental impacts are estimated based on EU-averaged data and for a selection of products, modelled as representative of five areas of consumption.

Each of these approaches is associated with different strengths and drawbacks, and the appropriate application of existing methods depends mostly on the scope and objectives of the analyses. Considering the existing frameworks and their potential to support the design, implementation and monitoring of local actions, several gaps can be identified in the literature (Bastos et al., 2026). Top-down approaches, including EEIO and MRIO methods, typically draw on aggregated and average sectoral data at the global and national levels to estimate the environmental impacts associated with consumption. The aggregation of average data with limited or no granularity at the city scale (and at the product level) provides limited insight into context-specific local activities and emission sources. The linkages between local activity data and environmental impacts are paramount in the design, implementation and monitoring of effective local action. Moreover, the translation of monetary flows to environmental impacts can be associated with particularly high uncertainties; in addition, data updates are often not regular or recent enough, which can hinder prompt action. Together with other environmental impact assessment and carbon footprint methods that provide insights into a single environmental impact or aggregated results, this type of methods can provide consistent and comparable analyses at the regional and city levels, which are particularly useful for screening and benchmarking, but are insufficient to inform and monitor local action that can promptly and effectively contribute to environmental goals.

Bottom-up approaches combining consumption (e.g., building on MFA or statistical data) and LCA may provide more detailed insight, and they can provide information on the linkages between environmental impacts and context-specific local activities. However, they are often associated with high data and modelling requirements, which limit their application to large and complex systems such as regional and urban systems (Bastos et al., 2026; Elliot and Levasseur, 2022). These approaches have been mostly applied to a limited number of representative products, sectors or activities. Bottom-up frameworks focusing on specific systems, sectors or impacts (i.e., with limited scope and coverage) can support local action, however, without a holistic scope, they may overlook important improvement opportunities, trade-offs and burden shifts (Bastos et al., 2026; Elliot and Levasseur, 2022). Research is needed to advance the relevance and applicability of holistic meso-level approaches specifically tailored to informing and monitoring local action that circumvent the drawbacks of both top-down and bottom-up approaches.

This article presents a novel assessment framework to calculate consumption-driven life-cycle environmental impacts associated with a city or region, in a holistic and systematic manner, including a comprehensive set of subsystems and sectors. Specifically oriented to support decision-making, the framework can provide valuable insight on (i) the overall environmental impacts of a city or region, with a consumption-based perspective, and the relative contributions of different consumption areas, sectors and systems, and (ii) potential environmental hotspots (e.g., consumption areas or product types associated with particularly high environmental impacts). This article builds on the approach proposed by Lavers Westin et al. (2019) coupling urban metabolism (UM) with LCA and on the EU Consumption Footprint methodology developed by the European Commission's Joint Research Centre (Sanyé Mengual et al., 2025).[6] In brief, Lavers Westin et al. (2019) used an MFA model to estimate domestic material consumption (DMC) in a region or city for a reference year, selected representative products of urban consumption based on their relative mass consumption and on their potential environmental impacts, and then estimated cradle-to-gate environmental impacts of the overall urban material product consumption, by modelling impacts for representative products and upscaling those to total consumption. The EU Consumption Footprint framework (Sanyé Mengual et al., 2025) estimates life-cycle environmental impacts of consumption in the EU and in its Member States, structured by areas of consumption. Consumption is estimated for a selection of representative products in

[6] The EU Consumption Footprint platform can be accessed at:
https://eplca.jrc.ec.europa.eu/ConsumptionFootprintPlatform.html

each consumption area (the so-called basket of products), namely housing, mobility, food, household goods and appliances. Then, a process-based LCA model is developed to estimate the impacts of consumption for multiple environmental impact categories, aggregated into a single-score indicator (Andreasi Bassi et al., 2023). For consumption areas with products that are typically used in cities and regions across several years (associated with a 'stock'), namely mobility and buildings, the Consumption Footprint framework considers annual consumption and environmental impacts of the 'current stock' in the reference year.

The present framework models annual urban and regional product consumption for a comprehensive set of consumption areas and representative products with an MFA model, and it estimates the potential life-cycle environmental impacts for a wide range of environmental impact categories, with a cradle-to-grave perspective. For mobility and buildings, our framework models the environmental impacts of the 'addition to stock', which is deemed relevant to inform, assess and monitor local action (Bastos et al., 2026). To the best of our knowledge, no previous study has systematically estimated the overall environmental impacts of consumption in a city or region including all relevant consumption areas and urban sectors, combining material flow analysis with LCA to provide detailed results at the product level for a wide range of environmental impacts, with an 'annual addition to stock' perspective. In this article, the framework is applied to calculate potential environmental impacts associated with consumption in the Autonomous Province of Trento (APT) and its capital city, Trento, in northern Italy, for 2019. Trento is a medium-sized city, a size that is representative of a large part of the EU's urban fabric. Drawing on this application, we analyse the relative contribution of each consumption area and potential environmental hotspots. Furthermore, we compare cradle-to-grave with cradle-to-gate results, to assess the importance of an extended perspective across the different consumption areas. This work contributes to the body of scientific literature and knowledge on environmental impact assessment of urban areas and consumption. The framework advances the state of the art by addressing the research question 'How can cities consistently account for and monitor their consumption-based environmental impacts to effectively inform local policy and action?', and its application demonstrates the significance of a cradle-to-grave, life-cycle perspective for assessing the environmental impacts of urban consumption.

2. Materials and methods

The framework follows a set of interconnected methodological steps to develop a life-cycle model for final consumption in a city or region (summarized in Figure 1), structured into four consumption areas: food, mobility, household goods and buildings. Together, these consumption areas account for most consumption-based environmental impacts associated with the EU (Sanyé Mengual et al., 2025) and its cities (Ivanova et al., 2016, 2017; Goldstein et al., 2017; C40, 2018; Pichler et al., 2017). First, representative products are selected drawing on two approaches. For food, mobility and household goods, the approach combines the UM-LCA methodology applied by Lavers Westin et al. (2019), which draws on an MFA model to select products based on their mass consumption, with the EU Consumption Footprint (Sala & Castellani, 2019; Sanyé Mengual et al., 2023) results to ensure representative coverage for each consumption area. For buildings, a bottom-up stock model is developed using four building archetypes as representative products, based on the 'Environmental improvement of products' project (IMPRO) archetypes (Nemry & Uihlein, 2008). Second, life-cycle inventory (LCI) modules are developed for each representative product across all consumption areas, including five life-cycle (LC) phases: primary production, processing, packaging, logistics and use. These LCIs are applied to annual consumption, which is estimated, in the third step, based on the urban metabolism analyst (UMAn) model (Rosado et al., 2014) for food and mobility, complemented with consumption data for household goods from the EU Consumption Footprint framework, and with building permit data for buildings. Lastly, LC environmental impacts of final consumption are calculated and a comparative analysis is performed to provide insight on the potential significance of a cradle-to-grave versus a cradle-to-gate perspective across consumption areas. A summarized description of the framework and of the main modelling assumptions is provided in the next subsections, and further details can be found in the supplementary materials.

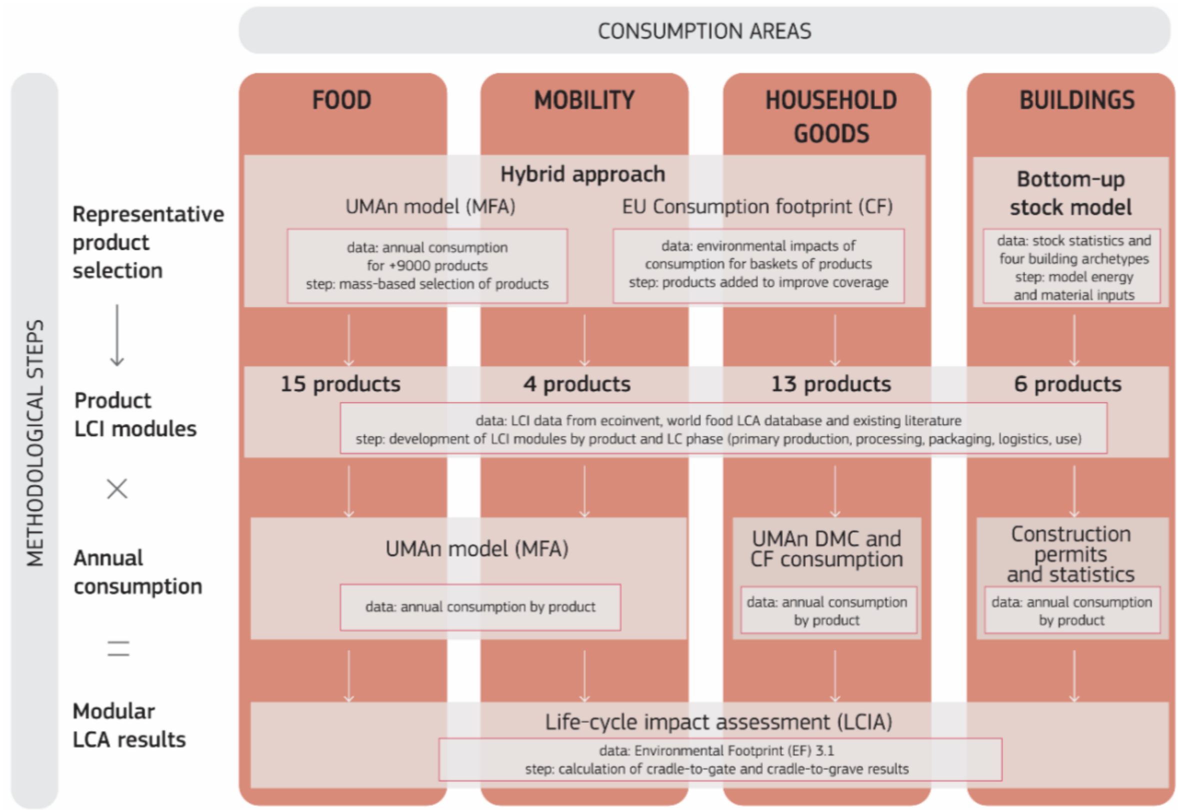

Figure 1. Schematic overview of the methodological framework

2.1. Annual consumption of representative products

As mentioned, annual consumption is calculated using the MFA-based UMAn model (Rosado et al., 2014) for mobility, food and household goods (with the final group complemented with EU Consumption Footprint data). The model calculates domestic material consumption (DMC) in a reference year for thousands of product types, categorized according to the combined nomenclature (CN) 2007, a classification system used by Eurostat for data on international trade in goods. The DMC had a total of 9 720 product types (CN8 level) structured in 98 product categories (CN2 level). From the DMC, a selection of representative products is performed based on two criteria: (i) product consumption share in terms of mass (Lavers et al., 2017) and (ii) representative coverage of products and environmental impacts among product consumption areas, based on the EU Consumption Footprint framework (Nuss et al., 2023; Sala et al., 2019; Sanyé Mengual & Sala, 2023b). For the selection of representative products based on their consumption mass shares, we first select product categories (CN2) that account for at least 1% of the overall mass consumption; and then select the product types (CN8) with the highest mass shares, accounting, together, for at least 60% of each selected product category. We then compare the selection with relevant product types in the comparable basket of products (BoPs) of the EU Consumption Footprint framework for each consumption area, to check whether we have a reasonable amount and variety of product types to be representative of that consumption area and of its environmental impacts, adding products when necessary.

In the DMC, the final products in some product categories are, in practice, components of other final consumption products. This is primarily the case for construction materials (e.g., stones and metals) and products (e.g., bricks and windows) which are regarded as final products in the MFA model but belong to buildings and other final products. To account for the final use of these materials and products, the buildings consumption area followed a different approach: a bottom-up model was developed using building stock and archetypes data for the EU context from past literature and local statistical data on construction permits. The model drew on the EU Consumption Footprint approach and its BoP for housing (Baldassarri et al., 2017; Lavagna et al., 2018) and on IMPRO building archetypes for Europe (Nemry & Uihlein, 2008). It consists of residential and commercial buildings added to stock in the reference year, including (i) construction of new buildings, (ii) building extensions and (iii) building renovations.

It is important to highlight that, for buildings and mobility, our framework considers the annual consumption and environmental impacts associated with products ‘added stock’ in the reference year (i.e., we model all life-cycle emissions and environmental impacts of the added stock, even if a large share of these will occur well beyond the reference year). That is, we perform a static assessment of the inflow of products to in-use stock in a single year and calculate the environmental impacts of the overall products’ service life. The EU Consumption Footprint framework, on the other hand, considers yearly emissions and environmental impacts associated with current stock, modelling emissions and environmental impacts that occurred before (e.g., construction of buildings in previous years) and in the year of reference.

2.2. Life-cycle model

After completing the selection of representative products, we develop a modular LC model, building on LCI datasets for products and processes matching the selected products, or proxy products with similar materials and use, using ecoinvent (version 3.9) and other complementary LCI data as needed. The LC phases modelled for the four consumption areas are summarized in Table 1. When combining LCA with MFA, using a modular structure can help to simplify the model, thus overcoming the constraints of traditional LCA software and making analyses easier (Barkhausen et al., 2023).

Table 1. Life-cycle phases and activities included in the selected product categories (drawing on Sala et al., 2019).

Life-cycle phase	Food (lifetime: less than 1 year)	Mobility (lifetime: 55 000 to 1 million km)	Household goods (lifetime: n/a*)	Buildings (lifetime: 40-50 years; renovation 30 years)
CRADLE-TO-GATE				
Primary production	Agricultural activities; animal breeding.	Construction of mobility infrastructure; maintenance and materials’ end-of-life treatment. Vehicle production; maintenance; dismantling and materials’ end-of-life treatment.	Materials used in furniture, clothes and footwear: raw material extraction, production and end-of-life treatment.	Construction materials used in new construction and building renovation: raw material extraction, production and end-of-life treatment. Transport of construction materials.
Processing	Meat slaughtering; processing of juice/jam; freezing.		Clothes production processes (e.g., dyeing, weaving); energy use in furniture, clothes and footwear production.	
Packaging	Production of packaging materials.	n/a	Production of packaging materials.	n/a
GATE-TO-GRAVE				
Logistics	Transport from production site to retail (refrigerated and non-refrigerated).	n/a	Transport from production site to retail (considering national origin, intra-EU and extra-EU import shares).	n/a
Use	Cooking.	Production of fuel; emissions related to vehicle use; tyre wear emissions, brake wear emissions; road wear emissions. Maintenance: production of components replaced during the vehicle lifetime (e.g., tyres); end-of-life of substituted components.	Clothes washing with laundry machine across service life.	Energy use including space heating and electricity requirements (including for building installations and appliances).

* Lifetime is relevant only in the LC model of clothes, which considered the ‘number of washes’ for the use phase. NB: n/a, not applicable

2.2.1. Food, mobility and household goods In the food consumption area, we developed a modular LC model with separate datasets for: primary production (agricultural production for each product type); processing (animal slaughtering and processing of olive oil, fruit juices and jam); logistics (including transport with and without refrigeration, for frozen and non-frozen goods, respectively); and use (cooking). For upstream and production phases we complemented ecoinvent data with data from the World Food LCA Database (WFLDB) version 3.5 and, when needed, with data from previous LCA studies.

The mobility consumption area comprised the transport of people by car, motorcycle and bus. As mentioned, we modelled the environmental impacts of vehicles added to the fleet in the reference year; these impacts will occur across the vehicles' service life. Statistical data on the registration of new vehicles and fleet composition data in relation to emission (Euro) standards was used to support the selection of representative ecoinvent LCI datasets and the modelling of environmental impacts. Mobility considered only vehicles for the transport of people (excluding vehicles for people with disabilities, babies, transport on snow, camping). Vehicles for the transport of goods or for production/industrial activities were not modelled because they should be accounted for in the LC of other final consumption products.

Representative products and consumption estimates for household goods were defined using both our DMC results and the relevant consumption per capita in the basket of products of the EU Consumption Footprint. Only products with a DMC that was comparable to the average EU consumption per capita were selected, to avoid distortions related to the MFA model limitations (see section 3.7). The modular LC model was developed with separate datasets for primary production, packaging and logistics for all the representative products modelled, based on ecoinvent data. For clothes, the use phase was also included, accounting for detergent and water requirements for washing (electricity consumption for washing is included in the buildings consumption area). Logistics considered waterborne and road transport, depending on the origin of imported products.

2.2.2. Buildings A bottom-up model was developed for residential and non-residential buildings added to stock in 2019 using data on construction permits and building stock for the Autonomous Province of Trento (APT) (ISTAT, 2020) and on building archetypes for the EU context from past literature (Baldassarri et al., 2017; Lavagna et al., 2018; Nemry & Uihlein, 2008). For each of the two types of buildings, we modelled (i) the construction of new buildings, (ii) building extensions and (iii) building renovations.

We modelled four building archetypes: single-family house, multi-family house, apartment block and office building. The building archetypes drew on the EU Consumption Footprint and its basket of products for housing (Baldassarri et al., 2017; Lavagna et al., 2018) and on the IMPRO archetypes for moderate (central European) climate (Nemry & Uihlein, 2008). Adjustments to the building archetypes were made based on statistics for the APT (e.g., on building footprint (width and length), number of floors and number of dwellings). Non-residential building stock includes commercial and tertiary buildings (e.g., offices, hotels and restaurants). An office building archetype was modelled based on archetypes developed for Switzerland (Ostermeyer et al., 2018; Sasso et al., 2023), with similar construction solutions and material compositions to those of the new residential building stock. The service life assumed for buildings was 50 years for residential buildings and 40 years for non-residential buildings. Deep renovations were assumed to take place at the end of the service life and then every 30 years (deep renovation cycle). In the use phase of buildings, energy consumption was considered for space heating, domestic hot water, cooking, lighting and appliances. Space cooling was assumed to be negligible in energy-efficient buildings in this climate zone. The model included the transport of materials and components to the building site and energy use in on-site construction activities. Buildings' maintenance and end of life were not considered.

As mentioned, in addition to the construction of new buildings, we calculated material requirements and environmental impacts of building extensions and building renovations. Building extension requirements and impacts were derived from the relationship between permits' construction area for new buildings and for building extensions (residential and non-residential). For building renovation, we considered gross floor area of the existing building stock by period of construction (Pezzuto et al., 2017) and considered that existing building stock built before 1975 was the share of stock in a renovation cycle (i.e., after the initial service life) in 2019. Further details on the modelling and data for the buildings consumption area are provided in section S3.5 in the supplementary materials.

2.3. Life-cycle impact assessment

Results are calculated in terms of potential consumption-driven environmental impacts associated with the region or city. We calculated impacts for midpoint impact categories using characterization models and factors recommended for the Environmental Footprint (EF) package 3.1 (Andreasi Bassi et al., 2023). In this article, we present and discuss the results for the APT for the following impact categories: climate change (CC), ozone depletion (OD), fine particulate matter ($PM_{2.5}$), ionizing radiation - human health (Ion Rad-HH), photochemical ozone formation (POF), acidification (ACID), eutrophication - terrestrial, marine and freshwater (EUT-ter, EUT-mar, EUT-FW, respectively). The characterization models for these impact categories have high levels of recommendation, namely level I or II (Fazio et al., 2018). Results for the remaining EF midpoint impact categories, which should be used with caution (due to the lower levels of recommendation), can be found in the supplementary materials, together with the results for the city of Trento.

2.4. Case study: the Autonomous Province of Trento

The methodological framework presented in this article was applied to the APT, in northern Italy, and its capital city, Trento. In 2019, the population of the province was 545 425, and about 22% of the population lived in the provincial capital Trento (ISPAT, 2022). The province has a relatively high quality of life: the gross domestic product (GDP) of the APT in 2020 was EUR 37 140 per capita, compared with a national GDP of EUR 27 949 per capita in the same year (ISTAT, 2023). Located in the Dolomites, part of the Alps, the APT is characterized by a mountainous territorial morphology, and the provincial economy relies strongly on the tourism and manufacturing sectors. The overall DMC estimated for the APT and for its capital city, Trento, for 2019, were 11.2 and 11.4 tonnes per capita, respectively, building on the UM model described by Bastos (2023) and Bastos and Rosado (2024). Figure 2 presents the relative DMC shares for the 21 combined nomenclature (CN) categories, in the APT (outer circle) and in the city of Trento (inner circle).

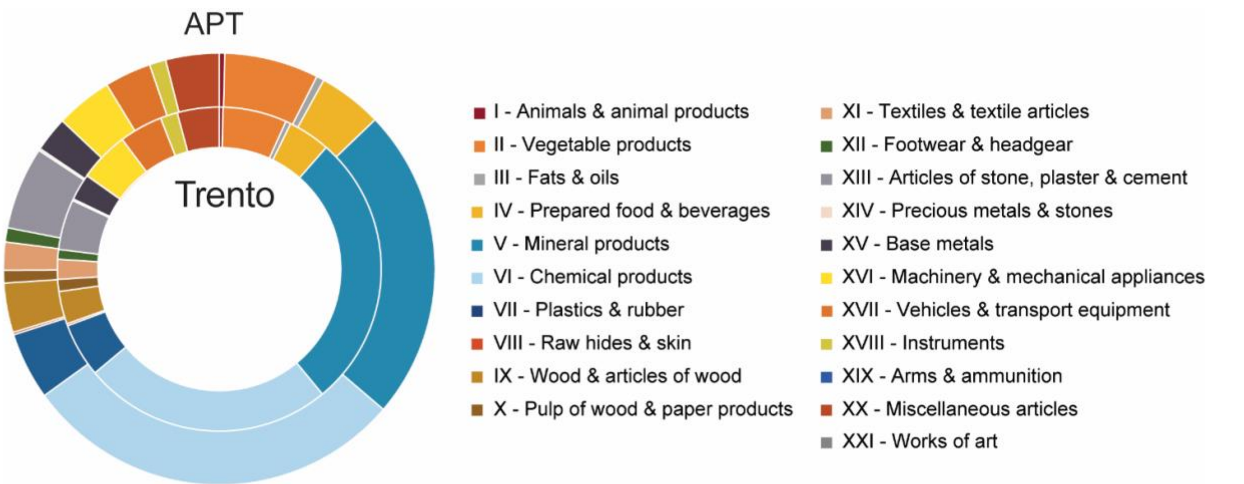

Figure 2. Domestic material consumption (DMC) in the Autonomous Province of Trento (APT, outer circle) and in the city of Trento (inner circle) for 2019. Adapted from Bastos and Rosado (2024).

2.5. Main assumptions

The assumptions made and the calculations performed in the MFA-based model, together with the adopted product structure of the combined nomenclature (CN), may result in limitations and uncertainty in the DMC results. In particular, the level and type of detail used in the product type disaggregation is not always adequate for use in an LCA and might skew results. In the case of household goods, in particular, the DMC for several product types showed large discrepancies with BoP estimates for EU consumption. For this reason, the selection of representative products for household goods drew on a hybrid approach, which considered products from the BoP of the EU Consumption Footprint framework for which DMC per capita was comparable. This means that we included furniture, clothes and footwear in our model, but left out of the assessment detergents, sanitary products (absorbent hygiene products), personal care products (rinse-off cosmetics), bed mattresses, paper products and plastic products, which are included in the EU Consumption Footprint framework's BoP for household goods.

The model and data are associated with several aspects that may result in limited coverage and underestimated environmental impacts of urban consumption. The most relevant of these is related to the exclusion of a significant share of the estimated DMC at the point of the selection of representative products, because modelling thousands of products would be unfeasible. Additionally, LCIs for the representative products have inherent truncation errors, due to the omission of higher-order upstream flows in process-based LCA databases.

Potential double-counting issues may also arise because the DMC includes products that can be used both in final and intermediate consumption (e.g., cereals, which can be used as food for human consumption, but also as an input in the life-cycle model of a range of animal products, as animal feed). Lastly, the framework draws on limited context-specific data on the origin and supply chain of products, or on their use, often relying on general national or EU data (e.g., on the origin of clothes) to calculate their LC impacts. The potential implications of these assumptions are discussed in section 3.2.

3. Main results and discussion

This section presents the main results for the APT. First, we present LC impacts of the annual consumption in the region, including results for overall consumption and comparing cradle-to-gate with cradle-to-grave results (section 3.1). We then look into each consumption area and the relative contribution of its representative products (subsections 3.1.1 to 3.1.4). We also briefly discuss the potential implications of modelling limitations (section 3.2) and the research advances and practical contributions (section 3.3). Further results are presented in the supplementary materials, including results for the city of Trento, which follow similar trends to those of the APT.

3.1. Life-cycle environmental impacts of consumption

Figure 3 shows the results for domestic material consumption (DMC) and associated environmental impacts in the APT, comparing the cradle-to-gate with the cradle-to-grave perspective. In terms of mass consumption, food and buildings dominate the results, with 48 and 46% of the total, respectively, while mobility and household goods account for only 5 and 1%, respectively. In total, we estimated that 1 000 kt of representative products were consumed, which averages out as 1.8 t per capita.

In terms of environmental impacts, an initial group of impact categories can be identified, namely those that are dominated by mobility and food: these two consumption areas account for over 80% of the results for the ACID, EUT-mar and EUT-ter impact categories. For these impact categories, buildings still account for a significant share of the impacts (7–14%). EUT-FW shows somewhat similar trends, with lower variability across consumption areas: mobility accounts for 48%, followed by food (25%) and buildings (20%). POF is dominated by mobility alone (72%), which is followed by food (18%).

Despite accounting for significant mass consumption, buildings' environmental impacts account for a significant share of the total in only a subset of environmental impact categories. Mobility and buildings dominate the results (70–82% of the overall impacts) for CC, PM, Ion-rad and OD, while food still accounts for significant impacts (15–21%). The relatively minor overall impact of household goods (2–12%) across categories is primarily attributable to the low relative consumption modelled. On the other hand, mobility shows disproportionally high impacts in relation to mass consumption. These results show that, for policies prioritizing specific environmental issues, such as climate change mitigation or air quality, an initial focus on mobility and buildings may be adequate. However, for a more integrated perspective to fostering environmentally sustainable consumption, food must be considered. Household goods are likely to be underestimated, and more detailed analyses in this area might be important, for example for OD, EUT-mar and EUT-FW impacts.

Comparing cradle-to-gate and cradle-to-grave perspectives, results depend largely on the consumption area. For food, a cradle-to-gate approach covers more than 60% of the cradle-to-grave impacts across all categories (more than 80%, excluding OD and CC). For household goods, cradle-to-gate accounts for more than 90% of the overall impacts. For mobility and buildings, the relative share of cradle-to-gate shows large variability across impact categories, ranging from 29 to 83% in mobility, for OD and EUT-FW, respectively, and from 5 to 92% in buildings, for POF and PM, respectively. For mobility, it is particularly important to consider a cradle-to-grave perspective. Results for cradle-to-gate cover less than half of the impacts in all categories except for PM, EUT-FW and Ion-rad. On the other hand, a focus on the use phase alone would account for 70–75% of the impacts for CC, EUT-mar, EUT-ter, OD and POF, while still significantly underestimating impacts and leaving room for burden shifts.

Figure 4 shows the relative contribution of representative products to the overall mass consumption and environmental impacts by category. While the model included 38 representative products (six being building products, which drew on a building stock model using four building archetypes and including 24 types of building materials/components), eight alone accounted for 73–86% of the environmental impacts across all categories and for 64% of the overall mass consumption, namely: olive oil and wine in food; diesel and petrol cars in mobility; and new residential buildings, residential building renovations, new non-residential buildings and non-residential building renovations. Cars (petrol and diesel) alone account for less than 5% of mass consumption but account for between 25 and 63% of the impacts (for OD and POF, respectively). The 38 representative product types selected and modelled in our study are listed in Table S14 in the supplementary materials, together with the type of selection (whether it was mass based or added), the annual mass consumption and the respective CN codes. Further details on the environmental impacts and relative contributions of representative products for each consumption area are detailed in the next subsections.

In line with our results, Tukker et al. (2006) observed in previous environmental impact assessments that about 20% of consumption product groups accounted for as much as 80% of the environmental impacts (some 60 product groups out of 283, in their review). The life-cycle impact assessment (LCIA) categories used in most studies were global warming, acidification, photochemical ozone formation and eutrophication. The product groups that had high environmental impacts across all studies that provided systematic assessments were private transport (cars in particular), food and drinks, and housing. Together they accounted for about 70-80% of the total life-cycle impacts of final consumption.

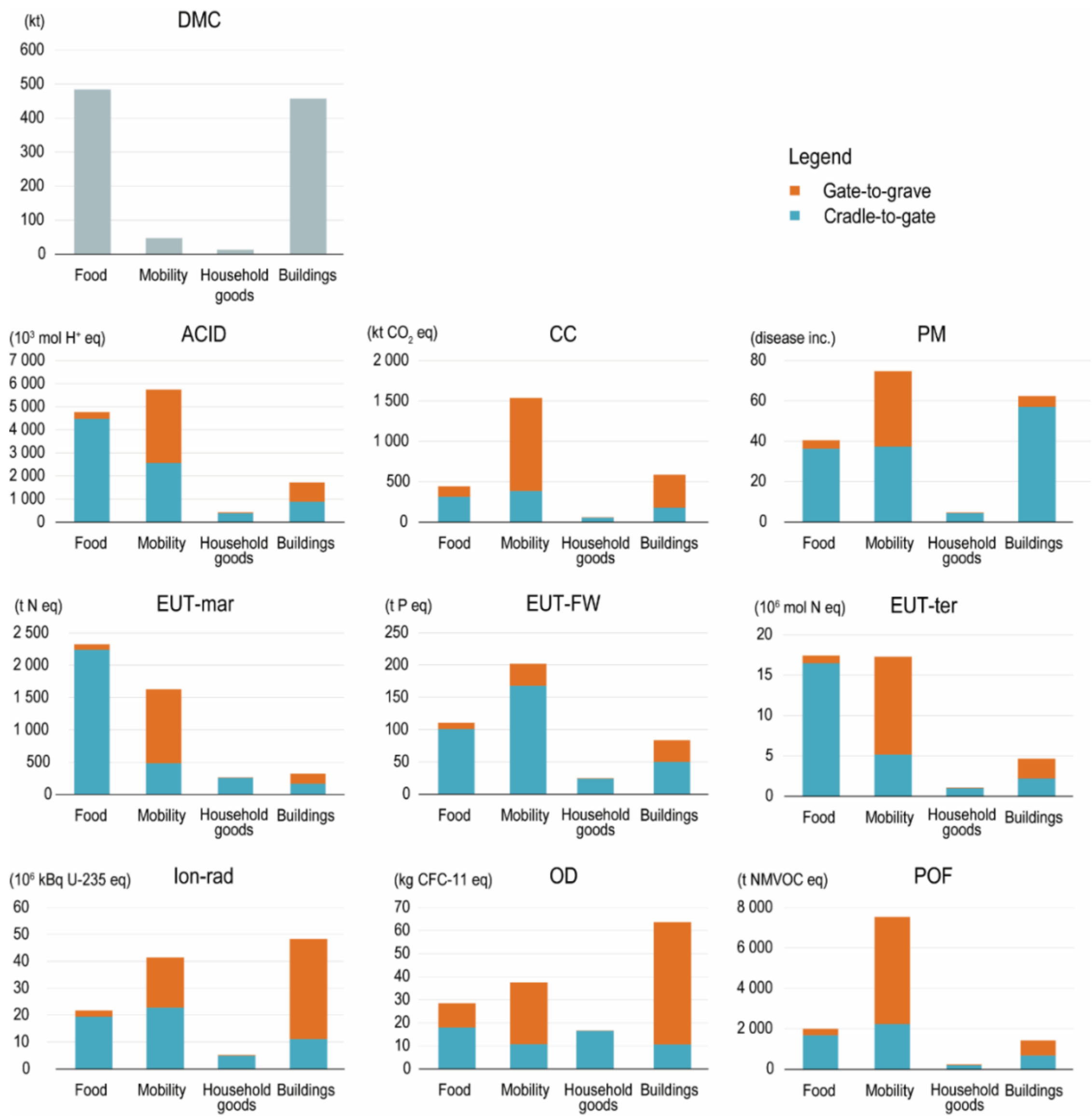

Figure 3. Mass consumption of representative products and their life-cycle environmental impacts in the APT.

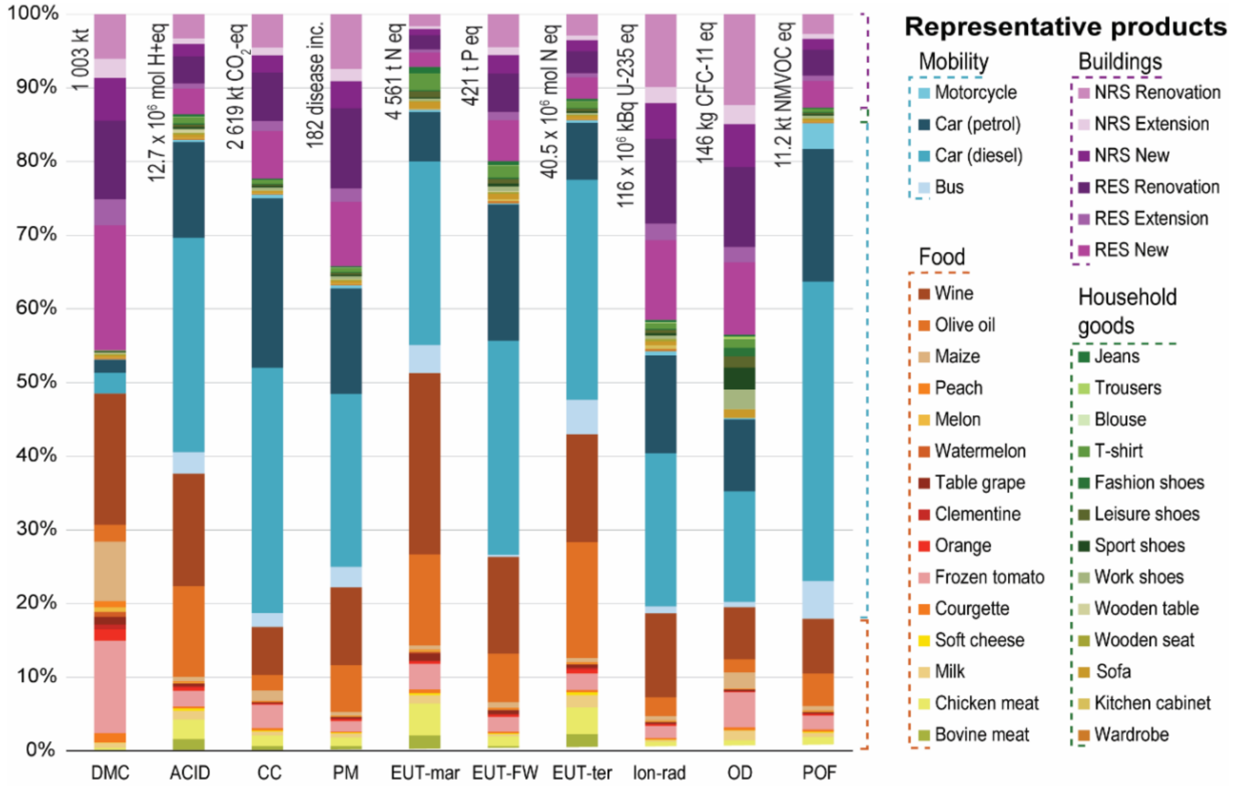

Figure 4. Relative contribution of representative products to mass consumption and life-cycle environmental impacts (cradle-to-grave). DMC: Domestic material consumption; ACID: Acidification; CC: Climate change; PM: Particulate matter; EUT-mar: Marine eutrophication; EUT-FW: Freshwater eutrophication; EUT-ter: Terrestrial eutrophication; Ion-rad: Ionizing radiation; OD: Ozone depletion; POF: Photochemical ozone formation; NRS: Non-residential; RES: Residential.

3.1.1. Food In total, 486 524 t of representative products in the food area were consumed in the APT (see Figure 4 and Section S4 in the supplementary materials) and 106 350 t in Trento, corresponding to 0.89 and 0.88 t per capita, respectively. The annual food consumption modelled in the EU Consumption Footprint's was 0.64 t per capita, which was estimated to account for 69% of the overall food and beverage product consumption for the reference year (0.93 t per capita) (Sala et al., 2019). FAOSTAT data on food balances for Italy in 2019 estimated an overall food supply of 0.9 t per capita (FAO, 2024). Based on our MFA model, representative products covered more than 60% of the overall food consumption estimated at 1.42 t/cap in the APT (considering the total DMC of CN2 categories 02-04, 07-11 and 15-22). While consumption in the APT may be above the national average, it is important to highlight that food consumption calculated with the MFA model is likely to be overestimated, as it might include food products used in the region for intermediate consumption (e.g., cereals for animal feed).

As regards the relative contribution of representative products to overall environmental impacts, three products accounted for the majority of environmental impacts (>70%): wine, olive oil and frozen tomato. These three products accounted for 67% of mass consumption and for between 70 and 84% of the environmental impacts (for CC and PM, respectively). Wine consumption represented 37% of mass and 34–61% of impacts of food consumption, mostly associated with production and packaging processes. Olive oil, on the other hand, accounted for a low share of food consumption (less than 5%), but its contribution to environmental impacts ranged from 12 to 37% (for OD and EUT-ter, respectively), mostly due to production processes. Frozen tomato had a relatively significant contribution to environmental impacts because of its high mass consumption: it was the second most consumed product in terms of mass (26%). It accounted for much lower impacts than the first two products, ranging from 4 to 11% in all categories, except for CC (19%). The individual contributions of all the other 12 representative products stayed below 10% across all categories. Maize was the product with highest relative mass consumption (17%), but it accounted for only up to 8% of the environmental impacts. In the food BoP, beverages, dairy and meat dominated mass consumption and environmental impacts. Tukker et al. (2006) also identified meat and dairy as the main contributors to life-cycle environmental impacts (across global warming, acidification, photochemical ozone formation and eutrophication) among the food and drinks category. In our model, animal-based products had high environmental impacts per mass unit, but their contribution to overall impacts was low due to low consumption.

Regarding the relative significance of cradle-to-gate impacts (see Figure 3 and Section S4 in the supplementary materials), these accounted for more than 71% of life-cycle impacts of food across all impact categories. The food BoP also identified the stages of agricultural production, and packaging in the case of beverages, as hotspots (Castellani et al., 2017). The use phase was relatively significant for products that were cooked and had relatively low production impacts (e.g., maize, frozen tomato and zucchini). It is worth noting that electricity use for refrigeration, cooking or other processes in the use phase was not considered in the food consumption area because it is accounted for in the buildings consumption area.

3.1.2. Mobility The total consumption of the four representative products selected in the mobility area (see Figure 3 and Section S4 in the supplementary materials) was 46 693 t in the APT and 10 272 t in Trento, corresponding to 0.085–0.086 t per capita. Regarding the relative contributions of the representative products, diesel cars dominated the results, representing over 60% of mass consumption and 57–70% of environmental impacts associated with mobility across all categories. Petrol cars, which represented 38% of mass consumption, accounted for 18–39% of environmental impacts across all impact categories. Buses, although representing only 1% of mass consumption, had contributions ranging from 7% to 11% for PM, EUT-mar, EU-ter and POF. Motorcycles' contribution to mass and environmental impacts was below 5%. In the case of mobility, a cradle-to-grave perspective is essential, as cradle-to-gate processes accounted for a relatively small share of impacts in most categories: it accounted for 25–30% in CC, EUT-mar, EUT-ter, OD and POF; 45–55% in ACID, PM and Ion-rad and 83% in EUT-FW.

The annual consumption and environmental impacts modelled for mobility are not directly comparable to data in the EU Consumption Footprint because, as mentioned, our framework models ‘added stock’ and the EU Consumption Footprint framework models ‘current stock’. When modelling added stock, we allocate to the reference year the overall life-cycle impacts (cradle-to-grave) of the stock added in that year. As an alternative, the emissions occurring in the reference year could be calculated by summing the total cradle-to-gate emissions of the added stock and yearly operational (use phase) emissions of the overall (current) stock for the reference year. Using our cradle-to-gate results for added stock, and applying current stock yearly operational impacts, we estimate a 53% increase of cradle-to-gate (and 40% overall) CC impacts for mobility, as illustrated in Figure 5. In brief, we applied our LCIA results for gate-to-grave to the current stock data in North-East Italy for cars, buses and motorcycles and divided life-cycle results by their service lives in years (assumed to be 12, 11 and 10 years, respectively). These results may be underestimated as they assume that current stock vehicles have the same performance and impacts as the added stock. It should also be noted that, as we allocated the total life-cycle environmental impacts of products added to stock to the reference year, instead of calculating yearly impacts across their service life, changes in performance across the lifetime are not modelled.

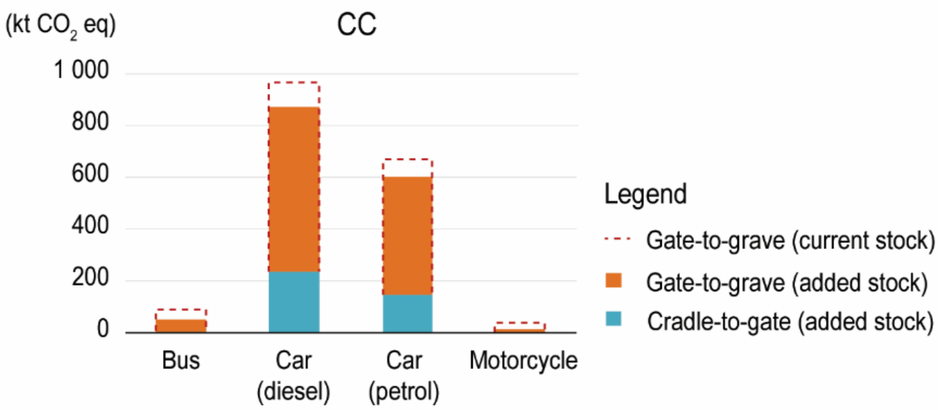

Figure 5. Comparison of life-cycle climate change (CC) impacts associated with mobility considering the use phase of added and current stock.

3.1.3. Household goods The total consumption of the 13 representative products selected in the household goods area (see Figure 4 and Section S4 in the supplementary materials) summed up to 12 566 and 3 100 t in the APT and in Trento, respectively, corresponding to 0.023 and 0.026 t per capita, respectively. The four clothes products accounted for less than 6% of household goods mass consumption, but between 16 and 54% of environmental impacts (for OD and EUT-mar, respectively). Within clothes, T-shirts had the highest impacts across all categories (4% of mass consumption and 11–38% of the overall environmental impacts of household goods consumption), followed by jeans (2% of mass consumption and 2–15% of the environmental impacts). Blouses and trousers had negligible mass consumption and impacts (<3%). The five furniture products accounted for 11-42% of the overall environmental impacts, mostly due to their considerable mass consumption (67% of the overall mass consumption of household goods). Lastly, shoes accounted for 27% of mass consumption and had generally low contributions to the overall environmental impacts across all categories (up to 38%), except for OD, in which they accounted for 73% of the impacts, mostly associated with production processes (production of polyethylene terephthalate).

Cradle-to-gate processes accounted for between 88 and 99% of the environmental impacts (for POF and OD, respectively), suggesting that, unlike other consumption areas, in the case of household goods a cradle-to-gate perspective could be fairly representative of the overall consumption impacts.

3.1.4. Buildings The total consumption of the representative products in the buildings consumption area (see Figure 4 and section S4 in the supplementary materials) was 457 641 and 112 303 t in the APT and in Trento, respectively, corresponding to 0.84 and 0.94 t per capita. Most of the material consumption was associated with the construction and renovation of residential buildings (37 and 23%, respectively, of overall material consumption in buildings), followed by construction and renovation of non-residential buildings (13% each of overall material consumption).

New residential buildings (RES_new), residential renovations (RES_ren) and non-residential renovations (NRS_ren) were the largest contributors across all categories, as shown in Figure 4. Together, these three groups accounted for 76–79% of the environmental impacts across all categories (each accounting for 20–32%). In the buildings consumption area, the environmental impacts of products did not show very large variability, and the results are strongly linked to the share of each type of intervention in the overall addition to stock. In terms of area, construction of new residential buildings, renovation of residential buildings and renovation of non-residential buildings accounted for 24, 44 and 18% of the addition to stock, respectively. Renovations had lower material consumption (DMC = 0.43–0.61 t/m^2 for residential and non-residential building stock, respectively) and environmental impacts per square meter than new construction (DMC = 1.23–1.67 t/m^2 for residential and non-residential building stock, respectively), but they had high environmental impacts, due to the large share they accounted for in the overall addition to stock (particularly the renovation of residential buildings, which accounted for 44% of the overall additional gross floor modelled).

Cradle-to-gate accounted for 92% of PM impacts in the buildings consumption area. For all other environmental impact categories, a cradle-to-grave perspective is essential, since use-phase impacts account for a significant share of impacts. In OD, Ion-rad and CC cradle-to-gate accounted for only 17, 23 and 30% of the impacts, respectively. For all other categories, cradle-to-gate accounted for 47–60% of the life-cycle overall impacts.

Similarly to the mobility consumption area, the consumption and impacts modelled for buildings are not directly comparable to the EU Consumption Footprint results, as the latter framework calculates impacts for housing, not buildings, and it models current stock impacts, represented by 24 building archetypes and divided to calculate yearly impacts across the lifetime of buildings (assumed to be 100 years). Based on EU Building Stock Observatory (BSO) data, Italy's building stock had usable floor areas of 60.7 and 9.8 m^2 per capita for residential and service sectors, respectively. Our 'added stock' model covered about 0.8 and 0.28 m^2 per capita for residential and non-residential gross floor area, respectively. If we multiply gate-to-grave (use phase) CC impacts of buildings by the area coefficients (79 and 35, for residential and service sectors, respectively) and consider an average service life of 30 years, we can estimate operational impacts of 'current stock' to provide a complementary perspective, as illustrated in Figure 6. The overall CC impacts of the buildings consumption area increased by 77%. An underestimation of these results is likely due to the different operational performance of current stock, since added stock performance was used as a reference.

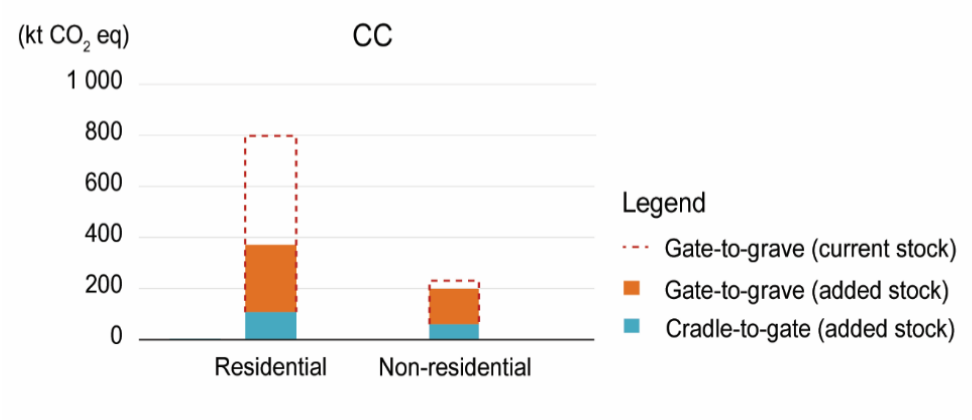

Figure 6. Comparison of life-cycle climate change (CC) impacts associated with buildings considering the use phase of added and current stock.

3.2. Implications of the main modelling assumptions

The use of a hybrid approach that includes MFA, the EU Consumption Footprint framework and LCA poses some relevant limitations. Despite being able to provide detailed mass consumption of products, the MFA model extrapolations at the city/region level are associated with significant challenges and uncertainties. A source of data uncertainty is the lack of statistical data for the MFA model at these spatial levels, to accurately calculate all input and output indicators at the product level (Barkhausen et al., 2023; Graedel, 2019; Patrício et al., 2015), which influences both the accuracy of the calculated DMC and its distribution amongst CN categories. Additionally, the need to use proxy products and generic LCI datasets that may not represent the exact product in the DMC, due to a mismatch between the CN used in the MFA and product categorization in LCI databases, adds to the overall data uncertainty. While LCIs for representative products were selected and adjusted to reflect local consumption (e.g., electricity mix, transport of goods), enlarging the scope of representative products in each consumption area and gathering more detailed data on each product type would reduce uncertainty.

Furthermore, the mass-based thresholds used in the representative products selection phase influence the number and types of products assessed. The CN structure used, which does not match directly the categorization of products into final consumption areas (such as buildings or household goods), may also affect the mass-based selection of representative products. One example is construction materials, which are spread across multiple CN categories and would be left out in the representative products selection phase. To ensure the inclusion of a range of product types that are representative and that provide reasonable coverage of all consumption areas, there was a need to adjust the model and complement the criteria of product selection used by Lavers et al. (2017), to better represent the consumption areas and not the corresponding CN categories. This was the reason we calculated consumption in the buildings area with an archetype-based model of the building stock, for example. These sources of uncertainty and their implications were not systematically evaluated. In the future, this could be addressed, for example, through sensitivity analysis (Groen et al., 2017; Wei et al., 2015). Despite its limitations, the framework offers advantages and complementary insights compared with models relying on input-output and household expenditure data. It avoids the uncertainty involved in the conversion of monetary to mass or environmental flows, and it provides detailed insight into the linkages between local activities (production and consumption) and environmental impacts, which is important for informing policymaking (Bastos et al. 2026).

3.3. Research advances and practical contributions

To date, the number of studies that have used bottom-up approaches to assess the life-cycle environmental impacts of consumption in a city or region is still limited. The methodologies used in the different studies for calculating the consumption of a set of materials and/or products ranges from the application of household expenditure surveys to the application of statistical data on material, energy and product supply and consumption, and to the development of detailed MFA models. The environmental impacts of consumption are then calculated by combining material and/or consumption data with an LCA.

The framework presented in this article is mostly comparable to three previously developed methodologies: the UM-LCA framework of Lavers Westin et al. (2019), the EU Consumption Footprint application at the city level (Genta et al., 2022) and the UM-LCA framework to inform circular economy strategies of Papageorgiou et al. (2024). The main types of products covered in these studies included food, transport, household goods and buildings or construction materials, which is along the same lines as the consumption areas and types of products focused on here (excluding appliances or electronic goods, which accounted for a low share of environmental impacts in previous studies). The number of products that have been modelled in previous studies ranged from around 70 (Lavers et al., 2017) to more than 150 (Genta et al. 2022). In our study, we modelled 38 representative products (including 4 building archetypes, which account for 24 additional materials or components) across four consumption areas, identified as the most significant urban consumption areas in the previous studies. The selected products had significant consumption in the region and/or were identified as relevant in previous environmental impact assessments of consumption in the EU. This ensures that the significance of the research is within an acceptable range, while balancing with the framework's complexity and data requirements.

It is worth highlighting that the number of representative products modelled is case-study dependent, as both the DMC distribution across CN categories and the mass-based selection threshold that was applied influences the number of products. A lower number of products does not necessarily reflect a more incomplete coverage of environmental impacts. For food, for example, we modelled 15 products representing an estimated consumption of 0.88-0.89 t per capita, which is aligned with the Food and Agriculture Organization global statistical database (FAOSTAT) estimate of overall food consumption in Italy of 0.9 t per capita. The Consumption Footprint includes a wider number of representative products, including products with a potentially low final consumption and impact contribution (e.g., soy milk and tofu). In the EU Consumption footprint, meat and dairy alone account for more than 50% of the environmental impacts (while accounting for only 6 out of 45 representative products for food), and with beverages and oils the relative shares increase to 70-80% (and accounting for only 14 out of 45 representative products). With the case-dependent selection of representative products embedded in our framework, it can considerably reduce the life-cycle modelling requirements while capturing most environmental impacts.

Our framework has specific features that have not been combined before: we based regional and urban consumption on an MFA model with high product-level disaggregation, considering annual consumption with an 'addition to stock' perspective and developing a cradle-to-grave LCA model. Lavers Westin et al. (2019) considered a cradle-to-gate LCA for a wide range of products; the EU Consumption Footprint (Genta et al., 2022) drew largely on statistical consumption data at the EU and national levels and considered annual environmental impacts of 'current stock'; and Papageorgiou et al. (2024) used a coarser material and energy flow model, with a low disaggregation level. Lastly, the range of environmental impact categories in our framework is also comprehensive, with a set of 16 impact categories that, together with the EU Consumption Footprint application to Turin (Genta et al. 2022), represents – to the best of our knowledge – the most complete coverage for studies at the region/city level.

The EU Consumption Footprint is the first bottom-up EU-scale framework to assess impacts of consumption with extensive coverage (cradle-to-grave impacts of more than 150 products) but, as mentioned, it builds on country-level statistical data and it models 'current stock' impacts, which provides limited insights to inform local action. The complementarity of results addressing environmental impacts of current stock versus added stock that our study presents is worth highlighting. By considering the impacts of current stock in mobility and housing, the EU Consumption Footprint provides insights on current operational emissions and impacts, for the reference year, and allocates vehicle production and building construction impacts dividing them by the products' service life. Thus, the EU Consumption Footprint results for a reference year include environmental impacts of construction of buildings occurring 20 years before (or production of vehicles 5 years before) the reference year, which has limited relevance for supporting local policymaking. In other words, by modelling the total life-cycle environmental impacts that the buildings and vehicles added to stock in the reference year will have across their service life, our framework provides complementary insight into current and future impacts of potential changes and actions, which is paramount for informing and monitoring local action.

The circular economy (CE) has been increasingly adopted to address urban sustainability (Ravikumar et al. 2024; Alhowaish, 2026). In recent years, cities across Europe have included CE in their local climate action plans and have started to develop and implement dedicated circular economy action plans (Möslinger et al., 2023; Booth et al. 2026). Researchers and practitioners have identified the quantification and monitoring of urban flows as a key challenge to enable targeted and efficient CE action (Redlingshöfer, 2024; Ravikumar et al. 2024; Booth et al. 2026). Circularity indicators have been increasingly used in this context to inform and monitor local CE strategies; however, these do not always adequately express environmental impacts, unless validated by adequate environmental impact assessments (Ravikumar et al. 2024). LCA frameworks have been widely applied to inform, support and monitor CE strategies, mostly at the single product or system level (Ravikumar et al. 2024). The EU Consumption Footprint framework has been applied to test CE measures in the built environment at the national level (Pristerà et al. 2025). There are few examples (Ipsen et al. 2019; Papageorgiou et al. 2024) at the city level, and advances are still needed. Ravikumar et al. (2024) identified challenges that remain unaddressed in the literature related, for example, to the selection of system boundaries and data availability and uncertainty. Among the research priorities identified by Ravikumar et al. (2024), our work advances the application of LCA to the city level by tackling challenges related to modelling and data requirements for different geographical levels and product systems, with high levels of detail and disaggregation, and the characterization of environmental impacts beyond climate change. Moreover, considering impacts from an 'addition to stock' perspective provides complementary insight for decision-making, which is crucial for informing and monitoring local action. All impacts occurring during the service life of all the products consumed in the reference year are accounted for, even if they occur only in the future. In fact, future impacts from energy-intensive, long-lived products are locked in at the moment they enter the stock. This is particularly relevant for the buildings and mobility consumption areas, where present decisions on how to build and what transport modes to encourage will influence cities' overall emissions in the coming years and decades.

The contribution of the framework to the quantification modelling of CE, through material flows and its connection to environmental impacts, allows for the expansion of this hybrid approach to include further aspects, such as the interaction between material flows and human behaviour. In this regard, agent-based modelling is seen as a natural next step that has been already acknowledged (Papageorgiou et al., 2024) and can capture the adoption dynamics, heterogeneous actor behaviour, and socio-technical feedback in circular urban systems. Another important aspect that should be added is the modelling of interdependencies and feedback loops through the combination with system dynamics (Gao et al. 2020) and ecological network analysis (Arbabi et al., 2020) that would allow providing the basis for simulating circular economy transition pathways and policy scenarios at the urban scale, quantifying the changes in the urban system through the implementation of CE strategies. These advancements have the potential to operationalising CE modelling and provide quantifiable targets for cities that are useful for civil servants in charge of CE policies at the urban level (Hynes et al., 2020).

Other than methodological contributions, the framework and the application presented in this article have practical implications for regional and local administrations. The finding that eight representative products alone accounted for 73–86% of environmental impacts shows how a context-specific assessment can provide crucial information to prioritize and target local actions, and to maximize their benefits. Since food-related impacts are mostly associated with the supply chain, food consumption is usually not accounted for in local climate action, despite its relevance to greenhouse gas emissions and other environmental impacts. This article highlights the importance of including scope 3 emissions from food, where opportunities for the mitigation of environmental impacts – and for implementation of circular economy strategies – are currently being overlooked. Lastly, the application of this framework highlighted significant modelling and data requirements. Cities should invest in systematic collection of relevant data, starting for example with material and product flows associated with public procurement. Public procurement accounts for roughly 15-20% of GDP in developed countries, and regional and local authorities are responsible for a significant share of procurement spending, up to 90% in some EU Member States (Zabala-Iturriagagoitia, 2022).

4. Conclusions

This article introduces a new framework to estimate life-cycle environmental impacts of annual consumption in cities and regions considering four product consumption areas – food, mobility, household goods and buildings – from a cradle-to-grave perspective and an 'addition to stock' perspective for a wide range of environmental impact categories. The framework was applied to the Autonomous Province of Trento and its capital city, Trento. When looking at mass consumption, food and buildings dominated the results, with a share of 94% of total weight; however, this mass dominance did not translate entirely into environmental impacts, with mobility accounting for significant impacts across several indicators. The results show that a cradle-to-grave approach is particularly relevant for buildings and transport: their use phase accounts for a large share of the overall impacts associated with regional and urban areas, but cradle-to-gate impacts are not negligible. On the other hand, cradle-to-gate phases account for most environmental impacts in the food consumption area, which highlights the importance of addressing environmental impacts associated with the upstream activities and processes, occurring mostly outside the region or city boundaries (typically excluded from city-level greenhouse gas inventories, for example).

While our model included 38 representative products, eight alone accounted for 73%–86% of the environmental impacts across all categories. Analysing each of the consumption areas, three products (wine, olive oil and frozen tomato) accounted for most environmental impacts of food consumption, some due to their large mass consumption but others due to their environmental impacts per mass unit. For mobility, diesel cars dominated the results from both a mass and an environmental impact perspective, across all categories. As expected, gate-to-grave impacts were significant in mobility added stock. In the case of household goods, given that the representative products that were selected mostly belong to 3 large categories – clothes, furniture and shoes – the importance of cradle-to-gate is evident. Clothes contributed significantly to the environmental impacts despite a low mass consumption share, showcasing the environmental impact intensity of products such as T-shirts. By contrast, furniture contributed to environmental impacts mostly due to its mass consumption. Finally, in buildings, the construction of new residential buildings together with the renovation of residential and non-residential buildings dominated environmental impacts.

In the future, researchers and practitioners should improve data collection on consumption at the city level, in particular in the food and construction sectors (e.g., monitoring flows associated with public procurement). It is also important that cities consider the life-cycle impacts of electrification in the buildings and mobility sectors to adequately assess the potential co-benefits and trade-offs of local action. Future research should improve the balance between accurate data and assessments and the practical and wide applicability of LCA frameworks that can promptly inform action. One of the main issues in tackling out-of-boundary emissions is the scarcity of data and models to effectively analyse and inform policy decisions at the local level. Cities need practical approaches to capture upstream impacts and identify trade-offs and burden shifts.

A systematic multiscale assessment framework should be developed for the EU that can consistently estimate life-cycle environmental impacts of consumption at the national, regional and local (city) levels. The combination of an economy-wide MFA-based methodology with high product-level disaggregation and the EU Consumption Footprint further advances and solidifies bottom-up detailed approaches as an alternative to using input-output methods that rely on monetary units as the basis of the modelling. Additionally, complementing the framework with agent-based modelling, system dynamics and ecological network analysis could provide a further understanding about human behaviour, interdependence and feedback loops that are relevant to the environmental assessment and monitoring of CE strategies at the urban scale. This article also contributes to the literature by providing another case study region and city, providing relevant knowledge with a methodology that can be applied across the EU. Reducing the complexity, the processing requirements and the associated uncertainty of the proposed approach could lead to significant improvements as part of further research and future applications of the framework.

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Author contributions Joana Bastos: conceptualization, data curation, formal analysis, methodology, validation, visualization, writing – original draft preparation, writing – review & editing. Riccardo Fraboni: data curation, validation, writing – original draft preparation, writing – review & editing. Rita Garcia: conceptualization, data curation, formal analysis, methodology, validation, writing – original draft preparation, writing – review & editing. Leonardo Rosado: conceptualization, methodology, validation, writing – original draft preparation, writing – review & editing.

Data availability Supporting data is provided in the supplementary materials file. The data sources that support the findings of this study are provided in the manuscript and in supplementary materials. All original data sources are publicly available, except for ecoinvent data.

Declarations

Competing Interests The authors declare no competing interests.

Disclaimer The views expressed here are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission.

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