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Citation for the original published paper (version of record):
Bastos, J., Rosado, L. (2024). Regional Metabolism: A Material and Product Flow Accounting Model for Trentino, Italy. Green Energy and Technology: 47-59.
http://dx.doi.org/10.1007/978-3-031-39206-1_4

Regional Metabolism: A Material and Product Flow Accounting Model for Trentino, Italy

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Abstract Material flow accounting (MFA) can be applied to systematically quantify material inputs, outputs and throughputs to and from a geographical area, providing particularly relevant insights into managing resource flows and stocks, and identifying opportunities to close material cycles, moving from a linear to a circular economy. Remarkable advances in recent years have been made on the application of MFA to regions and cities, in particular going beyond material to product flows and providing increased details on life-cycle stages of products across these flows, which are crucial to estimate, understand and manage their associated environmental impacts. This chapter presents an MFA model of the Autonomous Province of Trento (Trentino) in northern Italy, and of the province's capital city Trento. The main purpose is to establish a model to estimate direct material inputs (DMI) and domestic material consumption (DMC) in thousand tonnes per year (reference year 2019), relying on publicly available online data on domestic resource extraction, industrial production, trade, freight transportation and waste generation. The DMC was 12.8 and 13.5 tonnes per capita in the province and in Trento, respectively; the result is below the EU mean of 14.2, but significantly higher than the reported DMC for Italy in the same year of 8.3 tonnes per capita. Accounting and characterizing resource flows associated with urban areas and regions is crucial to increase resource efficiency and mitigate environmental impacts at local, regional and global levels. Advanced detailed MFA models at city and regional levels can inform and support environmentally sustainable planning and policymaking.

Keywords Urban metabolism · Material flow analysis · Region · Material consumption · Product flows

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A. Bisello et al. (eds.), *Smart and Sustainable Planning for Cities and Regions*, Green Energy and Technology, https://doi.org/10.1007/978-3-031-39206-1_4

1 Introduction

1.1 Goal and Scope

Material flow accounting (MFA) can be applied to systematically quantify material inputs, outputs and throughputs to and from a geographical area, providing particularly relevant insights into managing resource flows and stocks, and identifying opportunities to close material cycles, moving from a linear to a circular economy. This chapter presents a regional MFA model of the Autonomous Province of Trento (Trentino) in northern Italy, and of its capital city—Trento. The main purpose is to estimate the annual direct material inputs (DMI) and domestic material consumption (DMC), relying on publicly available online data. Key results include the accounting and characterization of material and product flows going into and out of the regional economy, and of the overall consumption at city and regional level, by type of product.

2 Background

Cities have more than half of the world's population and contribute to about 80% of global economic output, concentrating trade, business, innovation and skills [1]. They are associated with 60–80% of global resource requirements, energy use and anthropogenic greenhouse gas (GHG) emissions [2, 3]. Despite the global and local sustainability challenges associated with increasing urbanization, the concentration of population and economic activities in cities also offers unique opportunities, and cities play a key role in climate change mitigation and sustainable development. The central role of cities in sustainable development is demonstrated by EU policies and the UN 2030 Agenda for Sustainable Development, including the Sustainable Development Goals (SDGs) [4]. Urban environmental sustainability is focused on Goal 11—Make cities and human settlements inclusive, safe, resilient and sustainable—and it directly contributes to a wide range of other SDGs [4].

Industrial ecology (IE) approaches and tools can help support the design, development and implementation of sustainable urban development strategies. These include, for example, urban metabolism (UM), material flow accounting (MFA) and life-cycle assessment (LCA). UM is widely supported as an approach to inform and support urban sustainability. In brief, the metabolism of cities entails visualizing a city as an organism or ecological system, and it addresses all socio-economic and environmental processes associated with urban activities. Such a system is composed of many interlinked subsystems and components (e.g., people, built environment, water, energy, waste, health, transportation) [1]. As such, UM can build on a system thinking perspective to provide a broader understanding of urban functions, needs, linkages across different domains, systems and processes, and identify hotspots and opportunities for improvement with an integrated perspective. System theory provides a systematic approach to system integration and to understand and predict changes within the system, and their implications [1, 2]. It can potentially address urban complexity, providing insight on the diversity and intensity of urban activities on a multiscale perspective (from urban blocks to neighbourhoods or cities). Within UM, a commonly used method is Material Flow Accounting (MFA), which considers the inputs and outputs of resources, emissions and waste [3].

2.1 Material Flow Accounts and Indicators

Physical accounting approaches are important to complement monetary approaches, which are often insufficient and provide limited understanding of the relationships between the economy and the environment. For over 20 years, the UN has called for the integration of environmental and economic accounting, to quantify services provided by natural capital as well as human-made capital. This is essential to characterize and manage the use and/or depletion of natural resources (in production to consumption chains) and the associated environmental implications [4]. Material flow accounting (MFA) can serve as a basis for environmental monitoring and for managing urban areas—accounting and characterizing material and product flows to evaluate their environmental impacts [5, p.12]. MFA relies on the principle of mass balance—total material inputs (entries) into a system equal total outputs plus the net accumulation within the system [5, p.12]. The principle of mass balance applies to the economy as a whole, but also to any of its subsystems (economy sectors, companies, etc.) [5, p.12].

Economy-wide material flow accounts (EW-MFA) are a statistical accounting framework applied at a national level in the EU to report material flows into and out of an economy in thousand tonnes per year. The general purpose of EW-MFA is to describe the physical interaction of a national economy with the natural environment and the rest of the world economy in terms of material flows (covering solid, gaseous, and liquid materials, except for bulk flows of water and air). In 2011, EU regulation No. 691/2011 implemented a legal obligation for EU Member States to report the EW-MFA to Eurostat; and in 2013, mandatory annual data collection and reporting started. Eurostat published a methodological guide for EW-MFA [6] and its derived indicators, including overall material flow balances and aggregated indicators on total resource requirements, resource efficiency and total domestic outflows to the environment. In 2012, the System of Environmental-Economic Accounting—Central Framework (SEEA–CF) was adopted as an international statistical standard by the UN [7], including a section on EW-MFA, which supports the need and appropriateness of MFA for accounting and reporting material flows.

2.2 The UMAn Model

UM and MFA can support a holistic, systematic and integrated analysis of complex systems and help to inform on resource use and efficiency. However, important limitations have prevented wider application to analyse urban areas, and to support decision-making towards sustainable urban development. For example, MFA has high data requirements, and it generally lacks insights on the environmental implications of material flows [8]—it does not account for upstream and downstream processes that occur beyond the city or system boundaries (e.g., extraction, production, transportation, end-of-life) [8]. Thus, increasing the level of detail of UM and MFA models could increase and improve their application. Further details, for example, on the specific use of materials are important to evaluate the potential environmental impacts associated with resource flows.

Remarkable research advances have been made by the Urban Metabolism Analyst (UMAn) model, which provides a methodological framework to account for material and product flows and stocks at regional and urban levels, building on the EW-MFA methodology [9]. The framework contributed to advancing UM research, by:

- Providing a systematic and harmonized MFA-based methodology, particularly suitable for EU regions and cities, as it builds on EW-MFA and on Eurostat standard statistical data for products (complemented with other datasets and sources);
- Assigning product composition to 28 harmonized material types, thus increasing the disaggregation/categorization level of material types; and
- Disaggregating data by economic sector and characterizing the life cycle phases of products, providing insight into the origin and destination of flows.

This paper presents a detailed MFA that applies the UMAn model to the Autonomous Province of Trento and its capital city.

2.3 Case Study: The Autonomous Province of Trento

The Autonomous Province of Trento is located in Northern Italy in the Alps (Fig. 1). In 2020, the population of the province was 542 166 [10], registering a 13% increase over the previous 20 years [11]. About 35% of the population lives in the province capital Trento. The province has a relatively high quality of life: GDP in 2020 was 37 120€/capita in the province, compared to a national GDP of 27 938€/capita [12]. The province is in the northern Italian Alps, in the Dolomites, characterized by a mountainous territorial morphology and the provincial economy relies strongly on the tourism and manufacturing sectors.

Fig. 1 Case study: the Autonomous Province of Trento in Italy

3 Materials and Methods

This section summarizes the materials and methods used in the MFA model, including sources, input datasets, and data analysis and processing. It is structured in four subsections, which draw on the four steps of EW-MFA: (3.1) System boundaries; (3.2) Data compilation and treatment; (3.3) Data analysis and classification by material type; and 3.4) Calculation of indicators.

3.1 System Boundaries

National, regional and urban MFAs can be characterized by two types of boundaries, which need to be clearly defined to ensure consistent accounting of material flows: one is the boundary between the economy and the natural environment (cross-border flows that consist of environment-economy inputs and outputs, such as domestic extraction); the other is the border with other economies (cross-border flows that consist, for example, of imports and exports) [5, p.22]. Borders with other economies usually correspond to geographical boundaries—often administrative units. The selection of geographical boundaries is particularly important since the model strongly depends on the type, quality and disaggregation of available data, generally collected for different administrative units.

In our model, geographical borders are considered to be the administrative borders of the Autonomous Province of Trento, which correspond to a NUTS3 territorial unit (code ITH20), and of the municipality of Trento, which corresponds to a local territorial unit (code 022205). Borders between the economy and the natural environment are associated with domestic extraction flows, namely: animal breeding and slaughtering, forestry activities (wood harvesting), fishing and aquaculture, the production of milk, milk products and eggs, mining and quarrying.

3.2 Data Compilation and Treatment

Data used in the model to calculate and characterize material and product flows were collected using 2019 as the reference year (the most recent year before the COVID-19 crisis in Italy), and compiled into: main tables, correspondence tables and support tables, as described below.

- **Main tables**

These tables have statistical data on material flows. Four main tables were compiled: Domestic Extraction, International Trade, Transport of Goods and Industrial Production.

Domestic Extraction—the domestic extraction table compiles data from seven sectors or groups: (a) mining and quarrying, (b) agricultural production, (c) wood harvesting (forestry), (d) fishing and aquaculture, (e) meat, (f) milk products, and (g) eggs. This came from a range of national and regional datasets on extraction and primary production. When data at regional/provincial level was not available it was allocated based on the number of employees in the respective sector. Data were collected from the national and regional statistics office databases, ISTAT and ISPAT, respectively [12, 13], and compiled according to the Combined Nomenclature (CN) classification system, which is the main classification for the European international trade in goods statistics used by Eurostat. Data were collected for Italy, the Autonomous Province of Trento and the city of Trento.

International Trade—international trade is reported at national level with CN structure—an allocation had to be done on the volume of international imports that go to the modelled region and that of international imports that go to rest of the country (ROC), and the same applied to international exports (disaggregating them into exports from the province and from the ROC). To do this, international trade data were combined with data on economic sectors of the destination of imports and the origin of exports, and with data on the significance of economic sectors in the province and in the ROC (in terms of the number of employees per economic sector).

Inter-regional Trade—to apply MFA to regions and cities we need to account for national imports and exports, i.e., flows from the ROC to the modelled region, and from the modelled region to the ROC. The model used national annual road freight transport by region of loading and unloading and by groups of goods from Eurostat, structured with the Standard Goods Classification [14]. The Standard Goods Classification for Transport Statistics (NST2007) provides statistical information about flows of products between NUTS2 units, based on their economic activity of origin. It is available for four modes of transport: road; rail; air; and water. Rail was assumed to account for 26% of the overall inter-regional trade based on a report on the transport of goods across the Brennero axis [15]. Water and air transport were excluded, due to the specificities of the region (no seaports or major airports exist in the province).

Industrial Production—data on manufactured goods by industry sector were used to model product transformation, i.e., the processing of raw materials and intermediate products into final products for consumption. Industrial production data are available at a national level [13], in ProdCom NACE Rev 2 categories. Harmonization was needed on several product units to convert non mass units into mass (in tonnes), which was based on the Eurostat Conversion Factors Table (with information on the average weight of several Combined Nomenclature Codes that are not accounted for in mass weight). For products that were not in the Eurostat conversion factors table, conversion factors were selected from literature (bibliographic and desk research). Data were collected for Italy, the Autonomous Province of Trento and the city of Trento.

- **Correspondence tables**

These tables have correspondences across classification systems and they build mostly on the Reference and Management of Nomenclatures system of Eurostat, RAMON.

CN to CPA and NACE—this table provides the correspondence between CN and EU Classification of Products by Activity (CPA) codes and Statistical Classification of Economic Activities (NACE), made available by Eurostat. The CPA follows the production origin criterion, i.e., products are grouped according to the economic activity of origin.

NST to CN—national and international transport data are available in different disaggregation levels and nomenclatures. The most common is the Standard Goods Classification for transport statistics (NST or NSTR, depending on the year), which is linked in this table to the CN structure.

CN correspondences—the database developed to support the UMAn model was built according to a CN2007 structure. Thus, a correspondence table between CN2019 and CN2007 was built, based on the changes reported by Eurostat.

- **Support tables**

These tables draw on ISTAT data [13], and they were mostly used to support extrapolations when provincial or municipality-specific data was not available.

Employees—the number of employees by NACE sector by municipality was considered from ISTAT data on enterprises—the number of people employed in local units of active enterprises (annual average values) in 2019. The number of employees in domestic extraction sectors was added.

Residents—the number of residents by municipality, to allocate goods for final household consumption in the city of Trento.

- **UMAn model plugins**

Plugins previously developed for the UMAn model [5] were used to (i) characterize material composition, (ii) estimate additions to stock (by identifying products with average lifespan longer than 1 year); and (iii) separate final and intermediate products in input flows.

3.3 Data Analysis and Classification by Material Type

With the data collected and treated as described, we (i) calculated domestic material inputs to the region (domestic extraction + imports) and estimated overall available resources (preliminary balance); (ii) characterized available resources in terms of life-cycle stage, i.e., splitting them into intermediate and final products; (iii) modelled product transformation in the region (transformation of intermediate products into final products, for consumption in economic sectors or final household consumption); and (iv) calculated domestic material consumption. As mentioned, classification of products by predominant material type (into 28 material types) used a UMAn model plugin [5].

3.4 Calculation of Indicators

With domestic extraction (DE) and imports to the region, we calculated the direct material input (DMI), as described in Eq. (1). Then, the transformation of intermediate products into final products was modelled, based on industrial production data. Domestic material consumption (DMC) was then calculated with final products (DMI_f) (which excluded waste generated in product transformation) and exports, as described in Eq. (2). Lastly, to downscale DMC to the provincial capital Trento, the "Use table" of CPA products by NACE sector was considered (for service sectors using predominantly final products): the relative share of employees by NACE sector in the municipality of Trento and in the province; and the share of residents in the case of using CPA products for final consumption (by households, social support organizations and public administration).

$$DE + Imports = DMI \tag{1}$$

$$DMI_f - Exports = DMC \tag{2}$$

4 Results and Discussion

In this section, we summarize the key results of the MFA model applied to the Autonomous Province of Trento, including domestic material inputs (DMI) and domestic material consumption (DMC) in 2019.

4.1 Available Resources

Figure 2 illustrates the available resources modelled by CN section, including domestic extraction, national and international imports, and national and international exports. These represent the inputs and outputs considered in the model, and are the modelling results with the lowest level of uncertainty, before significant extrapolations were made on product transformation. Most flows were associated with inter-regional trade: only 6 and 9% of overall exports and imports were international, respectively. Section V on Mineral products, was significant in all types of flows, except for international exports: it accounted for 66% of domestic extraction, 27% of national imports, and 25% of national exports. Two other sections were particularly relevant: section IX on Wood and articles of wood, and section X on Pulp of wood and paper products. The first accounted for 13–19% of all types of flows; while the second accounted for 9–18% of imports and 6–13% of exports (no domestic extraction). Lastly, exports were always lower than the respective imports—national and international—however, in international trade exports were 62% lower, while in national trade only 4%.

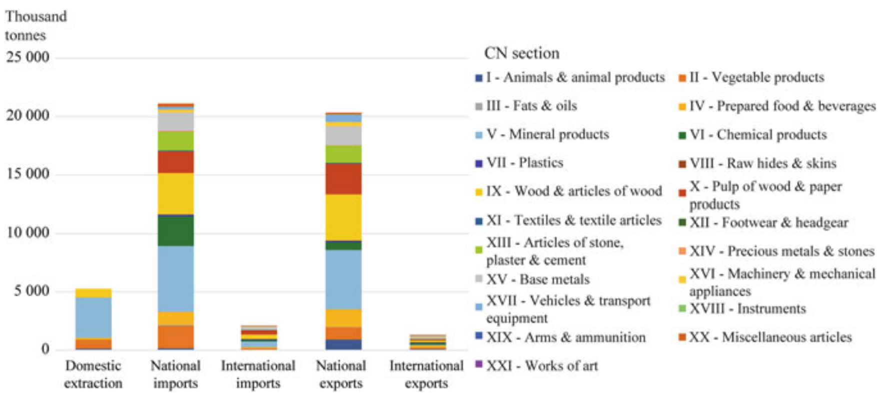

Fig. 2 Available resources by combined nomenclature (CN) section

4.2 Direct Material Inputs

Direct material inputs (DMI) to the province in 2019 were 28 500 thousand tonnes, 49% of which were final products. Figure 3 shows the product composition of inputs for final and intermediate products by CN section. Three CN sections were particularly relevant in both types of inputs—intermediate and final products: II on Vegetable products (these accounted for 8% of intermediate products and 12% of final products); V on Mineral products (31–37%) and IX on Wood and articles of wood (14–18%). Sections IV, VI, and XIII had significant inputs that entered the province mostly as final products corresponding to Prepared food and vegetables, Chemical products and Articles of stone, plaster and cement, respectively. These CN sections accounted for 8, 14, and 9% of the final product inputs, respectively. Lastly, two sections had significant inputs that consisted primarily of intermediate products, for processing/transformation in the province: X on Pulp of wood and paper products, and XV on Base metals, accounting for 13 and 10% of the intermediate product inputs, respectively.

Figure 4 shows the material composition of direct material inputs (DMI), for 28 types of materials. Non-metallic minerals and biomass accounted for over 77% of the DMI. This is closely linked with the results observed in the preliminary material balance, where sections V, IX, and X on Mineral products, Wood products, and Wood pulp and paper products were particularly significant. Within non-metallic mineral products, inputs were mostly composed of stone and sand; while in biomass wood and biofuels, agricultural biomass, and paper accounted for most inputs.

In the step of product transformation from intermediate to final products, about 364 thousand tonnes of waste were generated. It is important to highlight, however, that any other waste generated in the region stayed in our modelled DMC (final consumption), such as household waste and waste from construction activities, which are expected to account for the large majority of generated waste.

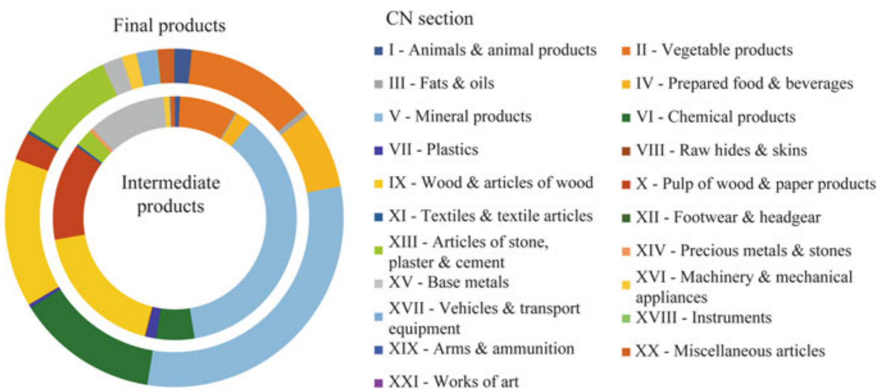

Fig. 3 Composition of direct material inputs (DMI) by CN section: intermediate and final products

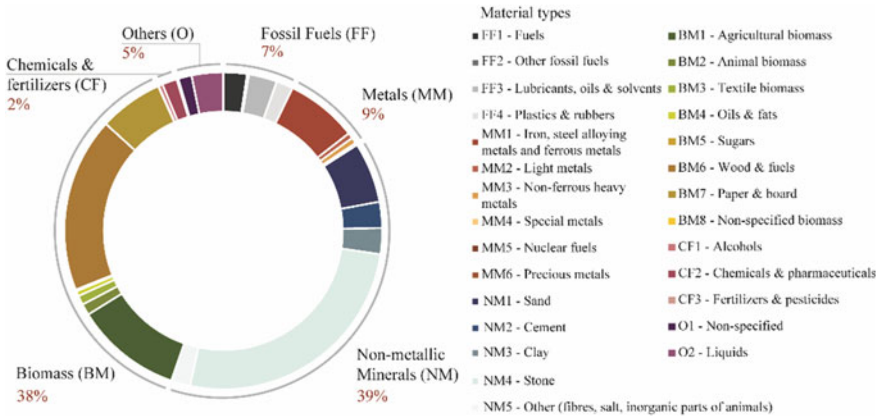

Fig. 4 Material composition of direct material inputs (DMI)

Table 1 Domestic material consumption (DMC)

	APT	Trento
Overall DMC (tonnes)	6 941 796	1 620 013
Population (source: [13])	543 721	119 616
DMC per capita (tonnes/capita)	12.77	13.54

APT—Autonomous Province of Trento

4.3 Domestic Material Consumption

Table 1 presents domestic material consumption (DMC), and Fig. 5 shows DMC distribution by CN section in the Autonomous Province of Trento and its capital city Trento. The overall DMC was 12.8 and 13.5 t/capita in the province and in Trento, respectively; the result is below the EU mean of 14.2, but significantly higher than the reported DMC for Italy in the same year of 8.3 t/capita [14].

The overall DMC per capita results were relatively similar in the province and in Trento. In 2019, Trento was home to 22% of the province's population; the DMC across CN sections varied between 20% in section XIII and 34% in section XVIII, which correspond to Articles of stone, plaster and cement, and Instruments, respectively.

5 Concluding Remarks

This paper presents an MFA model of the Autonomous Province of Trento and the provincial capital Trento. Its main purpose was to establish a model to estimate direct material inputs (DMI) and domestic material consumption (DMC) in thousand tonnes

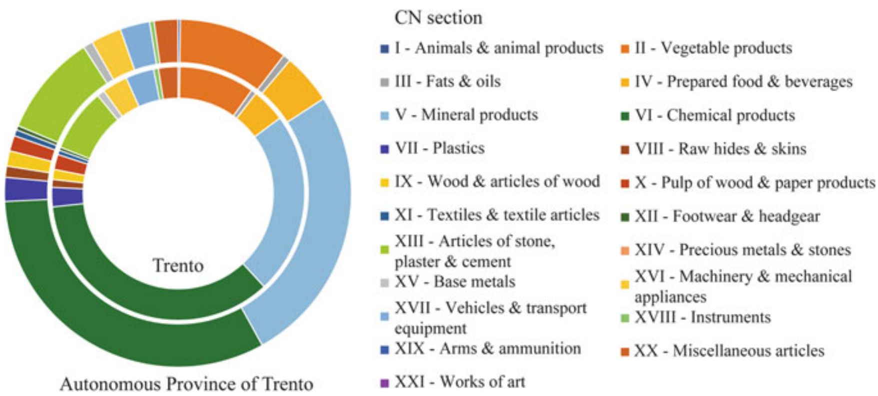

Fig. 5 Domestic material consumption (DMC) in the autonomous province of Trento (outer circle) and in the city of Trento (inner circle), for 2019

per year relying on publicly available online data on domestic resource extraction, industrial production, trade, freight transportation, and waste generation. The DMI in the Province was 28 500 thousand tonnes. The DMC was 12.8 and 13.5 t/capita in the province and in Trento, respectively; both results are below the EU mean of 14.2, but significantly higher than the reported DMC for Italy in the same year of 8.3 t/capita.

Accounting and characterizing resource flows associated with urban areas and regions is crucial to increase resource efficiency and to mitigate environmental impacts on a local, regional, and global scale. Advanced detailed MFA models at city and regional levels can inform and support environmentally sustainable planning and policymaking.

Acknowledgements The research is framed within the ARTEMIS project, funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement number 101026073.

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