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Dipartimento di Energia

Master of Science in Energy Engineering

Analysis of urban metabolism and policy assessment: building a Nested Multiregional Input-Output model

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Nomenclature

Notation

a, A	Vectors and matrices

$\hat{a}$	Diagonalization of vector a
a^T, A^T	Transposed vectors and matrices
A^{-1}	Inverse matrices
I	Identity matrices

Acronyms

CBA	Consumption-Based Accounting
EE-IOA	Environmental-Extended Input-Output Analysis
EET	Emissions Embodied in Trade
GDP	Gross Domestic Product
GHG	Greenhouse Gasses
GPC	Global Protocol for Community-Scale GHG emission Inventories
GRP	Gross Regional Product
ICLEI	International Council for Local Environmental Initiatives
IEA	International Energy Agency
IO	Input-Output
IOA	Input-Output Analysis
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
MFA	Material Flow Analysis
MIOT	Monetary Input-Output Table
MRIO	Multiregional Input-Output
OECD	Organization for Economic Cooperation and Development
PBA	Production-Based Accounting
SRIO	Single Region Input-Output
RoW	Rest of the World
WRI	World Resources Institute

Symbols

x	Total production vector
X	Total gross output
f	Final demand vector
Z	Intermediate transactions matrix
A, a_{ij}	Technical coefficients matrix and technical coefficients
L	Leontief inverse matrix
R	Exogenous resources/wastes matrix
B, b_{ij}	Input coefficients matrix and input coefficients
ee	Specific embodied exogenous resources matrix
EE	Embodied exogenous resources matrix
Va	Value added vector
v	Value added coefficients vector
m	Imports vector

e Exports vector

Sommario

In accordo con le proiezioni dell’Intergovernmental Panel on Climate Change (IPCC), la limitazione del riscaldamento globale sotto 1.5 °C rispetto al livello preindustriale è strettamente collegata alla riduzione di emissioni di gas serra. Ad oggi più di metà della popolazione mondiale vive in zone urbane e le città contribuiscono circa al 75% delle emissioni di gas serra. Considerando che è previsto il raggiungimento del 68% di popolazione urbana entro il 2050, le città assumono un ruolo chiave nella lotta al cambiamento climatico. Infatti, in accordo con l’International Energy Agency (IEA), le aree urbane rappresentano due terzi del potenziale per ridurre efficientemente le emissioni globali di carbone in termini di costi. Alla base della lotta al cambiamento climatico, le città devono calcolare le loro emissioni di CO_2 in modo efficace e completo. Il tradizionale Production-Based Accounting deve essere integrato con il Consumption-Based Accounting per valutare la “responsabilità” delle emissioni di CO_2. I responsabili delle politiche devono essere informati tramite precise e specifiche analisi che sottolineino le connessioni intersettoriali all’interno e all’esterno dei confini cittadini. L’obiettivo di questo lavoro è lo sviluppo di un modello ambientale multiregionale Input-Output a tre livelli spaziali applicato all’Italia, alle sue regioni e all’area metropolitana di Milano. Il sistema è stato modellato a partire dai database Exiobase 3 e Istat, applicando metodologie tradizionali e revisionate di regionalizzazione e urbanizzazione dei dati. Il modello permette di calcolare, secondo una logica CBA, l’impronta di carbonio e i flussi di carbonio associati a 17 settori produttivi dell’economia italiana, regionale e dell’area metropolitana di Milano per analizzare come tali settori interagiscano l’uno con l’altro. I risultati ottenuti mostrano come il duplice scaling dei dati (da nazione a regione e da regione a città) dia una rappresentazione più realistica del sistema urbano rispetto a quella che si otterrebbe scalando i dati direttamente dalla dimensione nazionale a quella cittadina. In aggiunta all’analisi attributiva, è stato realizzata un’analisi consequenziale per una prima valutazione di impatto ambientale ed economico della politica sui tetti verdi contenuta nel nuovo Piano di Governo del Territorio di Milano (PGT).

Keywords: Analisi ambientale e multiregionale di Input-Output, Impronta di Carbonio, Flussi di Carbonio, Emissioni di CO_2 “embodied", Metabolismo Urbano.

Abstract

According with the projections of the Intergovernmental Panel on Climate Change (IPCC), the limitation of global warming below 1.5 °C above pre-industrial level is strictly related to the reduction of GHG emissions. Nowadays, more than half of the world's population lives in urban areas and cities contribute approximately to 75% of world's GHG emissions. Considering that the share urban population is forecasted to reach 68% by 2050, cities will play a key role in the fight for climate change. Indeed, according to the International Energy Agency (IEA), urban areas account for up to two-thirds of the potential to cost-effectively reduce global carbon emissions. As a basis for action on climate change, cities should report their CO2 emissions in an effective and complete way. The traditional Production-Based Accounting should be integrated with the Consumption-Based Accounting to assess the "responsibility" of CO2 emissions. The policy-makers should be informed through precise and specific analysis highlighting the inter-sectoral connections arising inside and outside the city boundaries. The objective of this work is to develop a Nested Environmental-Extended Multiregional Input-Output (Nested EE-MRIO) model with three spatial levels, applied to Italy, Italian regions and the metropolitan area of Milan. The framework has been modeled through Exiobase 3 and Istat databases, applying traditional and modified methodologies of downscaling of data at regional and urban dimensions. The model estimates, according to a CBA logic, the Carbon Footprint and the carbon flows associated to 17 production sectors of Italy, of the Italian regions and of the metropolitan area of Milan, in order to analyse how these sectors interact with each other. The results show that the double scaling of data (from nation to region and then from region to city) gives a more realistic representation of the urban system than the one obtained by scaling directly national data to the urban dimension. The attributional analysis has been followed by a consequential analysis to give a first environmental and economic assessment of the green roofs policy that is included in the new Piano di Governo del Territorio (PGT) of Milan.

Keywords: Environmental-Extended Multiregional Input-Output Analysis, Carbon Footprint, Carbon Flows, Embodied CO2 emissions, Urban metabolism.

1. Introduction

1.1 Urbanization phenomenon and environmental pollution of cities

The post-industrial society has been characterized by a steady shift from rural to urban living. Nowadays 55% of the world's population lives in urban areas and, according to the World Urbanization Prospect published by the United Nations, this percentage is expected to reach a share of 68% by 2050 [1]. The OECD countries have shown this tendency since the half of the twentieth century, increasing their urban percentage from 56% to 80 % in the last seventy years. Despite this, a further increase of that share in developed countries is forecasted. Developing countries have subsequently followed the same path and nowadays their urbanization rate is faster compared to historical trends of OECD countries [1].

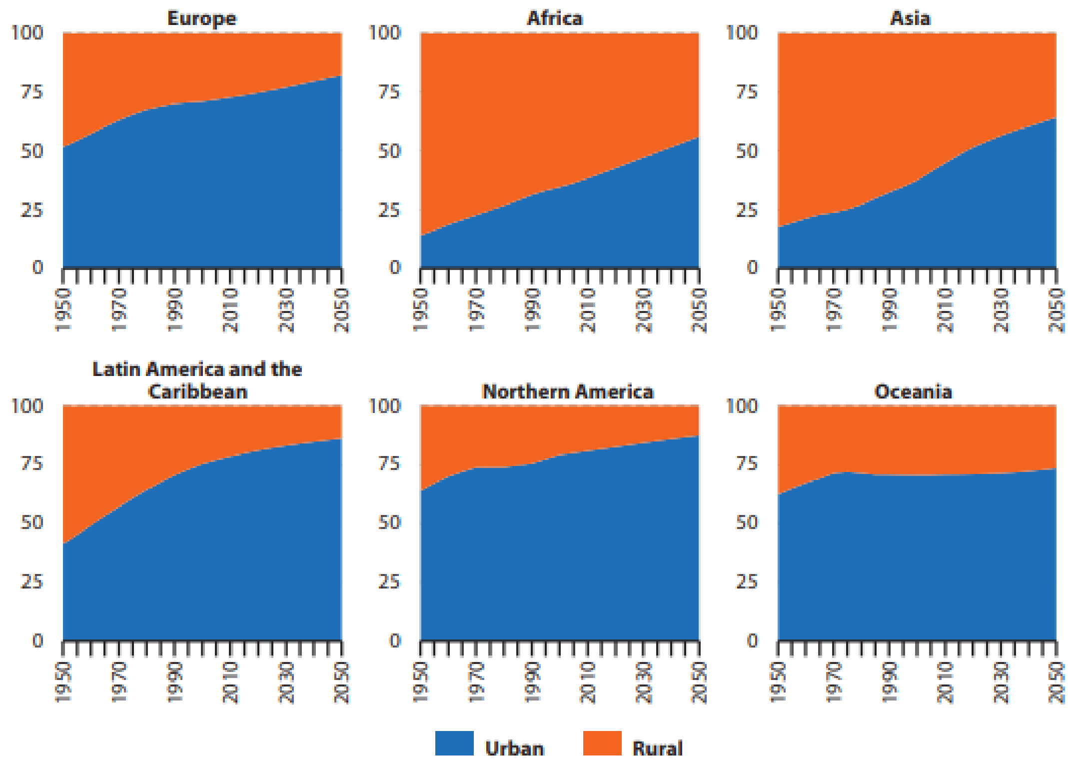


Figure 1. Share of urban and rural population by region 1950-2050 [2]. Source: Eurostat.

Metropolis are the poles of the process of centralisation, hosting a quarter of the world's population. Generally, metropolitan areas tend to outperform in economic terms other areas of the same nation, showing a GRP (Gross Regional Product) above the national average [3]. A higher GRP is related with higher average income for people working in the region. Higher wages, better education and services the city can offer, attract people from other areas and foster the progressive transformation of rural areas into peripheral urban districts. In the years to come, metropolis will further expand and smaller cities will become metropolis as well.

The massive demographic density, registered in the cities' environment, goes hand in hand with a great resource consumption, both for public administration and for private use. Energy, regardless of the source, is the engine of all the activities of cities. It is needed for transport, buildings, infrastructures, industrial and commercial activities, water and food distribution. Cities account for about 70% of the world energy demand [4].
It is straightforward that a great consumption of energy and resources is related with high polluting emissions: economic growth and Greenhouse Gasses (GHG) emissions move in tandem. Urban residents and activities contribute approximately to 75% of global GHG emissions. There is a direct correlation between the level of urbanization and the metric tons of CO_2 emissions per capita (Figure 2). According to the World Bank data, the higher is the percentage of urban residents on the total population, the higher are the CO_2 emissions per capita.

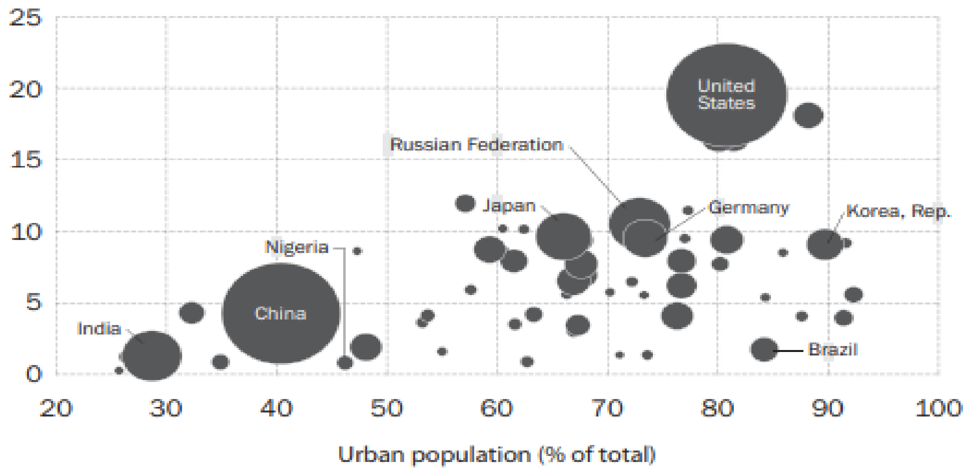


Figure 2. Metric tons of CO_2 emissions per capita and share of urban population [5]. Source: World Bank

In forecast of a worldwide increase of the share of urban population, a crucial target for policymakers is to reverse or at least stem this dangerous trend. Since most of the GHG emissions are concentrated in urban areas, cities have a key role in climate change. The fight for climate change has been one of the main global topics in the last years and it is going to play a central role in the national and international politics of the next decades. According to the Special Report [6] of 2018, carried out by the Intergovernmental Panel on Climate Change (IPCC), human activities are estimated to have caused 1.0°C of global warming above pre-industrial level. If current warming rate continues, the world would reach human-induced global warming of 1.5°C around 2040, causing impacts on human and natural systems. Adopting the Paris Agreement in 2015, for the first time governments from all over the world agreed to "hold the increase in the global average temperature well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" [7].

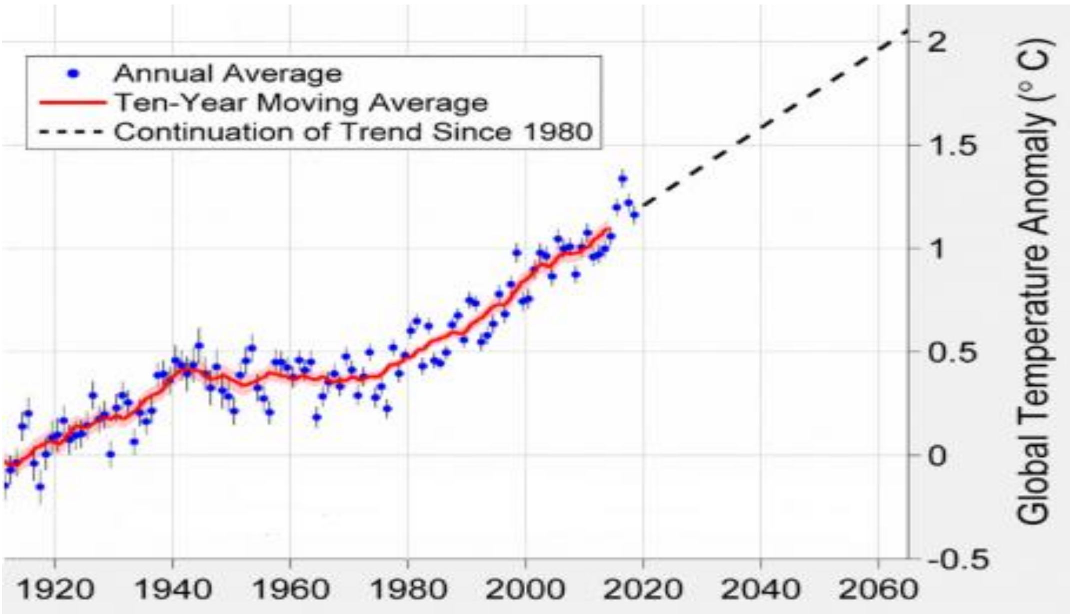


Figure 3. Global temperature anomaly 1920-2018 and trend [8]. Source: Berkeley Earth.

The challenge that national governments are facing is pushing cities to play a dominant role in sustainable development and in climate change mitigation, because they have the potential to initiate low-carbon infrastructure pathways and influence changes in lifestyle. Indeed, according to the International Energy Agency

(IEA), urban areas account for up to two-thirds of the potential to cost-effectively reduce global carbon emissions. Building cities that are green, inclusive and sustainable should be the foundation of any local and national climate change agenda, because sustainable development can be built only upon sustainable cities. The world is urbanizing quickly and under the Current Policies Scenario (CPS), GHG emissions will keep increasing dramatically [9]. In contrast, global GHG emissions in 2030 need to be approximately 25 percent and 55 percent lower than in 2017 to put the world on a least-cost pathway to limiting global warming to 2 °C and 1,5 °C respectively.

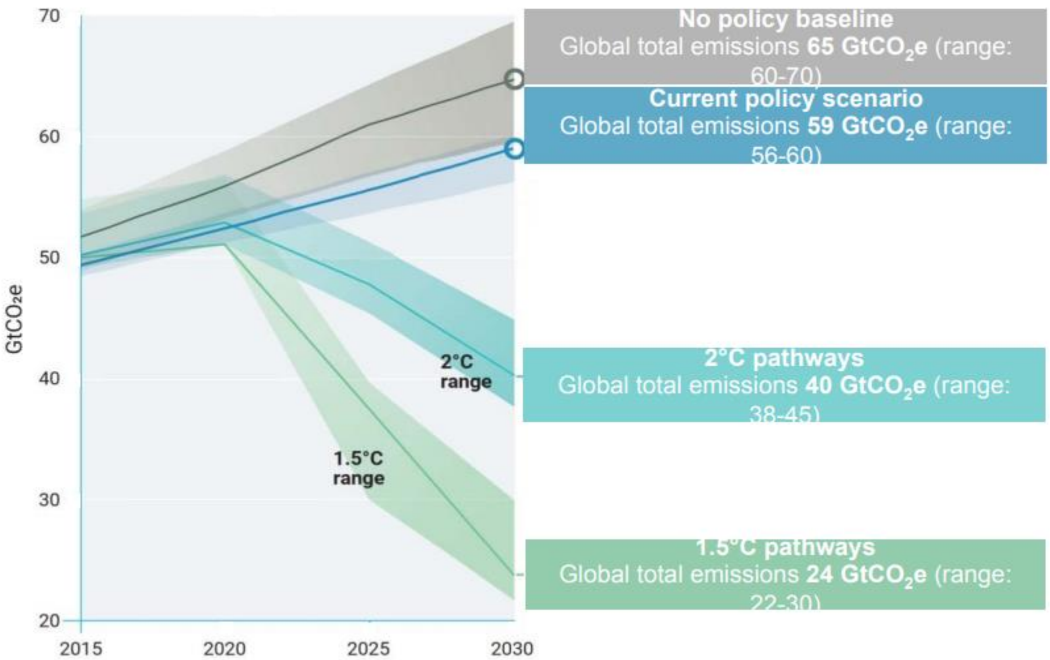


Figure 4. CO_2 emissions trends in different policy scenarios. Source: IPCC.

Cities are usually first-responders in a crisis; they are the first to experience trends, because of their proximity to the public and their commitment on providing day-to-day services. Cities governments tend to be more pragmatic than national ones. The target for the next years is to address global warming mitigation policies towards urban dimension instead of national dimension, in order to capture the variation of characteristics among different cities of the same country. The sustainability goals and the decarbonisation process should include all the metropolis, with a particular focus on the metropolis of developing countries, on the dominant world metropolis and on the metropolis of developed countries that are experiencing a significant demographic and economic growth. These are the cities that are mostly able to make a difference by becoming an example and influencing the behaviour of the other cities. The infrastructure of 2050 is being built today, yet the world of 2050 will be very different from today.

1.2 Pollution as a multi-perspective issue

The last century has seen the spreading of another phenomenon besides the urbanization: the globalization. The whole of the world is increasingly behaving as it were a part of a single market, with interdependent production, consumption and demand of similar products and responding to the same impulses. Globalization is manifested in a huge amount of material goods traded by every country all over the world. According to the World Bank data, during the 20th century the ratio of world imports to gross world product has grown from 7% in 1938 to 13% in 1970 to over 20% at the end of the century. The percentage has reached a kind of plateau in the 21st century, settling in a range from 25% to 28% [10]. The massive monetary flows associated with international trades are related with equally large GHG emissions embodied in the traded goods. With GHG embodied emissions of a product are indicated all the accumulated emissions emitted in the production and distribution of that product.
The “pollution heaven hypothesis” [11], which argues that developed countries are likely to transfer the polluting industry to developing countries that have lower environmental regulations, further justifies the embodied carbon’s crucial role in international carbon allocation.

As a basis for action on climate change, countries should quantify and report their GHG emissions. It is important that the accounting of GHGs emissions of nations is accurate, comparable and complete.
Typically, emissions statistics are compiled according to production-based accounting (PBA), also defined as territorial-based accounting or sector-based accounting: it measures emissions occurring within sovereign borders. However, these estimates do not reflect production chains which extend across borders and, although this is the traditional accounting method, it is not effective in describing the real emissions attributable to a country.
A more holistic way of analysing the responsibility for GHG emissions is to compile statistics according to consumption-based accounting (CBA), which considers both direct and indirect emissions, the latter of which refers to the GHG that is embodied in the intermediate products and material that are passed on to other sectors until

they reach the final consumer. In simple terms, PBA allocates emissions to the local producers, while CBA allocates emissions to the final consumer rather than the producer.

The consideration of emissions embodied in trade (EET) may have a significant impact on participation in and effectiveness of global climate policies, particularly for three aspects. First, a direct analysis of EET provides a better understanding of the separation between domestic consumption and domestic production, assessing the "responsibility" of pollution. Second, an analysis of carbon leakages reveals if pollution is shifted rather than abated. Third, trade-adjusted GHG emission inventories attempt to exploit trade to mitigate emissions.
Analysing the interconnections between countries could fill the lack of detailed knowledge about induced emissions occurring outside the country's boundaries, but this is not sufficient for a comprehensive description of the system. Indeed, the analysis of spatial linkages should be followed by the unravelling of inter-sectoral linkages, in order to describe the complexity of interconnections between industries and regions located upstream or downstream the supply chain.

As said previously, more than half of the world's population lives in cities, but cities' surface is just the 3% of the earth's surface [5]. Therefore, EET are even more impactful for cities than countries, because cities source a major part of their resource demand from their local, national and global hinterland, causing emissions across the whole global supply chain.
Several studies demonstrate that transboundary energy use in key infrastructures serving cities can usually be as large, or larger than the direct energy use and GHGs emissions within city boundaries [12].

To promote growth and also mitigate climate change, cities have to act on different aspects at the same time, without leaving none of them behind. Fiscal policy reform can create strong incentives for low-carbon investments and reducing GHG emissions. The use of carbon pricing is only emerging in many countries and generally not applied at a sufficient level to facilitate a shift towards low-carbon environments. Emission reduction potential from non-state and subnational action could be significant, allowing countries to achieve their targets, but the impact of pledged commitments are limited and poorly documented. Combining innovation in the use of existing technologies and in behaviour with the promotion of investment in new technologies and market creation has the potential to transform societies and reduce their GHG emissions. At the basis of these multi-perspective actions, cities as well as countries must quantify and report their GHG emissions. A city consumption-based GHG inventory can be defined as the emissions arising within city's boundaries, minus those emissions associated with the production of goods and services exported outside the city, plus emissions generated in the supply chains for goods and services produced outside the city but imported to meet the final demand of its residents. On the contrary, a city production-based GHG inventory can be defined as the emissions arising within city's boundaries, plus those emissions associated with the production of goods and services exported outside the city. A positive difference between CBA and PBA values indicates that the city is a net importer of GHG emissions. Vice versa, a negative difference between CBA and PBA values indicates that the city is net exporter of GHG emissions.

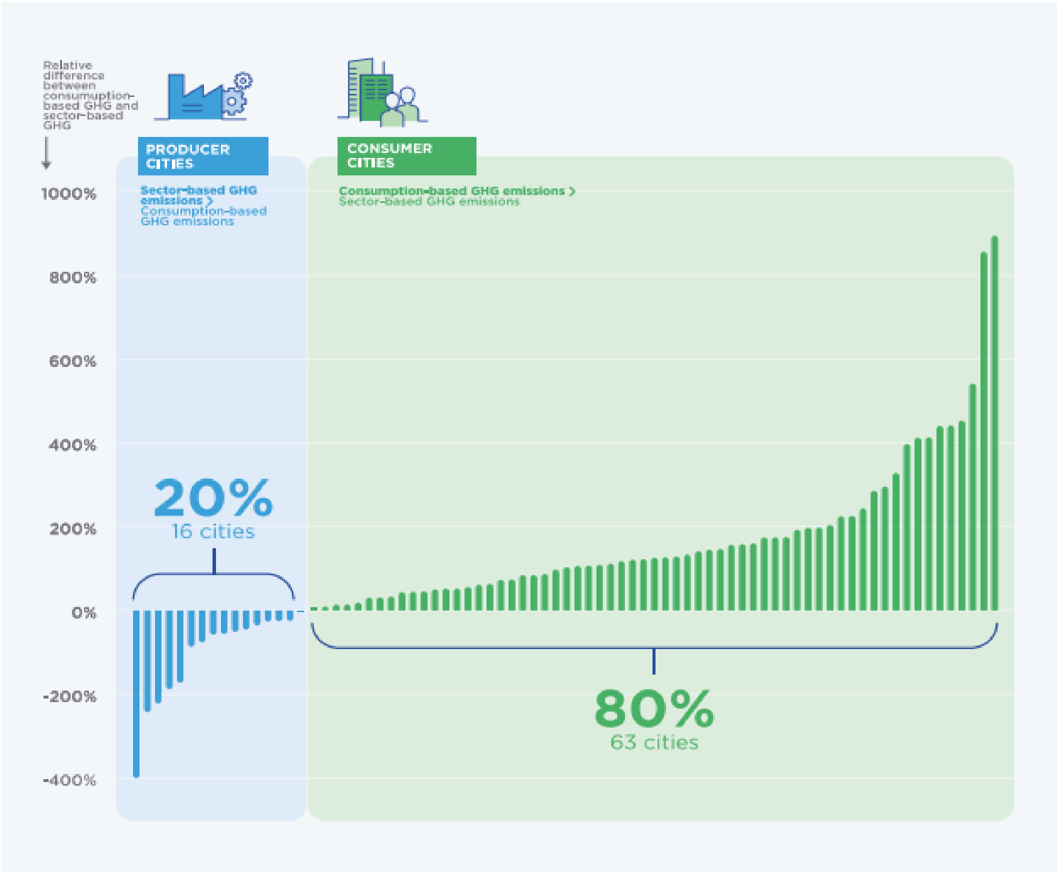


Figure 5. Differences between consumption-based GHG inventories and production-based GHG inventories for 79 C40 cities [13]. Source: C40 Cities.

An accurate assessment of urban GHG emissions should take into account both methodologies of accounting. The reasons why current urban climate change

mitigation initiatives overwhelmingly focus on territorial emissions are both pragmatic and political. Local decision makers are often unaware of the relevance of upstream emissions. The literature on upstream urban emissions is sparse and comparisons among cities are hampered by differences in methods, classifications and terminology [14].
However, since ICLEI published in 2009 the first version of the Local Government GHG Analysis Protocol [15], several other guidelines and standards have been published to assist cities to account for their GHG emissions. The most advanced and recent standards to date are the PAS 2070 specification for the assessment of GHG emissions of a city, which has been developed by the World Resources Institute (WRI), C40 Cities Climate Leadership Group, and ICLEI–Local Governments for Sustainability. The Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) distinguishes three scopes [16]. The scopes are the most used and standardized definition for classifying the direct and indirect emissions:

- Scope 1: direct GHG emissions from sources located inside the city boundary (direct emissions).
- Scope 2: **direct** GHG emissions caused by the use of grid-supplied electricity, heating and cooling inside the city boundary.
- Scope 3: GHG emissions occurring outside the city boundary for activities occurring inside the city boundary (other indirect emissions).

In this context, the understanding and the representation of the urban system complexity is the first key point to implement a specific and effective set of measures. The modeling of the urban structure should be capable of representing the specificities and the identity of the city. In this direction, it is fundamental to take into account strengths and weaknesses of its economic sectors, as well as the behaviour of its residents and the characteristics of the macro-region to which the city belongs. Nowadays, there is not a unified and standardized procedure of analysis of urban environmental impact, although the topic has been widely discussed and studied. Several analytical frameworks have been adopted to assess urban metabolism and these have be further discussed in the literature review (Chapter 2). Most of these analyses are carried out through proprietary software and not open datasets, making it difficult to understand the hypothesis at the base of the model and its building path. The absence of this information hampers the effectiveness of the comparison of results obtained with different models and the possibility to apply the same model to different systems.

1.3 Work objectives

The aim of this work is to develop a model that is able to achieve a comprehensive and deep analysis of the inter-sectoral and spatial linkages at urban, regional and national level. The model is applied to Italy and, since it utilizes public and free datasets, it is designed to be applicable to other nations by making few appropriate modifications. The urban analysis is carried out considering the metropolitan area of Milan, since it has a remarkable role in the Italian context and it is experiencing a rapid demographic and economic growth. The further development of the model is facilitated through the creation of an open-source Python script, which also permits a quick calculation of the results.

Spatial and sectoral interconnections are evaluated in a multidimensional way by considering both environmental and economic terms. It is crucial to characterize simultaneously the material and the monetary flows entering/exiting into regional and urban areas: how they are transformed by specific sectoral activities and how they impact on the environment through their consumption of resources and generation of wastes. The model is able to identify sectors and areas that need to be targeted in future interventions towards urban and regional decarbonisation, without hampering the economic dimension.

For what concerns the accounting methodology, the model can evaluate both consumption-based and production-based CO_2 emissions, deepening results at multi-spatial and multi-sectoral levels. Considering both CBA and PBA perspective, it is possible for policy-makers to study in detail sectoral and spatial carbon flows and implement proper and effective policies to reduce the carbon emissions of cities.

The innovative aspect of this work is the combination of a multi-level analysis at spatial scale, which considers three dimensions in the scaling process (nation, region and metropolitan area). In this way, with the application of a dynamic analysis, it is possible to obtain two-ways results: how an urban policy may affect urban, regional and national spheres, and how a national policy can influence national, regional and urban contexts.

To reach the targets of the study, several publications have been selected and analysed to deepen into the topic and to select the proper model to be developed. The findings of the literature review are discussed in chapter 2. The basic analytical structure of the model is illustrated in chapter 3, while the practical application of the model to our case is described in chapter 4. The results of the attributional and consequential analysis and the verification of the model are discussed in chapter 5.

2. Literature Review

The late 20th century and the beginning of the 21st century have marked a turning point in the awareness of how human activities affect local and global environment. Consequently, in the last years several studies have tried to evaluate the ecological role of cities, regions and nations and to estimate the scale of their impact.

A critical review of scientific literature has been conducted, in order to understand in which direction the scientific community is moving towards. Articles regarding analytical frameworks and analysis adopted to deal with urban pollution and urban planning strategies were the main topics of research.
Papers, reports and web articles published from 2007 to 2019 have been collected from online catalogues (Scopus, Elsevier, etc.) and classified according to the following categories:

- Year of publication
- Title
- Author
- Journal of publication
- Framework
- Analysis method
- Topic
- Accounting system
- Data source
- Type of indicator
- Boundaries of analysis

All the catalogued publications and the associated categories are listed in the table in the Appendix B.
In the section 2.1 the most interesting categories are examined in detail and in the section 2.2 are reported the conclusions regarding the critical analysis of the papers.

2.1 Critical analysis of the papers

2.1.1 Boundaries of analysis

Building a model for the study of regional and urban behaviour is strictly possible if there is a sufficient availability of detailed data. The collection of a great amount of data is a very expensive and complex operation. For this reason, almost the entire literature is focused on the most developed countries.
China, that is the largest GHG emitter in the world with nearly 10 billion tons of CO_2 emissions (28% of global emissions in 2015) [17], has attracted the interest of researchers, being the subject of 44% of the considered publications.
The other world powers, such as the North America and the major European countries, are splitting the remaining share (39%) of the analysed papers, leaving a slight percentage to Japan (5%) and Australia (3%).
There are also other publications, defined with "Global" (6%) that analyse the relationships between all countries with a multi-regional model, without focusing on a particular country.

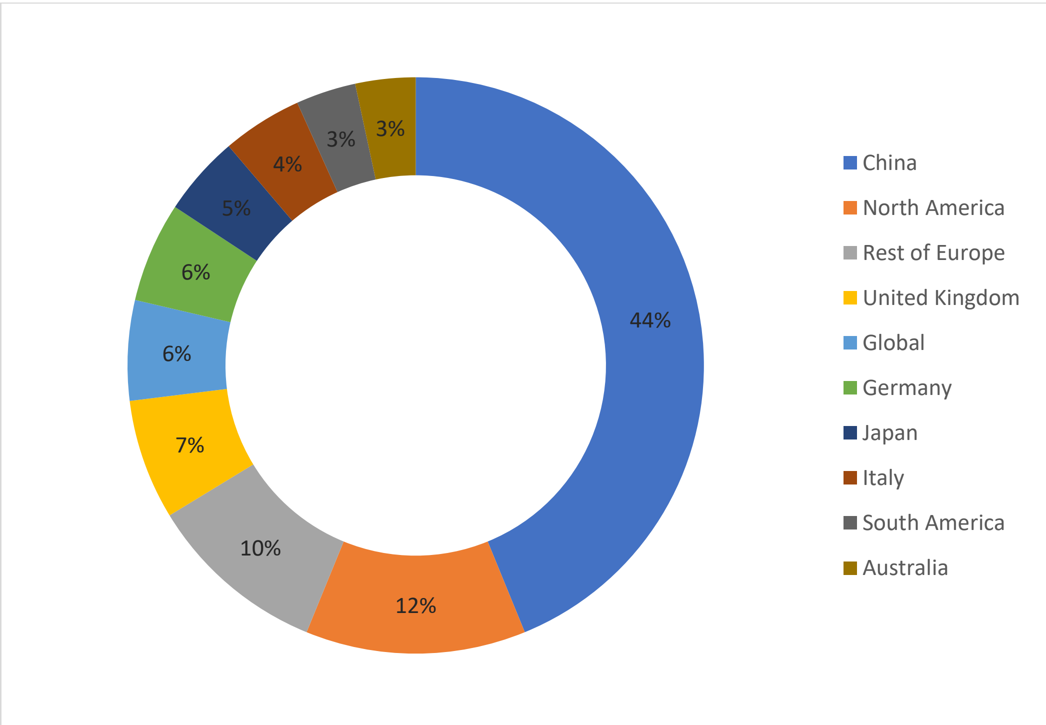


Figure 6. Percentages of the main world economies studied in the publications about urban and/or regional pollution.

2.1.2 Framework

Framework is defined as the analytical structure of the tool used to analyse the system. National, regional and urban environmental assessments are multidimensional and complex, therefore currently there is not a consensual method adopted. The authors choose the most suitable framework according to the target of the study and the availability of data.

Input-Output Framework

The Input-Output framework (IO) is a quantitative economic model that represents a national or regional economy by linking the different sectors of that particular economy. It shows the interdependencies between different sector, depicting how output from one sector becomes an input to another one and vice versa.
In a system with n sectors, the inter-industry matrix (n x n) is composed by column values and row values. Typically, column values represent input from the all sectors to a particular sector, while row values represent outputs from a given sector to the all other sectors.
When the framework is built for a single region, it is defined as Single Region Input-Output model (SRIO*)*. IO models for different regions can be aggregated to investigate spatial linkages within countries besides sectoral linkages: the resulting system is called Multi-regional Input-Output model (MRIO*)*.

Life Cycle Assessment

Life Cycle Assessment (LCA) is a technique used to evaluate environmental impacts related to the whole life of a product. This framework is generally built with a bottom-up approach, differently from the IO model, that usually makes use of a top-down approach.
The LCA model considers all the steps of the product's life, starting from raw material extraction, passing through material processing, manufacture, distribution, use, repair and ending with disposal or recycling.
This structure is very efficient for a critical analysis of a specific product or sector, but it results too detailed and difficult to implement for the study of all the sectors of a country's economy.

Material Flow Analysis

Material Flow Analysis (MFA) is an analytical framework used to quantify stocks of materials or substances and flows across different industrial sectors or within ecosystems. It is a tool to study the biophysical aspects of human activity on different spatial and temporal scales. MFA can be applied, depending on the purpose of the study, to a specific industrial installation or to a wider system as long as it is well defined.

Network Model

The network model is a quantitative framework used to predict a number of interesting urban or regional phenomena. It can be useful to explain the importance of particular junctions in transportation networks, the flow of traffic on city streets, the distribution of industry, services and retail establishments in urban or regional environments.
Most spatial network studies use to represent networks with two types of network elements: nodes and edges. Edges typically represent territorial segments, and nodes the junctions where two or more edges intersect. The analysis results illustrate the degree to which an edge or node is spatially connected to the surrounding path network.

Hybrid Frameworks

In the literature, hybrid models are defined as frameworks that are built by making use of two or more different types of framework. In our critical review, we found that the 8% of the publications rely on a hybrid IO-LCA model, which is developed by combining an IO structure with data derived with an LCA approach.

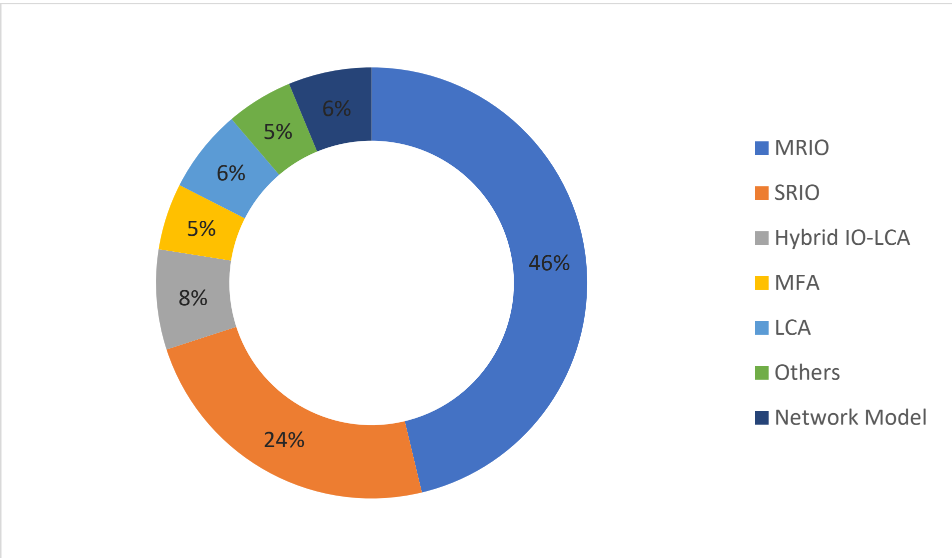


Figure 7. Percentages of the frameworks utilized in the cited publications.

2.1.3 Analysis Method

Once the framework is built, the model can be used to perform a deep analysis of the considered system. Several types of analysis follow different methodologies and give coherent results for the identified targets of the study. Most of those methods require very detailed data and are suitable for a focus on a specific industry, process or supply-chain.

When the willing of the publication is to investigate a wider and more complex system, like the entire economy of a region or a city and its interconnection with other economies, the most used techniques of analysis are the Environmental Extended Input-Output Analysis (34%) and the Emergy Analysis (8%).

The Environmental Extended Input-Output Analysis (EE-IOA) is performed by adding additional vectors to the traditional IO framework. Those vectors contain the quantitative amounts of resources/wastes that are directly absorbed/produced by all the sectors.

The Emergy Analysis evaluates all the work given by the environment to sustain a system and produce a certain level of output. Each form of energy in a system is translated into its solar energy equivalent, by multiplying its inputs and outputs for their respective solar transformities, which assess the energy's qualitative value. Once calculated the amounts of each element of the system, those can be compared by means of emergy related ratios and indices, revealing the characteristics of the system in terms of efficiency and sustainability.

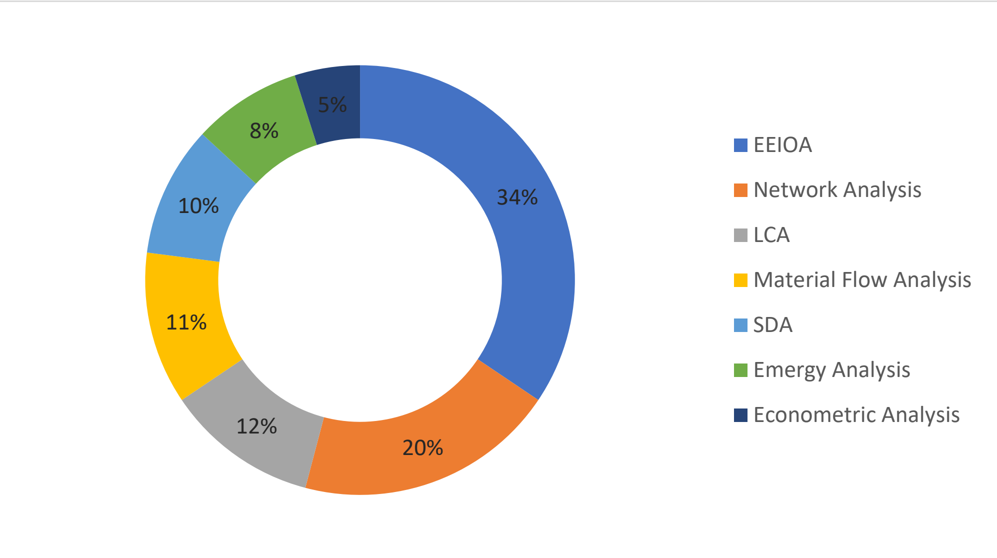


Figure 8. Percentages of analysis methods utilized in the cited publications.

2.1.4 Accounting system

To support effective climate action planning, GHG accounting frameworks should:

- Include both direct and indirect GHG emissions
- Provide sufficient detail to identify those sectors, processes and supply chains that have the largest potential for emission reductions
- Clearly identify the origin (location and industry or activity) of emissions
- Allow for consistent benchmarking and comparisons
- Apply internationally recognized environmental and economic accounting principles

Despite the traditional accounting principle is the Production-Based Accounting (PBA), only the 26% of the considered publications actually use it. This is due to the large amount of imports that play an important role in almost all the economies of the world, especially for cities.

In order to evaluate carbon leakages, Consumption-Based Accounting (CBA), which is used in the 65% of the considered publications, fully counterbalances the unilateral responsibility of the producer for the pollution inherent to the production of a good that is consumed elsewhere.

The third accounting method found in the analysed literature is the Value-added Based Accounting (VBA). As the CBA it takes account of the carbon leakage, considering the emissions hidden in the value-added gained by the producers through the supply chain. Due to very detailed data needed for the VBA method, it is very complex to calculate and it has been adopted only in the 9% of the considered publications.

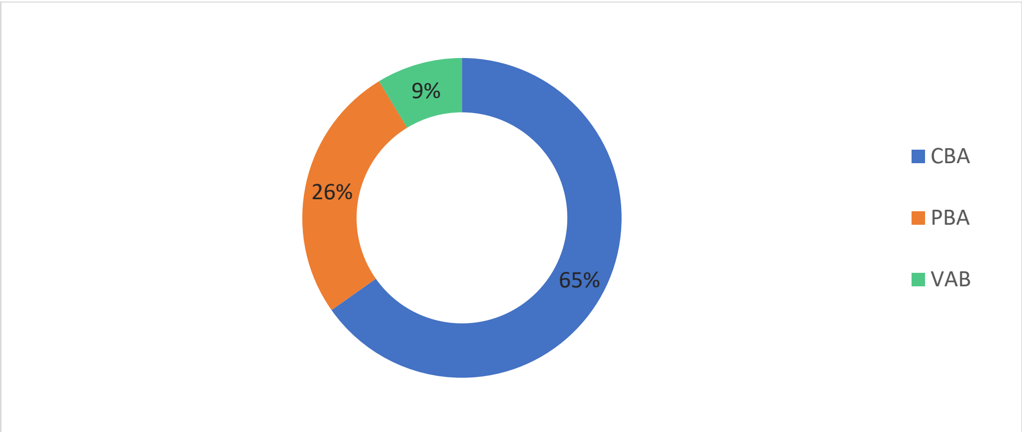


Figure 9. Percentages of accounting methods utilized in the cited papers

2.1.5 Indicators

Once the framework is built and the analysis is performed, the results have to be pointed out through appropriate and significative indicators, in order to obtain a successful description of the system.
We found in the literature that the 54% of the indicators in the considered papers are just environmental, while the 43% of them takes into account more than one dimension, in particular the 26% are environmental-economic indicators and the 17% are environmental-energy indicators.

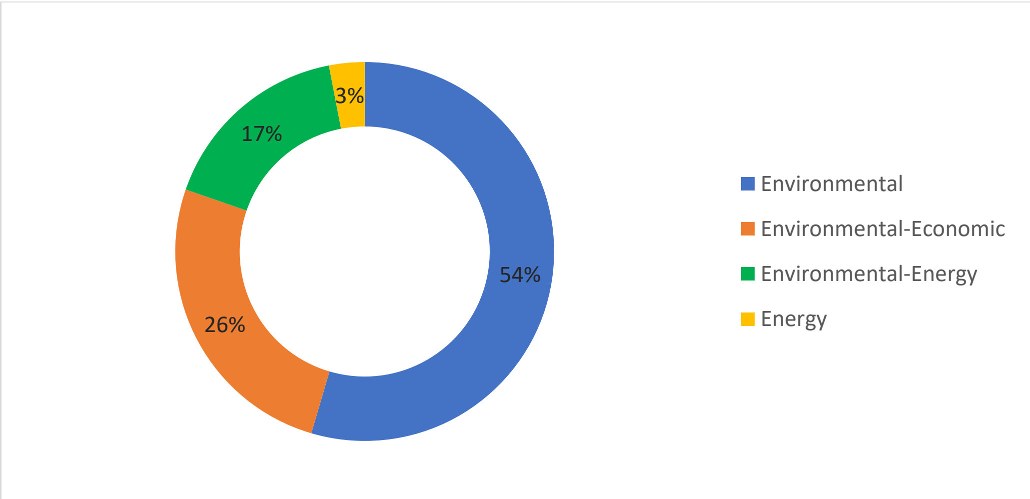


Figure 10. Percentages of the types of indicator used in the literature.

Using multidimensional indicators, gives a more complete and detailed analysis of a system, but it is not always possible to have a multidimensional result, because it depends on the framework and the analysis method. Therefore, we built a Sankey diagram to visualize which frameworks are the most appropriate to provide multidimensional indicators.
The Sankey diagram shows that MRIO and SRIO models are those that present the larger use of multidimensional indicators, due to its structure that permits a direct link between monetary flows and GHG emissions' flows. A multidimensional indicator can pinpoint crucial sectors that need to be targeted in future investments towards decarbonisation to minimise emissions and to maximise positive economic effects for urban and regional economies.

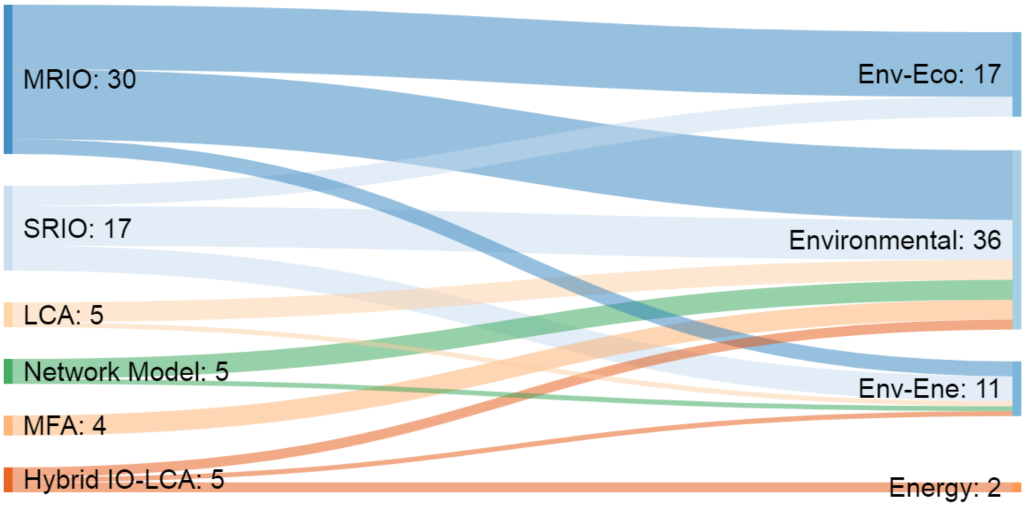


Figure 11. On the left side of the Sankey diagram are reported the frameworks utilized in the considered publications, while on the right side are reported the mono- and multi-dimensional indicators used in the same papers. The width of the flows connecting the left nodes with the right ones is proportional to the number of frameworks that provide the related indicator.

2.2 Results of the literature review

After an accurate and deep review of the literature, the most important conclusion is that the great amount of studies applies environmentally extended IO analysis to estimate environmental and economic indicators, due to the comprehensiveness of the model.
The 24% of the authors used the SRIO framework. It combines a good description of inter-industry linkages with a not excessive analytic complexity, but it assumes that imported goods and services are produced with the same technology of the domestic sector. Since the MRIO framework considers regional differences in production efficiency and tracks the supply chain, it has increasingly been adopted (46%) for global, national and sub-national studies, despite its more complex analytic structure.

We have identified that the type of model to implement, in order to obtain a sectoral and spatial analysis of Italy with a zoom on the city of Milan, is the Multi-Regional Input-Output model, because of its capability in capturing the linkages between sectors and regions. MRIO framework does not depend on defining system boundaries, thus it avoids truncation errors [18]. Moreover, with the

Environmental-Extended Input-Output Analysis, it is possible to provide multidimensional indicators that give environmental and economic measures.

In the end, this framework allows us to account the GHG emissions with both the traditional Production-Based approach and the Consumption-Based approach. The double possibility of accounting is important in order to assess if a country, a region or a city, are net importers or exporters of GHG emissions.

The building of the model is discussed in detail in chapter 4.

3. Methods and models

The large production of goods and services by industrial and human activities is sustained by a flow of resources that may be coming from the environment, as raw materials, or from other processes, as intermediate products. Therefore, the assessment of resources and wastes consumed or rejected by a process, strongly depends on the behaviour of other processes belonging to the same system. In order to analyse a system, it is crucial to understand how its partitions interact with each other.
Once defined the kind of resources and wastes to be accounted for, time span and sectoral boundaries have to be established, according to the purpose of the analysis. Inputs and outputs of every sub-level of the system have to be reported using the same unit of measure, allowing for coherent comparisons and significant evaluations.

In the following paragraph 3.1, it is described in detail the basic analytic structure of a Regional Input-Output framework, the assumptions behind it and its multiregional developments. In paragraph 3.2 are depicted the procedures and techniques used to build a Multiregional Input-Output Table. Paragraphs 3.3 and 3.4 concern the merging of urban-level data in the structure and the rationale of the environmental extension of the system.

3.1 Input-Output Analysis: the basic framework

In 1973 Professor Wassily Leontief received the Nobel Prize in Economic Science in recognition of the development, in the late 1930s, of an analytic framework that took the name of Input-Output analysis. Nowadays the ideas behind the work of Leontief are key concepts of many system-analysis and, indeed, Input-Output is one of the most applied analysis methods. Born as a purely economic tool, IO analysis has developed and its applications have been extended to employment and social accounting metrics associated with industrial production, as well as to the energy consumption and environmental pollution accounting related with international and interregional inter-industry activities.

Generally, an Input-Output model is constructed using observed data of monetary transactions in a defined time span for a specific region of interest (nation, state, county, province, etc.). It is preferable to use monetary terms instead of physical terms, because measurement problems could arise for industries that actually sell different types of goods.

The economic activity in the region is disaggregated in an arbitrary number of sectors. The level of the sector disaggregation depends on the availability of detailed data and the objectives that the model is expected to achieve. Considering a region with n sectors, the associated IO table is depicted in Figure 12.

The part of the table coloured in yellow is the Intermediate transaction matrix Z, wherein are reported the monetary transaction flows from each sector, considered as a producer, to each of the sectors, itself and the others, considered as consumers.

The first column of matrix Z is filled with the monetary flows associated to the physical input of intermediate products needed by sector 1 to produce its output and purchased from all the other sectors. Conversely, the upper row of matrix Z is filled with the monetary flows associated to the physical input of intermediate products needed by all the sectors to produce their outputs and purchased from sector 1. The diagonal elements of the matrix Z are the monetary flows associated to the physical amounts of intermediate products that are produced and consumed by the sectors themselves to produce their own outputs and are called intra-industry transactions.

The blue matrix is the Value-Added Matrix Va and accounts for the other inputs to production, such as non-industrial inputs (labour, depreciation of capital, taxes) and inputs coming from other regions, labelled as Imports.

The green portion of the table is the Final Demand Matrix f and records the sales of each sector to final markets. In particular are reported households and governmental expenditures, as well as gross private investments and the exports to other regions.

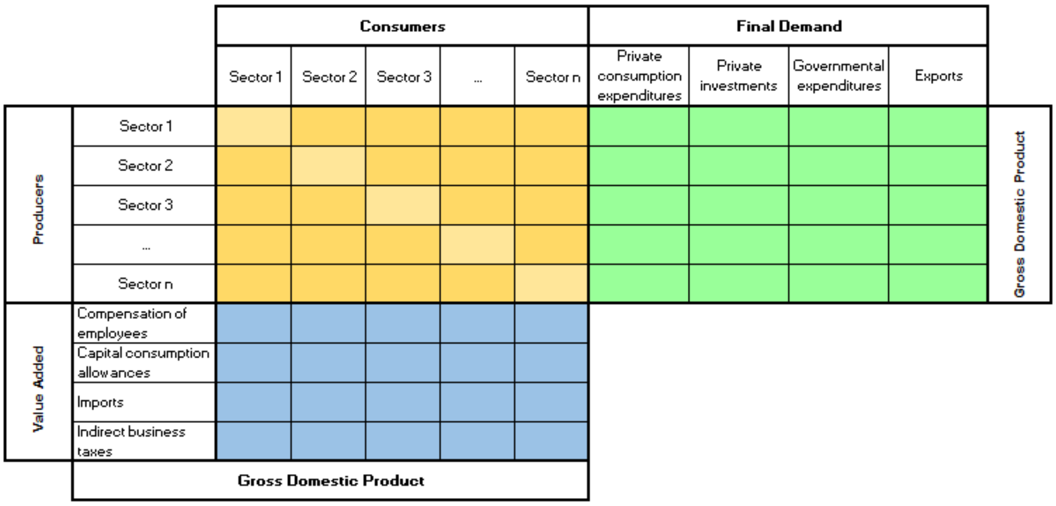


Figure 12. A basic structure of Leontief Input-Output model, constituted by three matrices: the Intermediate transaction Matrix Z (yellow), the Value-Added Matrix (blue) and the Final Demand Matrix (green).

The mathematical structure of a n sector system consists of a set of n linear equations. If we designate as z_{ij} the elements of the transaction matrix Z, as x_i the total output of sector i and as f_i the total final demand for sector i's products, the distribution of sector i's sales to other sectors and to final demand can be written as follow:

$$x_i = z_{i1} + z_{ij} + \ldots + z_{in} + f_i = \sum_{j=1}^{n} z_{ij} + f_i \tag{3.1}$$

There is an equation like this that identifies the distribution of the sales for each sector and all of them can be summarized in matrix notation (3.3), defining the total production vector x (n x 1), the intermediate transaction matrix Z (n x n) and the final demand vector f (n x 1) obtained as the sum of row elements of the finald demand matrix.

$$x = \begin{bmatrix} x_i \\ \cdots \\ x_n \end{bmatrix}, \; Z = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & z_{ii} & \vdots \\ z_{n1} & \cdots & z_{nn} \end{bmatrix}, \; f = \begin{bmatrix} f_i \\ \cdots \\ f_n \end{bmatrix} \tag{3.2}$$

$$x = ZI + f \tag{3.3}$$

In the equation 3.3, I is used to represent a column vector of 1 of appropriate dimension (n x 1 in this case), that is called "summation vector". The multiplication

for Z creates a column vector whose elements are the sums of the rows of the matrix.
Summing down the total output column, the result is the total gross output, X, throughout the economy. This same value can be found by summing across the total outlays row.

The contribution of a generic sector i to the total output of a generic sector j is defined by the technical coefficient $a_{ij} = z_{ij}/x_j$, that measures the intermediate inputs needed by sector j from sector i to produce a single unit of product. Technical coefficents can be calculated for each couple of sectors and are depicted in the technical coefficient matrix A ($n \times n$).

In a generic IO model, a fundamental assumption is that the inter-industry flows of products from sector i to sector j are entirely dependent on the total output of the sector j. The fact that, for example, the more cars are produced in a year, the more steel will be needed by the cars' producers during this year is a fair assumption. Some arguments may arise when technical coefficients a_{ij} are considered as fixed relationships between sectors, because economies of scales are not considered and production in a Leontief system operates under constant returns to scale.

The intermediate transaction matrix can be expressed as a function of the technical coefficient matrix $Z = A\hat{x}$, where $\hat{x}$ is a diagonal matrix filled with the values of the total production vector x. Then the equation 3.3 can be written in a compact form:

$$x = Axi + f \quad \rightarrow \quad x = (I - A)^{-1}f \quad \rightarrow x = Lf \tag{3.4}$$

L is defined as the Leontief inverse Matrix or the total requirements matrix and is the core of the Input-Output framework. Each element of L represents the embodied amount of input from sector i required by the sector j to produce one unit of its product as final demand.

Originally, applications of Input-Output model were performed at national levels and their main target was to assess the role of the different industrial sectors among the national economy. Over time, an additional interest regarding the inter-industry dynamics of a specific portion of national territory has risen, pushing the Input-Output analysis towards regional level. In order to reflect the peculiarities of a subnational system, the original Input-Output framework has been modified. Firstly, the structure of production may be identical or it may differ noticeably from that recorded in the national Input-Output table. Secondly, it is generally verified that small areas are more dependent than big areas on external trades, both for sales of regional outputs and purchases of imports needed for production.

In the following paragraphs will be examined the attempts that have been made to include the regional characteristics into an Input-Output framework, both for a single-region case and for a two or more-region case.

3.1.1 Regional Input-Output Table

Generally, single-region Input-Output analysis aims at quantifying the role of the producing sectors in that region and examining in detail the physiognomy of a particular region with respect to the nations to which it belongs. Moreover, several studies at regional level attempt to quantify, with a dynamic analysis, the impact on the sectors caused by a change of the regional final demand.
In order to perform those studies, two paths can be followed:

- Use a national table of technical coefficients jointly with an adjustment procedure designed to translate regional final demands into outputs of regional firms, since there is not a table of regional technical coefficients. The techniques used to "regionalize" national tables are described in detail in section 3.2.
- Build a regional model by surveying firms in the region and constructing a survey-based regional Input-Output table, based on true relationships between the regional sectors and not on estimations. Although this is the more precise of the two ways, the procedure of data collection is very expensive both in cost and time terms.

Single-region models fail to recognize what are the operative interconnections between different regions. The analysed region is "disconnected" from the rest of its home country, while in practice a number of important questions have several-region implications, because each of regional activities is expected to have trade relationships not only within the region where the activity takes place, but also to branch out towards other regions.

3.1.2 Multi-Regional Input-Output Table

In a many-regions Input–Output model (figure 13), the part of final demand that represents sales of sector i to the productive sectors in other regions (but not to consumers in the other region) is removed from the voice "export" of final demand category and specified explicitly in the transaction matrix.

The fundamental problem in a many-regions Input-Output model is the description of the transactions between regions. One approach, the interregional model, considers a complete and ideal set of intra- and interregional data. It is never the case, in practice, that such a model can be implemented, due to the magnitude and the difficulty of the collection of the data needed. Indeed, the requirements grow more than linearly with the number of the regions in the model: a three-region model has six interregional matrices, a four-region model has twelve, and so on.

Alternative many-regions Input-Output models have been developed and the most widespread in the literature is the Multiregional Input Output (MRIO) framework, due to an optimal trade-off between complexity of implementation and deepness of analysis. The MRIO model uses a regional technical coefficients matrix A^r, filled by regional technical coefficients a_{ij}^r, that respond to the question "How much sector i product did you buy yearly to produce a unit of your output?". The simplification made with respect to the interregional model is that the information about the region of origin of a given input has only one order of information and the sub-orders of information are ignored. In simple terms, considering as sector i the steel sector in region r and as sector j the automotive sector in the same region, the information regarding the inputs from steel to automotive sector does not account for the origin of the product of steel sector. This simplification holds true both for intraregional and interregional technical coefficients, respectively a_{ij}^r and a_{ij}^{rs}. For what concerns the estimation of interregional technical coefficients, survey data are even more complex and expensive to be collected with respect to the single-region case. Therefore, several methodologies for their estimation have been applied in the literature and have be explained in section 3.2.2.

As for single-region models, technical coefficients of intra- and interregional matrices are assumed to be constant even for variations of final demand and total output of sectors.

In more recent decades, several works have been carried out with multinational Input-Output models, where the spatial dimension of analysis has been shifted from regions (belonging to the same country) to nations.

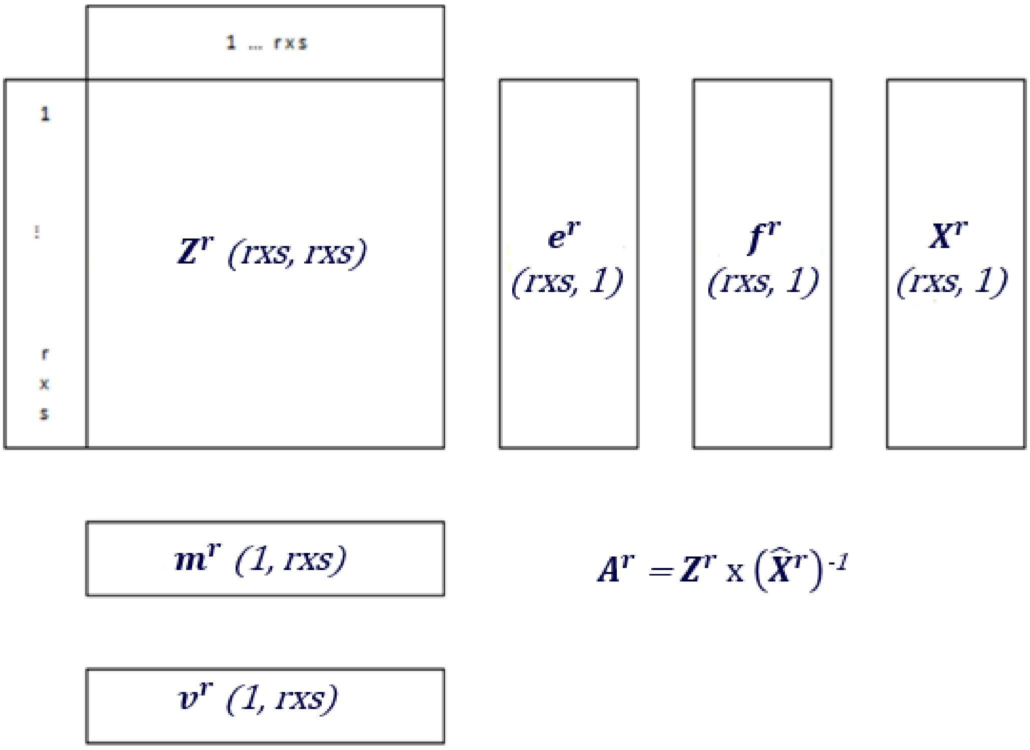


Figure 13. Generic multiregional Input-Output framework with r regions and s sectors. Z^{rs} is the intermediate flow matrix (or transaction matrix), e^r is the export vector, f^r is the final demand vector, x^r is the total production vector, m^r is the import vector and v^r is the value-added vector.

3.2 Building a Hybrid Multiregional Input-Output Table under limited information

There are fundamentally two types of data in any Input-Output model: survey and non-survey data. We refer to hybrid approach in constructing multiregional Input-Output tables when survey data are integrated into a non-survey procedure. It is widely used to adopt survey data, when available, to improve the precision of the model, because survey data are usually more trustable than non-survey ones and for this reason are defined "superior data". Jensen [19] and West [20] have done a great work for deriving regional Input-Output table, starting with a national table, applying methodologies for data regionalization and paying attention to "superior data" and expert opinion when and as available. This procedure has been named as GRIT (Generation of Regional Input-Output Tables).
While survey data are obtained by direct investigations of firms and households and can be found on national or regional databases, non-survey data are obtained by

means of several techniques, used either to update or to downscale existing data. Depending on the type of data that have to be estimated (intra-sectoral, inter-sectoral or inter-regional) different methodologies are used in the literature. In this section are explained the most common methodologies to estimate non-survey data. Subsequently, we analyse in detail the procedure that has to be followed to build a hybrid multiregional Input-Output Table.

3.2.1 Estimating regional technical coefficients

Techniques for regionalization of national coefficients are usually based on published information on regional employment, number of people living in the region and value-added or output by industry. Therefore, once the national Input-Output table is available, it is always possible to downscale data at regional or urban level. The real issue regards the coherence of the sectoral disaggregation between national or international dataset and the regional one. This problem is discussed in section 5.

- Simple Location Quotients

The simple Location Quotient for sector i in region r is defined as

$$LQ_i^r = \left(\frac{x_i^r/x^r}{x_i^n/x^n}\right) \tag{3.5}$$

In equation (3.5), x^r and x_i^r are respectively the total gross output of all sectors in region r and the total production of sector i in region r, while x^n and x_i^n are referred to the same data, but at national level. If regional output data for all the sectors are not available, it is possible to substitute the total production with other measures of the industrial activity in the region, such as number of employees, income earned, value added and population number per sector. The rationale behind simple Location Quotient is that it measures if a sector is less or more localized in region r than in the nation. Indeed, the numerator in (3.5) indicates the proportion of region r's total output that is produced by sector i and the denominator indicates the same at regional level. Whenever LQ_i^r is > 1, sector i's production is more localized in region r than in the nation as a whole, conversely if LQ_i^r is < 1 it means that sector i's production is less concentrated in region r than in the nation. In the first case, sector i will be able to supply the demand of final demand and intermediate products placed upon it by final consumers and other industries in that region, thus its regional technical coefficient is equal to the national one and its surplus is assumed to be exported out of regional boundaries. Otherwise, if the denominator is greater than the numerator, sector i is assumed not to be able to satisfy the final demand and the requirements of other sectors for its products, therefore the national proportion is modified downward.

$$a_{ij}^{rr} = \begin{cases} (LQ_{ij}^{r}) * a_{ij}^{n} & if\ LQ_{ij}^{r} < 1 \\ a_{ij}^{n} & if\ LQ_{ij}^{r} \geq 1 \end{cases} \quad (3.6)$$

The main complaint about LQ technique is about its underestimation of regional trade, since it ignores cross hauling, i.e. the simultaneous regional import and export of the same good. The phenomenon of cross hauling is often observed, but it's difficult to account for it in an estimation procedure.

- Cross-Industry Quotients

The Cross-Industry Quotients (CIQ) technique is a variation of the simple Location Quotients technique and is applicable only to calculate extra-diagonal elements (inter-sectoral transactions) of the regional technical coefficient matrix. Differently from LQ, that applies uniform adjustments along each row of A^{n}, CIQ allows for differing the adjustments cell-by-cell. The rationale behind this technique is the relative importance in the region respect to the nation of both buying sector j and selling sector i.

$$CIQ_{ij}^{r} = \left(\frac{x_i^r / x_i^n}{x_j^r / x_j^n}\right) \quad (3.7)$$

If the regional output of sector i in region r relative to the national output x_i^n is larger than the output of sector j in region r relative to the national output x_j^n (CIQ_{ij}^{r} > 1), than sector i will be able to supply j's needs of intermediate products without any requirement of i's products from outside the region. Viceversa, if CIQ_{ij}^{r} < 1, some of j's needs will be imported from other regions and the regional technical coefficient a_{ij}^{r} will be reduced.

$$a_{ij}^{rr} = \begin{cases} (CIQ_{ij}^{r}) * a_{ij}^{n} & if\ CIQ_{ij}^{r} < 1 \\ a_{ij}^{n} & if\ CIQ_{ij}^{r} \geq 1 \end{cases} \quad (3.8)$$

When i=j in the main diagonal, CIQ = 1 and there are no adjustments to the diagonal terms. Therefore, diagonal terms are modified using their associated Location Quotients instead of their Cross-Industry Quotients.

- Semilogarithmic Quotients

Location Quotients technique considers the relative size of the regional selling sector (x_i^r/x_i^n) and the relative size of the regional industrial activity with respect to the nation (x^r/x^n). Whereas, Cross-Industry Quotients technique takes into account the dimensions of both selling (x_i^r/x_i^n) and buying $\left(x_j^r/x_j^n\right)$ sector, without considering the relative size of the region. Semilogarithmic Quotient (SLQ_{ij}^r) considers all the three dimensions in a way that maintains the properties of both LQ and CIQ.

$$SLQ_{ij}^r = LQ_i^r / \log_2\left(1 + LQ_j^r\right) \tag{3.9}$$

- Flegg's Location Quotients

FLQ technique is another attempt to include those three factors in a measure and it was developed by Flegg and Webber [21]. This technique incorporates an additional measure of the relative size of the region to CIQ_{ij}^r by introucing a parameter λ.

$$\lambda = \{\log_2[1 + (x_E^r/x_E^n)]\}^\delta \tag{3.10}$$

$$FLQ_{ij}^r = (\lambda) * CIQ_{ij}^r \tag{3.11}$$

FLQ uses employment rather than industrial output to account for regional and national industrial activity, indeed in equation (3.10) x_E^r and x_E^n are respectively the number of employees at regional and national level. The parameter δ is included between 0 and 1, but it is not clear what this value should be: empirical works have suggested that δ=0.3 works well in a variety of situations.
The idea of FLQ technique is to reduce national coefficient less for larger regions, which theoretically should have more resources and rely less on imports from other regions.

- Augmented Flegg's Location Quotients

Augmented Flegg's Location Quotients (AFLQ) is a variation of FLQ that considers regional specialization. Such specialization leads to an increase of intraregional purchases by the specialized industry and hence to larger intraregional technical coefficients with respect to their national counterparts.

$$AFLQ_{ij}^{r} = \begin{cases} \left[\log_2\left(1 + LQ_j^r\right)\right] * FLQ_{ij}^{r} & if\ LQ_j^r > 1 \\ FLQ_{ij}^{r} & if\ LQ_j^r \leq 1 \end{cases} \quad (3.12)$$

$$a_{ij}^{rr} = \begin{cases} \left(AFLQ_{ij}^{r}\right) * a_{ij}^{n} & if\ LQ_j^r > 1 \\ \left(FLQ_{ij}^{r}\right) * a_{ij}^{n} & if\ LQ_j^r \leq 1 \end{cases} \quad (3.13)$$

The rationale is that an important firm which supplies sector j's products, may attract in the region r other firms that produce intermediate products needed by sector j. However, there is poor empirical evidence that AFLQ performs better than FLQ.

- Fabrication effects

The last technique found in our literature review considers the value-added/output ratios per sector as the discriminating factor for reduction or increase of the related regional technical coefficient. This technique is known as "Fabrication effects" and was proposed by Round [22]. The regional fabrication effect for sector j in region r is defined as:

$$\rho_j^r = \frac{1-\left(v_j^r/x_j^r\right)}{1-\left(v_j^n/x_j^n\right)} \quad (3.14)$$

The parameter ρ_j^r measures how much a regional sector is dependent on industrial inputs and value-added inputs with respect to its national counterpart. After the calculation of fabrication effects, these are used to estimate the regional technical coefficients:

$$a_{ij}^{r} = \rho_j^r * a_{ij}^{n} \quad (3.15)$$

Differently from the methodologies previously shown in this section, this one applies the modifications to columns and not to rows; the entire jth column of A^n is multiplied by ρ_j^r to generate the estimation of the jth column of A^r. The rationale behind the methodology is that if inter-industry inputs are less important for sector j in region r than in the rest of the nation, national coefficients for sector j should be scaled down. Vice versa, if inter-industry inputs are more important at regional level, the national coefficients should be increased.

3.2.2 Estimating interregional flows

When dealing with multiregional Input-Output model, the estimation of intraregional technical coefficients (section 3.2.1) is not sufficient to completely characterize the model, but an entire set of interregional technical coefficients is needed to populate the intermediate transaction matrix Z.
In this section are described in detail the two most common techniques used to estimate interregional flow of goods: the gravity model and a modification of the Cross-Industry Quotients.

- The Gravity Model

Introduced in 1950s, the gravity model is the prevailing framework to predict a number of phenomena that deal with a generic flow that goes from one place to another one, like bilateral trade flow between regions, population movement, inter-city phone calls and cargo shipping volume.
The idea at the base of the gravity model is that the flow of sector i's goods from region r to region s is assumed as a function of the total intermediate output of i in r ($z_i^{r\cdot}$), the total intermediate purchases of i in s ($z_i^{\cdot s}$) and the distance between the two regions d^{rs}, that is considered as a sort of impedance and is present at the denominator. The original gravity model is described by the following equation:

$$z_i^{rs} = k_i^{rs} * \frac{z_i^{r\cdot} * z_i^{\cdot s}}{(d^{rs})^{e_i}} \qquad (3.16)$$

where k_i^{rs} and e_i are parameters to be estimated (in the Newtonian form e_i=2). The multiplicative form implies that there can be no flow of sector i's commodities between regions r and s, if either one of demand pool and supply pool is zero.

A subsequent version of the gravity model was suggested by Leontief and Strout [23], in order to avoid two parameters to be empirically estimated and such a great dependence on the distance between the two regions of interest, d^{rs}. The modified gravity model still uses the "supply pool" of good i in region r ($z_i^{r\cdot}$) and the "demand pool" of good i in region s ($z_i^{\cdot s}$), but at the denominator the measure of "impedance" is no more the distance d^{rs}, but the total production of commodity i in the system ($x_i^{\cdot\cdot}$).

$$z_i^{rs} = \frac{z_i^{r\cdot} * z_i^{\cdot s}}{x_i^{\cdot\cdot}} * Q^{rs} \qquad (4.17)$$

It is important to underline that if $z_i^{r\cdot}$, $z_i^{\cdot r}$, $z_i^{s\cdot}$, $z_i^{\cdot s}$, $x_i^{\cdot\cdot}$, Q^{rs} and Q^{sr} are all non-zero terms, this model allows cross-hauling, hence both z_i^{rs} and z_i^{sr} are greater than zero.

Q^{rs} is a parameter that has to be estimated for every combination of two regions of the system, in order to characterize the existing relations between them. In the most optimistic scenario, the values of $z_i^{r\cdot}$, $z_i^{\cdot s}$, $x_i^{\cdot\cdot}$ and z_i^{rs} are known for at least one sector and Q^{rs} can be calculated by making explicit it in the equation (3.17). Otherwise, the parameter Q^{rs} has to be estimated, the methodologies that we have used to estimate it are described in the section 5.

- Cross-Industry Quotients

The family of Location Quotients, described in section (3.2.1) regarding the estimation of intraregional technical coefficient, can be used also for interregional coefficients' estimation. Given two regions, r and s, if region r is estimated to be an exporter of sector i's products, it is assumed that all the demand for sector i's products in region r is satisfied by local production and there is no import of those goods, hence cross-hauling is not allowed. Moreover, if region r is an exporter of sector i's products, region s is necessarily an importer of sector i's goods, in particular region s purchases exactly the same quantity of commodities exported by region r.

$$a_{ij}^{sr} = \begin{cases} \left(1 - CIQ_{ij}^{r}\right) * a_{ij}^{n} & if\ CIQ_{ij}^{r} < 1 \\ 0 & if\ CIQ_{ij}^{r} > 1 \end{cases} \qquad (3.18)$$

The two-region logic can be applied to cases in which are present more than two regions. It is possible by using CIQ, adopting a series of two-region models and in the end balancing the resulting intermediate transaction matrix through a mathematical technique named RAS. A three-region system is appropriate to illustrate the five-step procedure.

1. Given three regions r, s and t, we initially consider a system made up of region r and a fictitious region f obtained by aggregating the remaining regions. CIQ is used to estimate matrices A^{rr} and A^{ff} as illustrated in equations (3.7) and (3.8), starting from a known national technical coefficient matrix A^{n}. Consequently, interregional technical coefficients

a_{ij}^{fr} and a_{ij}^{rf} are found as $a_{ij}^{fr} = a_{ij}^{n} - a_{ij}^{rr}$ and $a_{ij}^{rf} = a_{ij}^{n} - a_{ij}^{ff}$. Then the estimated submatrices are merged in a resulting matrix $\begin{bmatrix} A^{rr} & A^{rf} \\ A^{fr} & A^{ff} \end{bmatrix}$.

2. This procedure has to be repeated for all the other possible two-region partitions (s and f, t and f), obtaining $\begin{bmatrix} A^{ss} & A^{sf} \\ A^{fs} & A^{ff} \end{bmatrix}$ and $\begin{bmatrix} A^{tt} & A^{tf} \\ A^{ft} & A^{ff} \end{bmatrix}$.
   All this information can be gathered in a matrix like this one below, where the missing elements are all the technical interregional coefficients:

$$A = \begin{bmatrix} A^{rr} & & & A^{rf} \\ & A^{ss} & & A^{sf} \\ & & A^{tt} & A^{tf} \\ A^{fr} & A^{fs} & A^{ft} & \end{bmatrix} \tag{3.19}$$

3. Coefficients are converted to monetary flows using known outputs $\hat{x}^r$, $\hat{x}^s$, $\hat{x}^t$ and the outputs of all the possible fictitious region aggregations $\hat{x}^f$. The following operation is repeated for all the partitions and the results are put together to form matrix Z:

$$Z^{rf} = \begin{bmatrix} A^{rr} & A^{rf} \\ A^{fr} & A^{ff} \end{bmatrix} \times \begin{bmatrix} \hat{x}^r & 0 \\ 0 & \hat{x}^f \end{bmatrix} = \begin{bmatrix} Z^{rr} & Z^{rf} \\ Z^{fr} & Z^{ff} \end{bmatrix} \tag{3.20}$$

$$Z = \begin{bmatrix} Z^{rr} & & & Z^{rf} \\ & Z^{ss} & & Z^{sf} \\ & & Z^{tt} & Z^{tf} \\ Z^{fr} & Z^{fs} & Z^{ft} & \end{bmatrix} \tag{3.21}$$

4. The void elements in equation (3.21) are filled by splitting the elements Z^{rf}, Z^{sf}, Z^{tf}, Z^{fr}, Z^{fs} and Z^{ft}. The most simplifying assumption is that interregional import and export are equally distributed among regions, that is $Z^{rs} = Z^{rt} = \frac{1}{2} Z^{rf}$. There are several possible assumptions to split interregional flows more effectively and these are described in section 5.

5. The final intermediate transaction matrix Z is obtained by means of a mathematical balancing and iterative technique named RAS, which is described in the next paragraph.

3.2.3 Balancing and updating multiregional Input-Output Tables

As anticipated in the previous sections, the RAS method is a mathematical iterative scaling technique for data reconciliation. It aims to achieve consistency between the entries of a non-negative matrix with known row and column totals. In particular, given a rectangular non-negative matrix, as Z, it multiplies each entry in the rows by a factor, that is chosen in a way that the sum of all the entries in the row equals the known row total targets. Then, the same operation is applied to the column entries. As a result target column totals are achieved, but it is possible that the constraints on the row totals are violated again. The operation is applied to rows and columns in turn, until the method converges to a matrix that is consistent with the pre-specified row and column totals.

The RAS technique is suitable also to update national, regional or multiregional models, thus it is able to adjust coefficient matrices across time other than across space. Given a set of $3 * n$ informations for the year of interest t, regarding total gross outputs x_j, total interindustry intermediate sales and total interindustry purchases, it is possible to update a table of year $(t - 1)$ by using it as the starting matrix in the RAS iteration process.

Generally, RAS procedure converges to with an acceptable tolerance in a reasonable number of iterations, often less than fifty [24]. However, examples of non-convergence are present in the literature. The most common explanation for this behaviour, is that the starting transactions matrix is very sparse (contains too many zeros) [25]. A very disaggregated transactions matrix is more likely to have more zeros than, for example, a highly aggregated national table. Intuitively, the problem with zeros is that the entire burden of balance is forced on the remaining non-zero elements and they may be inadequate to this task.

It is important to underline that the starting in matrix is fundamental for the final result, hence solution is not unique, thus the unknown factors are n^2 and the constraints are $2 * n$.

3.3 Nested Multiregional Input-Output Analysis

Multiregional Input-Output have taken an important role in the analysis of the inter-correlations of national and sub-national systems and in environmental policy designing. A further improvement could be the simultaneous analysis of different spatial scales through the construction of a Nested Multiregional Input-Output

Table. The verb "nest" literally means "fitting an object inside a larger one". In an Input-Output context, a nested table is built by integrating a sub-system that can be a city, a province or a nation, in a wider system like a region or a global coverage system. Bachmann and Roorda [26] cite regional specialization and spatial diversification of industrial endowments among a number of other reasons for why sub-national resolution is important for system analysis.

According to the aim of our work, building a Nested Multiregional Input-Output table is a very effective method to analyse deeply a city and its interconnections, without extrapolating it from its regional and national context.

In order to include a city in a Multiregional Input-Output analysis, it has to be considered as a further region of the system. In this way it is possible to incorporate the city in the starting table (Figure 14), following the same procedure for the estimation of intraregional and interregional monetary flows, as explained in section 3.2.

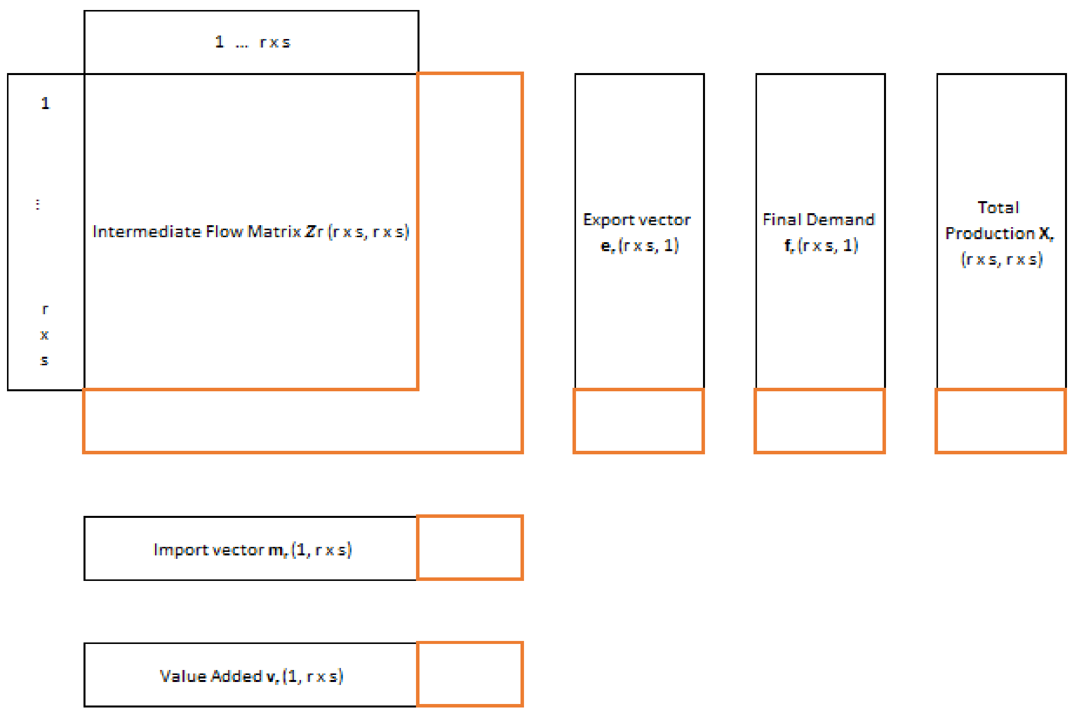


Figure 14. Representation of a Nested Multiregional Input-Output model. The orange lines are the row and column entries of the sub-region values that have to be nested to the original model (black lines).

3.4 Environmental Extended Multiregional Input-Output Analysis

Since the late 1960s, the Input-Output framework has been extended in order to account for environmental pollution and resource consumption related to inter-industry activities. Leontief developed in 1970 [27] a methodological extension that has been applied widely and further extended in the following researches.

The productive system composed by n sectors is characterized by m sectoral exogenous transactions of resources absorbed and wastes produced. The amount of resources and wastes embodied in the final demand can be evaluated by considering n embodied exogenous transactions balances (3.22), where the k stands for the type of the considered exogenous transaction (i.e. energy, CO_2 emissions, material, PM_x emissions, water usage, etc.).

$$e_{ki}x_i = e_{k1}x_{1i} + \cdots + e_{ki}x_{ji} + \cdots + e_{kn}x_{ni} + r_{ki};\ e_{ki}x_i = \sum_{j=1}^{n} e_{kj}x_{ji} + r_{ki} \quad (3.22)$$

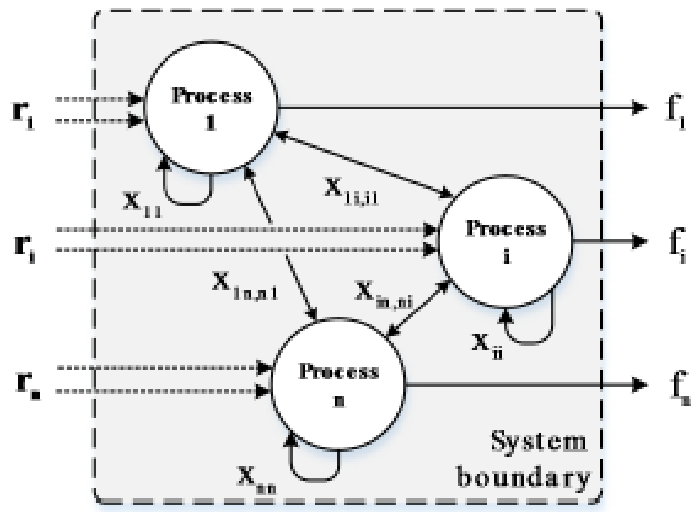


Figure 15. The resources/wastes r entering the system and addressed to the ith process are represented on the left side. Inside the system boundaries are represented the n processes and the rows connecting each process to the others are the intermediate flows of products between sectors. In the right side of the figure are represented the exiting flows of products needed to meet the n final demands.

For every exogenous transaction k the balance (3.22) describes the quantity of resource/waste embodied in the total production of the ith sector. The total $e_{ki}x_i$

is calculated as the sum of the exogenous transactions embodied in self-consumption inputs and all the other intermediate inputs to sector i, added to the exogenous transactions directly associated with the process i, that are indicated with r_{ki}.
The exogenous transactions directly absorbed or released by the processes r_{ki}, are listed in the exogenous transactions matrix $R(m \times n)$, where the m rows are all the types of exogenous transactions entering the system and every line is expressed in homogeneous units of measure (i.e. J, kg, tons, m^3 etc.).
In the equation (3.22), the matrix $e(n \times m)$ is a necessary data needed to perform the environmental extention of the framework. It represents the specific embodied resources/wastes directly and indirectly related to the production of all the ith units of final demand. In order to provide the equation to calculate matrix e, there are few definitions to be introduced. First of all, the input coefficient b is defined as the amount of exogenous transaction directly required to produce a unit of output. All these coefficients are grouped in the input coefficients matrix $b(m \times n)$ (3.24).

$$b_{kj} = r_{kj}/x_j \tag{3.23}$$

$$b = Rx^{-1} \rightarrow R = bx \tag{3.24}$$

Using the definitions introduced above and the equations introduced in this section, it is possible to rewrite the exogenous transactions balance (3.22) as a function of the technical coefficient matrix A and the input coefficient matrix B, starting from $\hat{x}e = Z^T e + R^T$:

$$\hat{x}e = (A\hat{x})^T e + (b\hat{x})^T \rightarrow \hat{x}^{-1}\hat{x}e = \hat{x}^{-1}\hat{x}A^T e + \hat{x}^{-1}\hat{x}b^T \rightarrow e = A^T e + b^T \tag{3.25}$$

$$e = (I - A^T)^{-1} b^T \rightarrow e = [(I - A)^{-1}]^T b^T \rightarrow e = L^T b^T \rightarrow e = (bL)^T \tag{3.26}$$

The total amount of embodied exogenous transactions is a conservative quantity, thus the sum of the exogenous resources absorbed by the system R_{tot} equals the sum of the total resources/wastes embodied in its products E_{tot}. Anyway, the elements of total embodied exogenous transactions matrix E differ from the ones of the exogenous transactions matrix R, indeed E represents the allocation of exogenous resources/wastes among final demand products ($E = fe$).

In the end, the Environmental Extended Input-Output framework (EE-IO) is composed by the endogenous transaction matrix Z, final demand vector f, total output vector x and the endogenous transactions matrix R.

From/To	**1 … n**	**Final demand**	**Total production**
Process 1 **Process 2** … **Process n**	Endogenous transactions matrix **Z** (*nxn*)	**f** (*nx1*)	**X** (*nx1*)
Resource 1 **Resource 2** … **Resource n**	Exogenous transactions matrix **R** (*mxn*)		

Figure 16. An example of the basic Environmental-Extended Input-Output Table for a system with n processes (sectors) and m resources/wastes.

4. Application of the model

The aim of this work is to build a Nested Multiregional Input-Output Table of Italy, dividing the nation in several regions to study the characteristics of each region and how they relate with each other. A further analysis is provided by nesting the province of Milan in the framework and consequently applying the environmental extension. The tool built in this way is able to evaluate the amount of CO_2 equivalent emitted both directly and indirectly, by the inter-industry activities at urban, regional and national level. The results are summed up by environmental and economic indicators, in order to provide multi-dimensional evaluations that may be useful for policymakers.

The analysis is performed both statically and dynamically. The results derived by the standard table are like a photograph of the system to which data are referred to, however, with a shock analysis, it is possible to simulate a variation of the consumption of a particular good (change of the final demand/import/export in a specific sector) and analyse the response of the system. The variation can be at national, regional or urban level, and the results can be analysed both with a top-down and a bottom-up approach, studying how urban policies affect indirectly regions and nation and vice versa.

In this chapter is described the construction process of the MRIO model and the rationale behind every assumption and estimation made to fill the table, starting from the analytical basis defined in chapter 4 and making some modifications when needed. Moreover, new methodologies are introduced to estimate the parameters for the calculation of interregional monetary flows and the related carbon flows. We have computerised the entire procedure by means of an open source Python script that carries out the huge amount of calculation to perform both the construction of the table and the environmental analysis. The script is interactive, indeed it is possible to choose between two different sectoral and regional disaggregation and also between different methodologies to estimate interregional monetary flows, for a total of nine different final Environmental Extended Nested Multiregional Input-Output tables.
Multiple results are useful for two main reasons:

- Providing a confidence interval to the policymakers; it is important to remember that the results of the analysis are estimations and, since at the time of writing, this work is the first Nested MRIO of Italy, the comparison with similar works is not possible.

- Evaluating which is the best level of disaggregation according to the results that we are expecting to be found. In particular, it is interesting to understand if there is a trade-off between regional and sectoral disaggregation by evaluating the nine different MRIO tables and the environmental indicators.

The procedure to build the Nested MRIO framework can be outlined in five steps:

1. Collection of Data
2. Nesting of Milan in the model
3. Estimation of Intraregional flows
4. Estimation of Interregional flows
5. Final Balancing of Z and Environmental Extension

4.1 Step One: Collection of Data

The first step in the construction process of a Nested MRIO is the selection of a starting table from which withdrawn the needed information. Among the available EE-MRIO, we chose the database EXIOBASE version 3 [27] for its compatibility with the System of Environmental-Economic Accounting (SEEA) [28] and for its high level of sectoral detail matched with multiple social and environmental satellite accounts. EXIOBASE 3 is a time series of EE-MRIO tables with 163 industries, ranging from 1995 to 2011, for the 28 EU member plus 16 major economies, for a total of 44 countries and 5 rest of the world regions.
We developed an aggregation tool that reduces the initial 163 to 20 sectors and merges the 7 items that constitute the final demand f and the 9 items that constitute the value-added Va into two single items. Moreover, all the nations but Italy are grouped together and considered as a single region named "Rest of the World" (RoW).

After the collection of national level data, it is necessary to define a regional breakdown of Italy and collect the regional level data in order to perform the regionalization of the starting national matrix with the techniques described in section 3.2.
In our Python script, it is possible to choose two different regional decompositions, which are depicted in Appendix A:

- Model A – 20 regions (traditional regional division of Italy) plus the additional RoW region.
- Model B – Six regions (Italian Electric Market division) plus the additional RoW region.

The Italian National Institute of Statistics (Istat), provides the most detailed and precise dataset of Italian regional statistics. In the most optimistic case, the regional dataset provides data about final demand f, export of final goods e, import of final goods m, value-added Va and total production vector x for each sector coeherently with the criteria of calculation of the dataset provided by EXIOBASE 3. However, Istat database does not include the regional total output x for any sector, therefore these values have to be estimated.
The regional total output of a generic sector i is estimated as a fraction of the national total output of the same sector i. The value of the fraction is a function of the size of the region respectively to the whole nation and, depending on the typology of the sector to estimate, we have selected three proxy indicators to account for the region size:

- The value-added Va_i^r generated by the ith sector of region r (known data) with respect to the national value-added generated by the ith sector Va_i^n is the proxy indicator to estimate the total output of financial and business sectors.

$$x_i^r = x_i^n * \frac{Va_i^r}{Va_i^n} \tag{4.1}$$

- The number of employees y_i^r in the ith sector of region r (known data) with respect to the number of national employees y_i^n in the ith sector is the proxy indicator to estimate the total output of industrial sectors.

$$x_i^r = x_i^n * \frac{y_i^r}{y_i^n} \tag{4.2}$$

- The population p^r in region r (known data) with respect to the national population p^n is the proxy indicator to estimate the total output of public services sectors.

$$x_i^r = x_i^n * \frac{p^r}{p^n} \tag{4.3}$$

Moreover, also the sectoral disaggregation of Istat and EXIOBASE 3 databases are slightly different, causing little variations of the values of value-added, final demand, import and exports. Thus, we have done a reconciliation of the datasets by proportionally modifying the regional values of Va, f, m and e with a redistribution of the difference between Istat and EXIOBASE 3 national values, to coincide the former to the latter.
The operation is described in the following equation (4.4) for the reconciliation of the value-added Va and its repeated for final demand, imports and exports:

$$\Delta = Va_{i,EXIO}^{n} - \sum_{k=1}^{r}\sum_{i=1}^{n} Va_{i,Istat}^{k};$$

$$Va_{i,Istat'}^{k} = Va_{i,Istat}^{k}\left[\frac{(Va_{i,EXIO}^{n} - Va_{i,Istat}^{k})}{\sum_{k=1}^{r}\sum_{i=1}^{n} Va_{i,Istat}^{k}}\right] \tag{4.4}$$

Despite the national values of the two different datasets are made consistent by this procedure, it does not guarantee the consistency of the whole system. In simple terms, each regional sector has to meet two constraints in order to build an Input-Output framework:

- the difference (4.5) between the regional total output of sector i, x_i^r, the regional exports of sector i, e_i^r, and the regional final demand of sector i, f_i^r, has to be positive

- the difference (4.6) between the regional total output of sector i, x_i^r, the regional imports of sector i, m_i^r, and the regional value-added of sector i, Va_i^r, has to be positive too.

Row's constraint: $x_i^r - e_i^r - f_i^r > 0$ (4.5)

Column's constraint: $x_i^r - m_i^r - Va_i^r > 0$ (4.6)

The presence of these two constraints is necessary to ensure the existence of intra- and interregional monetary flows (elements of Z), indeed:

Row's balance: $\sum_{j=1}^{n} Z_{ij}^r + e_i^r + f_i^r = x_i^r$ (4.7)

Column's balance: $\sum_{j=1}^{n} Z_{ij}^r + m_i^r + Va_i^r = x_i^r$ (4.8)

If the two constraint are respected, the estimation of the total production x_i^r and the reconciliation of Istat's data are acceptable. Otherwise, we need to aggregate sector i, for which the constraint is not respected, with a similar sector j that meets the conditions and so on (for example public health sector may be grouped with education sector).

The procedure of estimation and reconciliation has been carried out for both Model A and Model B, resulting in two different sectoral breakdowns, that are illustrated in Appendix A.

- Model A – 21 regions (20+RoW), 6 sectors
- Model B – 7 regions (6+RoW), 17 sectors

Once the starting data are consistent with each other, it is possible to work on the core of the Input-Output framework, that is the estimation of the intermediate transaction matrix Z.

4.2 Step Two: Nesting of Milan in the model

Milan is the second-most populous metropolitan city in Italy with more then 3,200,000 citizens [29] and the capital of Lombardy. According to GaWC [30], it is considered a leading alpha global city, that is the definition given to very important world cities that link major economic regions and states into the world economy. In terms of GDP, it is the third-largest economy in Europe behind Paris and London, but the fastest among the three in terms of growth. Moreover, it is the wealthiest among European non-capital cities [31] and its metropolitan area is considered one of the "Four Motors for Europe".

Considering the information above and that Milan hosts 5,3% of the total Italian population [29], generating 9% of the total value-added of Italy on its own [29], it is acceptable to assume that the province of Milan can be considered as a region for our modelling purpose. Consequently, Model A and Model B are modified to include Milan in the analysis by adding the fictitious region "Milan" respectively as the 21st and 7th region of the models. In this way it is possible to model how the urban area of Milan interacts with the other regions of Italy and with the region "Rest of the World".

The introduction of the sub-region is possible only if there are data about sectoral final demand f, value-added Va, imports m, exports e and total production vector x of Milan with a sectoral disaggregation that is consistent with the data already present in the model. Those data are collected from the Istat database [29], except for the total output x that is a missing data as for the regional case and has to be estimated. The estimation and the reconciliation of the data with the EXIOBASE 3 dataset is performed by following the same procedure used for the regions, described in section 4.1.

For what concerns the sectoral breakdown of data, the Istat database of provinces has an eleven-sector disaggregation, while we need a seventeen-sector disaggregation in order to perform the analysis without lowering the level of detail. The different sectoral breakdown is due to the aggregation of some of the regional sectors; therefore, it is possible to re-disaggregate the provincial data by assuming that the provincial sectors maintain proportionally the characteristics of the regions to which it belongs. More in detail, considering, for example, that the final demand of sector i for Milan is a data given as the aggregation of the respective sector i, j and k at regional level, we use their regional counterparts (Lombardy for Model A and Northern for Model B) to estimate the disaggregation of Milan's final demand sector i into sectors i, j and k:

$$f_i^{Milan} = f_i^{Milan} * \frac{f_i^{Lomb}}{f_i^{Lomb} + f_j^{Lomb} + f_k^{Lomb}} \tag{4.9}$$

This operation is repeated for each sector to estimate also value-added Va, imports m, exports e and total output x. Once all the estimations are done, urban data have to be reconciliated with the EXIOBASE 3 accounting with the same procedure adopted for regional data in section 4.1. In the end, the values of f, Va, m, e and x of Milan are subtracted from the respective items of the region to which they belong, with the aim of extrapolating the urban area from the region and evaluate their inter-linkages.

4.3 Step Three: Estimation of Intraregional Flows

The third and the fourth steps of the building procedure of the Nested MRIO table deal with the estimation of the intermediate flow matrix Z. The diagonal elements of the intraregional matrices Z_{ii}^{rr}, that are the intraregional intrasectoral flows, are estimated through the Simple Location Quotients technique (section 3.2.1). Instead, the extra-diagonal elements of the intraregional matrices Z_{ij}^{rr}, that are the intraregional intersectoral flows, are calculated with the Cross-Industry Quotients technique (section 3.2.1).

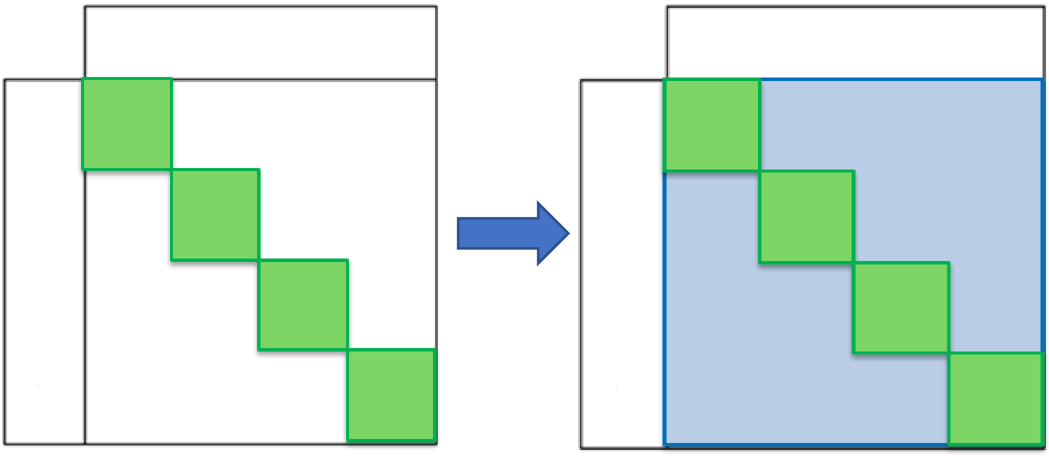


Figure 17. The intermediate flow matrix Z is firstly filled with intragional flows, in green, and then with the estimated interregional flows, in blue.

4.4 Step Four: Estimation of Interregional Flows

The estimation of the interregional flows can be performed by means of the techniques described in section 3.2.2: the Gravity Model and the Cross-Industry Quotients technique applied to a more than two-region case.

The Python script initially allows the user to select which technique to use between the two, then the user has to make a further choice regarding the parameter needed by both the techniques to give a better estimation of the interregional flows between the regions (Figure 18).

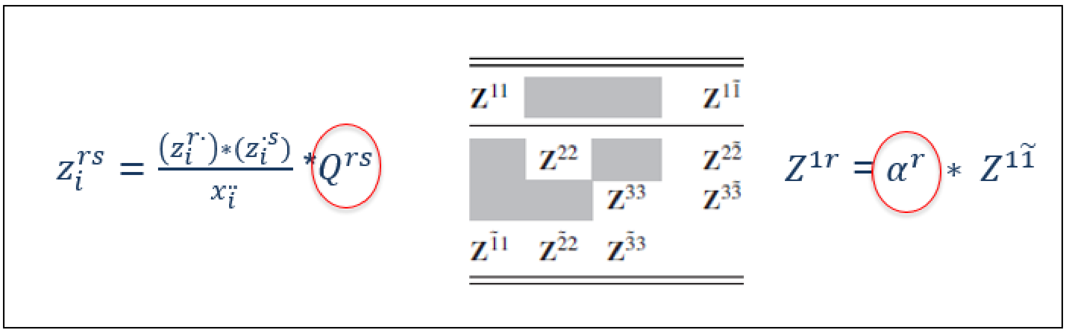


Figure 18. The two terms circled in red are the parameters that need to be estimated. Q^{rs} reshapes the initial allocation of intermediate goods' flow obtained with the modified Gravity model.
The application of the CIQ technique with more than two regions needs a parameter α^r to redistribute the interregional flows directed to the "fictitious regions" $Z^{i\tilde{i}}$ in the grey-shaded elements of the matrix.

According with previous studies of similar topics, the flow of goods between two regions is essentially a function of the demand and the supply of those particular goods in the two regions and in the regions that are close to them. However, the supply and demand curves for each sector are not available and their calculation, that would require survey data, is too expensive in terms of time and costs and probably not so effective in terms of precision. Thus, we need some other measures to represent the commercial relationship between two regions, which should be estimated considering available data.
We have assumed that the level of interconnection between two regions depends mainly on three factors:

- The higher is the number of the citizens living in the regions, the higher is the number of industrial and non-industrial activities that can interact with each other.
- The more is the attitude of the regions to trade, which can be explained by the amount of imports and exports, the more they trade with each other.
- The distance between regions is considered as a deterrent factor for trade.

Consequently, the parameters are calculated taking into account those factors.

Material Flow of Goods

The main assumption of this model is that the monetary flow between two regions is proportional to the material flow
In the Istat database [29] are present data about the amount of generic goods (not sector-specific) that are transported from each region to the others by land or by sea transport. In a model with r regions, there are $r * (r-1)$ region-to-region parameters that are grouped in a square matrix with zeros as diagonal elements. Considering for example Model A, which presents the classic regional division of Italy, the Lombardy-to-Tuscany parameter is calculated as the amount of goods transported from Lombardy to Tuscany, divided for the amount of goods transported from Lombardy to all the Italian regions. Vice versa, the Tuscany-to-Lombardy parameter is calculated as the amount of goods transported from Tuscany to Lombardy, divided for the amount of goods transported from Tuscany to all the Italian regions. Thus, these two parameters can be different and the matrix is not symmetric. The other important characteristic of the matrix is that the sum of the elements is equal to one for each row, therefore this parameter can be used both for gravity model, which allows cross-hauling, and for CIQ technique,

which does not allow cross-hauling and consequently needs sum-one elements for each row.

Openness Index

The Openness Index (OI) is an economic indicator that relates the values of export e^r and import m^r of a region to its Gross Domestic Product (GDP) (4.10).

$$OI = \frac{e^r + m^r}{GDP^r} \tag{4.10}$$

The greater is the index, the greater is the attitude of the region to trade. Therefore, regions with high values of OI are more likely to have strong commercial relationships. The region-to-region parameters will reflect this characteristic and after being calculated as the sum of the Openness Indices of the regions, parameters are grouped in a $r \times r$ square matrix with zero-elements on the diagonal. Considering again Model A, for example, the Lombardy-to-Tuscany and Tuscany-to-Lombardy parameters are both calculated as $OI^{Lombardy} + OI^{Tuscany}$, thus the matrix is symmetric. Moreover, the sum of the row elements differs from one allowing as to apply this parameter just to the Gravity model.

Radiation Model

The Radiation model is a variation of the traditional Gravity model. It was developed by Simini et al. [32] to analyse the mobility and migration patterns of U.S. citizens from one state to another one. The traditional gravity model would have taken into account only the population of the two states and their distance to predict the fluxes between them. However, the Radiation model considers a third factor, that is the presence of "alternatives".

Suppose that there are two couples of regions, A-B and C-D, that have the same distance between each other and the same population. In between of region A and region B there are no regions that have a number of citizens comparable to B. Instead, between region C and region D there is a big region F that has a population larger then D. Thus, the flux from A to B is supposed to be much bigger than the flux from C to D, because people moving from C will be attract mostly by region F. The simple Gravity model would predict the same flows between A-B and C-D, whilst the Radiation model would be able to capture the difference between the two flows and this is why the latter takes account of "alternatives".

In our case the Radiation model is used to calculate the parameter needed by the modified Gravity model. The amount of population living between the regions r

and s is taken into consideration as a deterrent factor to measure the possibility to region r to find other trading partners instead of region s.

$$Q^{rs} = \frac{p^r * p^s}{(p^r + p^s)(p^r + p^s + p^{rs})} \tag{4.11}$$

In the equation (4.11), p^r and p^s stand respectively for the population of region r and region s, whilst the term p^{rs} represents the number of residents in the circle which center is the capital of region r and which radius is the distance between the capital of region r and the capital of region s.

The region-to-region parameters Q^{rs} are gathered in a square matrix with zero-elements on the diagonal. The sum of the elements of each row is not one, thus this modelling of the parameter is not applicable to CIQ technique, but only to the modified Gravity model.

4.5 Step Five: RAS-Balancing of $\boldsymbol{Z}$ and Environmental Extension

After the estimation of the intra and interregional monetary flows, the intermediate flow matrix Z has to be balanced by means of the RAS technique, which is described in section 3.2.3.

Once the matrix is balanced, it is possible to apply the environmental extension of the framework. The traditional analytical methodology is described in section 3.4; however, we have applied some technical modification to the mathematical framework in order to obtain the target results of our study.

The exogenous transaction matrix R gathered from the EXIOBASE 3 dataset [27] accounts for 1077 different types of exogenous resources and wastes directly absorbed or emitted by nations. We have considered 184 of those items and grouped them in 12 categories of emissions to which we are interested in: CO_2, CO, CH_4, HFC, N_2O, NH_3, NO_X, PFC, PM10, PM2.5, SF_6 and SO_X.

For each of these emission categories we have calculated the corresponding kilograms of CO_2 equivalent emissions, according to the Fourth Assessment Report (AR4) about the 100-year time horizon global warming potentials (GWP) relative to CO_2 [33]. Matrix R and, consequently (3.23), matrix b have been vertically mashed, thus becoming two vectors of dimension $1 \times n$.

Since b is a vector, the equation (3.26) has to be modified and b must be diagonalized to obtain the specific embodied exogenous transactions matrix e as a square matrix:

$$e = (\hat{b}L) \quad (4.12)$$

Moreover, as we want to calculate the sectoral and regional carbon footprint (CF), it is necessary to know the amount of CO_2 equivalent embodied in the final demand f of each sector for each region, thus matrix e is multiplied for the final demand vector f (4.13). As for matrix e, we want to obtain a square matrix, so the final demand vector is diagonalized.

$$CF = (\hat{b}L)\hat{f} \quad (4.13)$$

$$CF = \begin{bmatrix} CF_{11} & CF_{1j} & CF_{1n} \\ CF_{j1} & CF_{jj} & CF_{jn} \\ CF_{n1} & CF_{nj} & CF_{nn} \end{bmatrix}$$

The Carbon Footprint matrix can be used to calculate the carbon flows between each sector of each region, as well as the CO_2 equivalent emissions that are embodied in import from and exports to the rest of the world (RoW).

The orange element represents the CO_2 equivalent emissions embodied in the intermediate products that are produced and consumed within the region. The blue terms represent the CO_2 equivalent emissions embodied in the intermediate goods that are produced within the region and consumed outside of the region, while the grey elements represent the CO_2 equivalent emissions embodied in the intermediate products that are produced outside of the region and consumed inside of the region.

Thus, it allows the estimation of the Carbon Footprint both through the Consumption-based Accounting (sum of orange and grey elements) and the Production-based Accounting (sum of orange and blue elements).

4.6 Model implementation in Python Environment

The procedure to build the Environmental Extended Nested Multiregional Input-Output Table, described in the previous paragraphs, is implemented in Python Environment. This approach has been adopted not only because of the flexibility of Python programming language in managing large datasets but also for the availability of Python as an open source software.

The implementation of the model has led to the creation of an interactive Python script able to elaborate the input data, allowing to choose between different sectoral and regional disaggregations and between different estimation methods and coefficients to obtain a set of results with an environmental and economic perspective. Figure 19 reports a schematic representation of the implemented Python script:

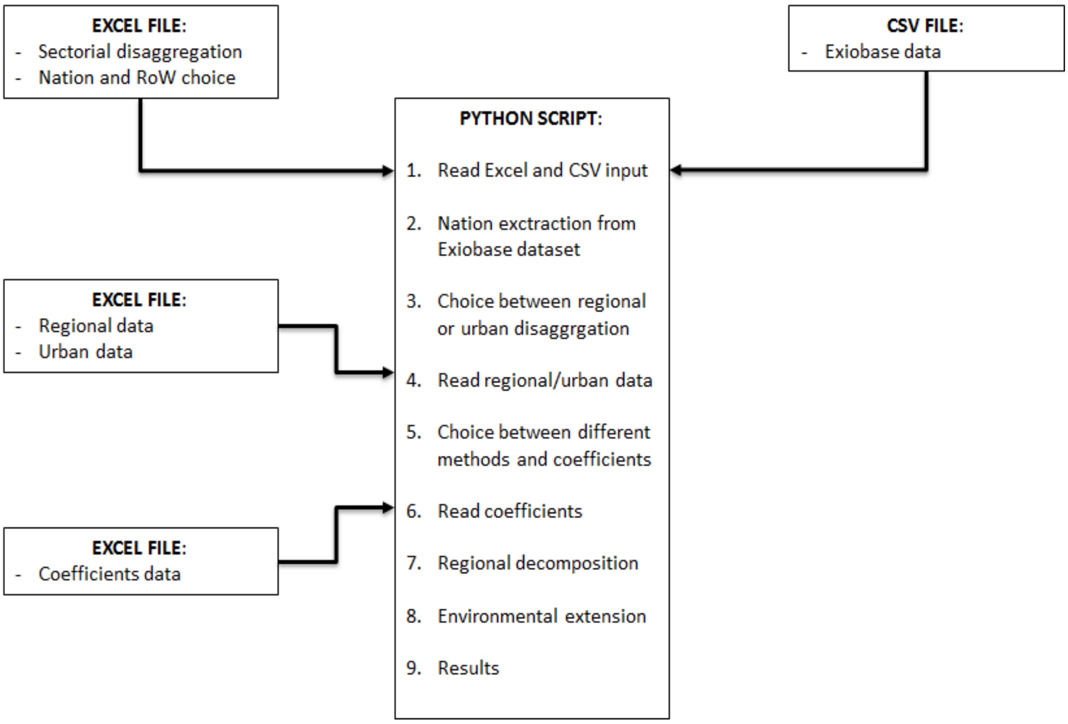


Figure 19. Functional layout of the Python script.

The strength of the script lies in the possibility of adapting the procedure of EE-IOT estimation to all the 44 nations of EXIOBASE 3 dataset, using different levels of sectoral disaggregation and different regional or urban breakdowns, only by modifying the data given as inputs. Thanks to the flexibility of the Input-Output framework to perform both static and dynamic analysis, the Python script is written to obtain both static and dynamic results.

There are several possible configurations of the model with a huge potential number of results. For this reason, it is necessary to concentrate the attention on a specific nation, with a specific regional and sectorial decomposition and on a specific city. As explained in the paragraph 4.1, our work is focused on the regional decomposition of Italy, focusing on the metropolitan area of Milan. All the results obtained through the Python script with different input data and assumption are described and analysed in chapter 5.

5. Results

This chapter aims at illustrating the main outputs of the work, pointing out its main strengths and weaknesses. To satisfy the requirements of the main objectives of the work, this chapter gives a quantitative overview about the following points:

- Verification of results with the respective survey data and comparison of different results with each other
- Modelling of regional and sectoral carbon emissions and estimation of embodied carbon flows between Italian regions and Milan's metropolitan area
- Analysis of Consumption-Based and Production-Based Carbon Footprint at regional, urban and sectoral level
- Assessment of an urban policy for Milan and its environmental and economic impact

5.1 Verification of results

The first step of the analysis of results is their verification through the comparison of the estimated values with the respective survey data to assess the quality of the main hypothesis and assumptions.

For what concerns regional total output vector x and regional input coefficients b, their verification goes hand in hand and can be done by taking advantage of the Istat database, which includes the regional direct CO_2 emissions. Since the results of the regional direct CO_2 emissions obtained by the model are directly proportional (3.24) to the regional total output vector x and the regional input coefficients b, their comparison with the Istat survey data can assess the goodness of our assumptions. Figures 20 and 21 represent the differences in the value of direct CO_2 emissions at regional level between the data taken from Istat database and the results obtained by our two models (A and B).

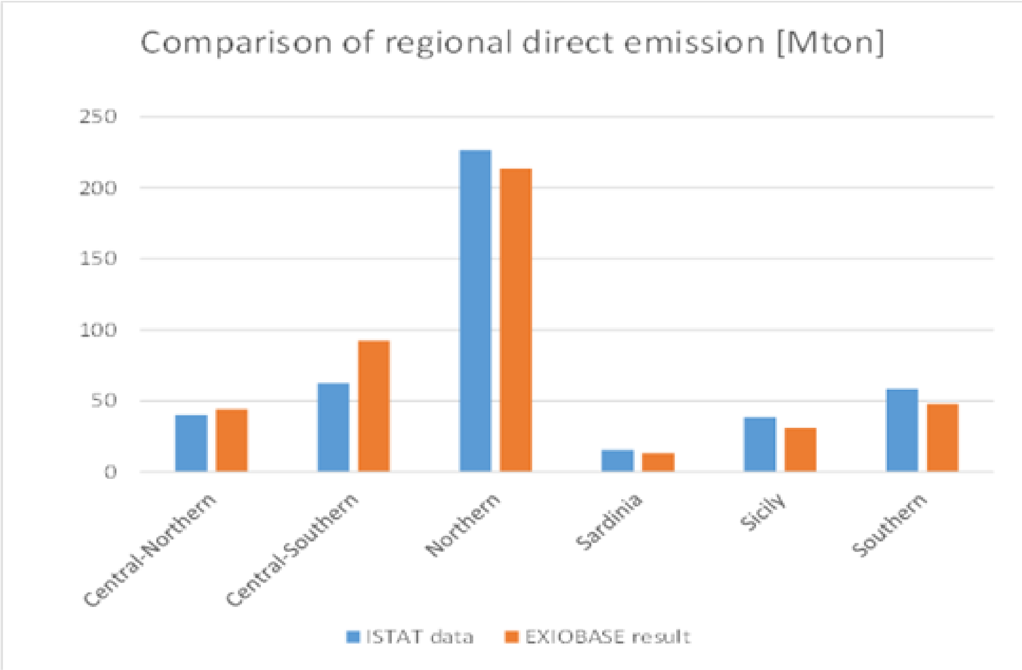


Figure 20. Comparison between regional direct CO_2 emissions obtained by model B and the ones of the Istat database.

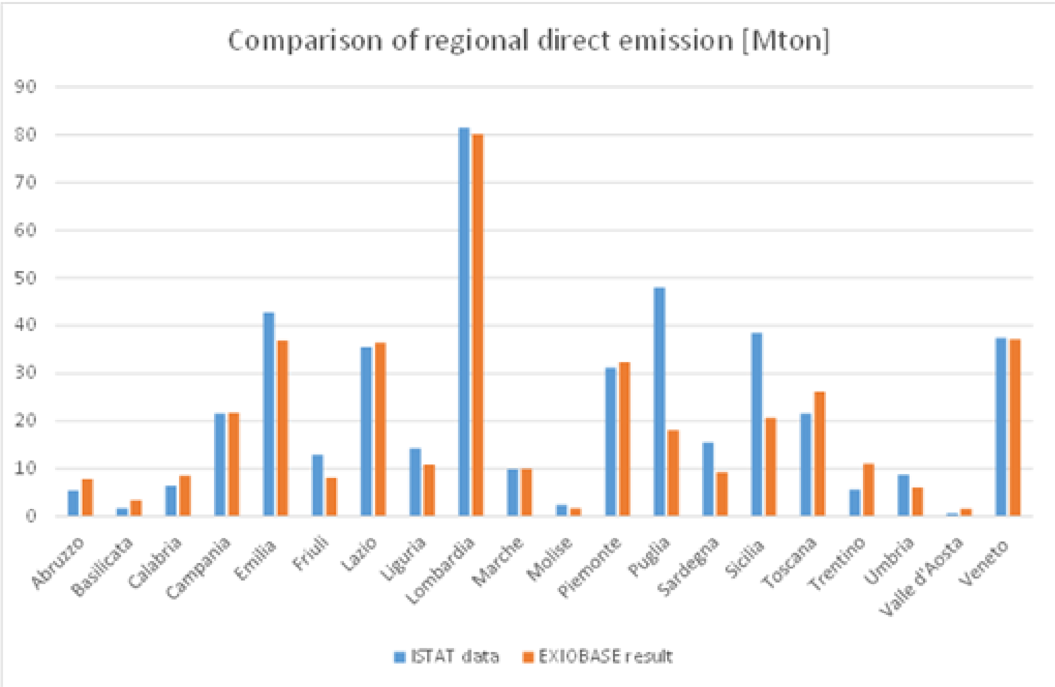


Figure 21. Comparison between regional direct CO_2 emissions obtained by model A and the ones of the Istat database.

The results are similar for more or less all the regions for both models, but there are some inconsistencies in few regions for model A (Apulia, Sicily and Sardinia) and in "Central-Southern" region for model B. The high discrepancy of the values can be traced back to the territorial peculiarity of the regions, indeed Sicily and Sardinia are two islands with particular and specific production activities and technologies. This similarity between Istat data and the results of the models guarantees the consistency of the estimation procedure for regional total production x and the assumption regarding regional input coefficients b.

On the other hand, survey data about interregional and intersectoral carbon (or even monetary) flows are poor or totally inexistent, making it impossible to perform a comparison of the results regarding interregional flows z_{ij}. Considering that, at the time of writing, this is the first Nested Multiregional Input-Output model applied to Italy, it is also impossible to make a comparison of the results about interregional carbon flows with other previous studies.

In order to evaluate the mutual consistency between the different methodologies and parameters applied to calculate the interregional carbon flows, all the possible regional results that can be obtained from the Python script are reported in figures 22 and 23 to understand if they are similar or not.

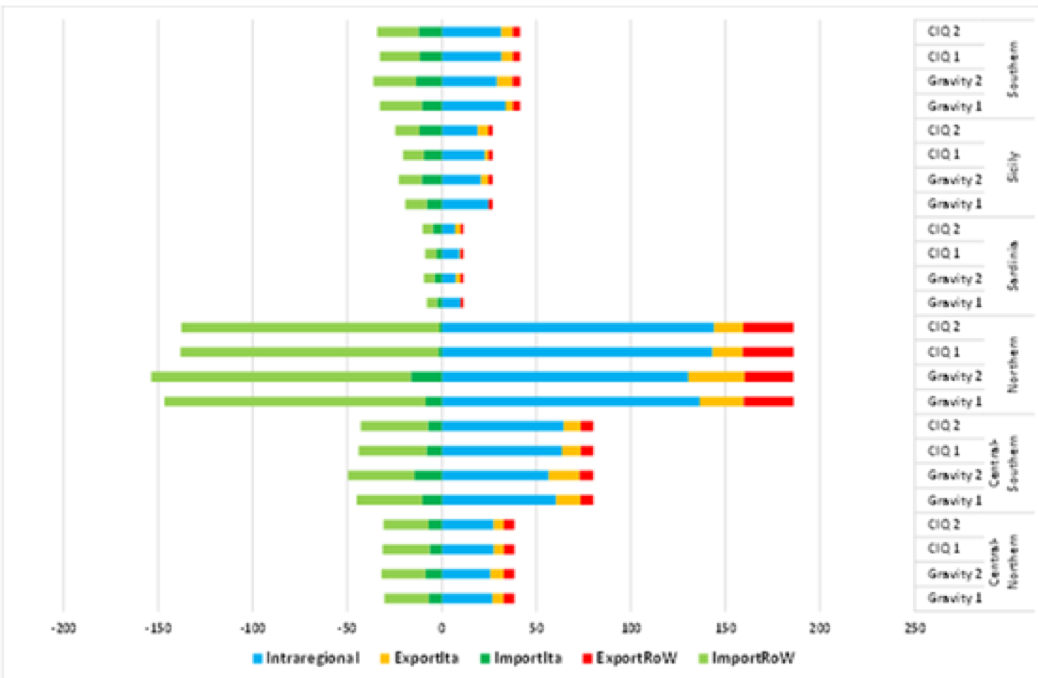


Figure 22. Comparison of Mton of CO_2 emissions embodied in the flows of products for 6 regions for the four possible configurations of model B.

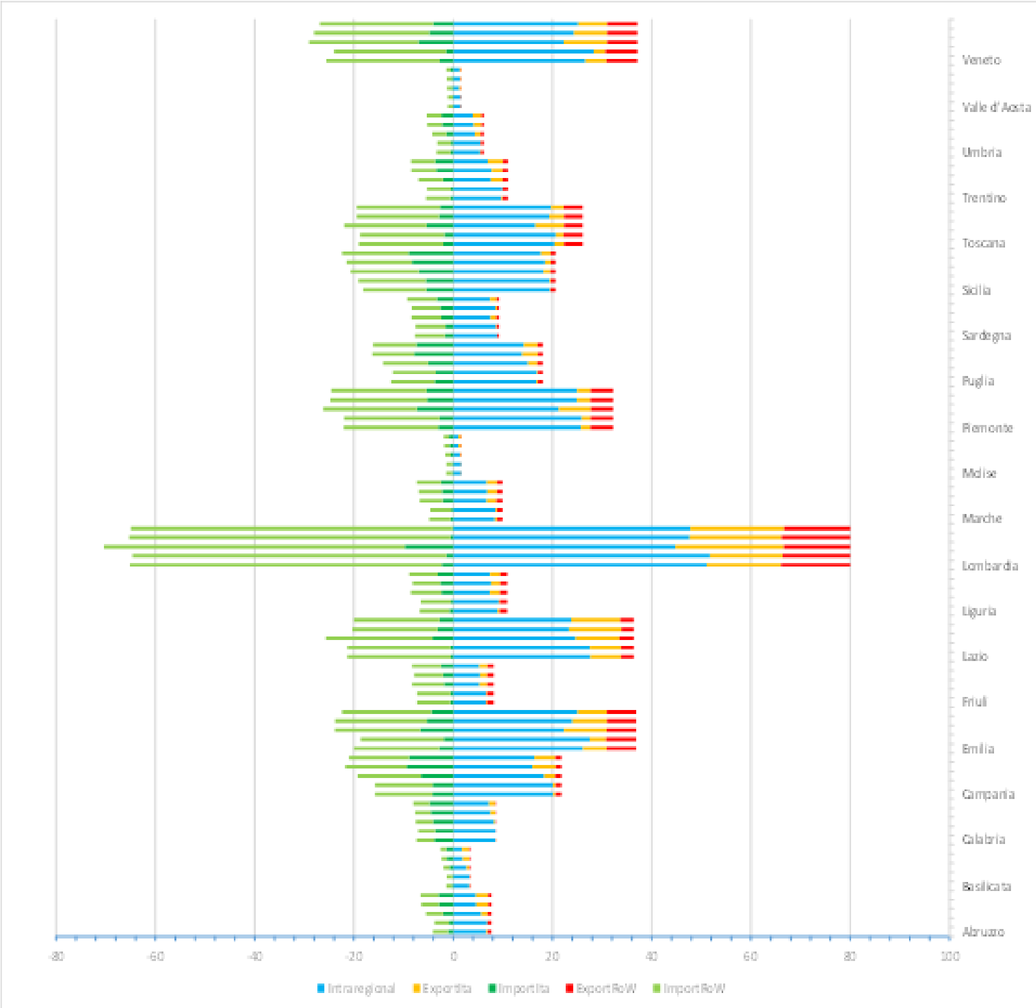


Figure 23. Comparison of Mton of CO_2 emissions embodied in the flows of products for 20 regions for the five possible configurations of model A.

Figure 22 and 23 report the carbon embodied emissions of different regions by dividing them into five components:

- Intraregional: carbon emission embodied in goods that are produced into the region to satisfy the final demand of the same region.
- Export Ita: carbon emission embodied in goods that are produced into the region to satisfy the final demand of the other Italian regions.
- Import Ita: carbon emission embodied in the goods produced into the others Italian regions to satisfy the regional final demand.

- Export RoW: carbon emission embodied in the goods produced into the region to satisfy the final demand of the rest of the world.
- Import RoW: carbon emission embodied in the goods produced into the rest of the world to satisfy the regional final demand.

From figures 22 and 23, it is clear that the values of the carbon emissions obtained using different methodologies and parameters are very similar both considering the Carbon Footprint of each region and the values of intraregional, exported and imported carbon emissions. The high level of similarity indicates that all the different methodologies converge towards one solution and that they are consistent with each other. For the sake of brevity, the consistency of the different models permits us to report the results considering only the gravity model with the parameter obtained by means of the material flow of goods.

The same comparative reporting is applied to the results of the production system of Milan's metropolitan area and, also in the case of urban scaling, the different methodologies converge towards similar results (figure 24 and 25).

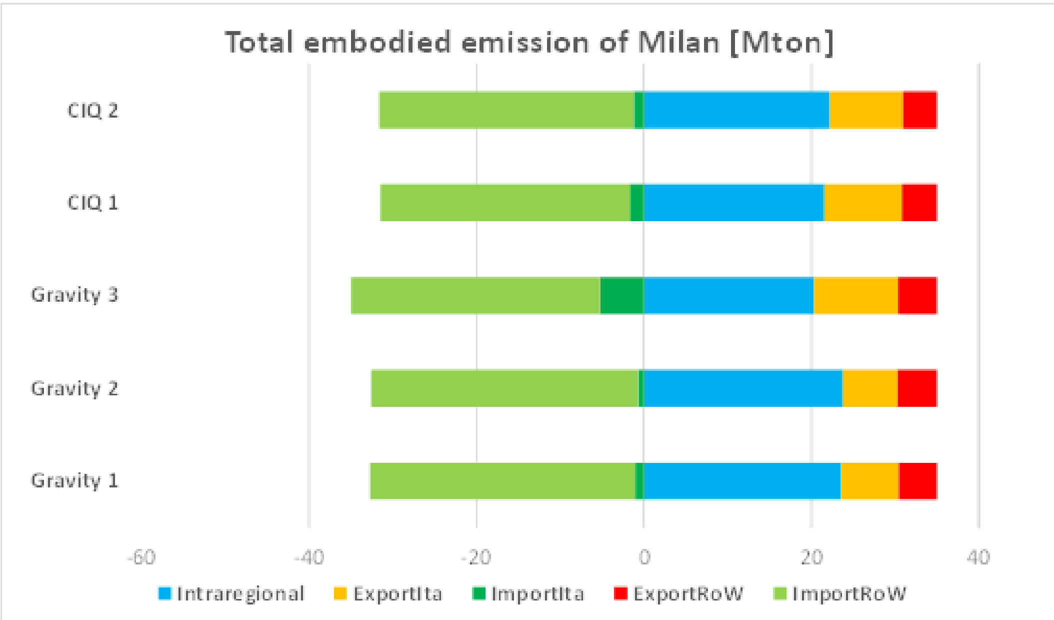


Figure 24. Comparison of Mton of CO_2 emissions embodied in the flows of products for Milan for the five possible configurations of model A.

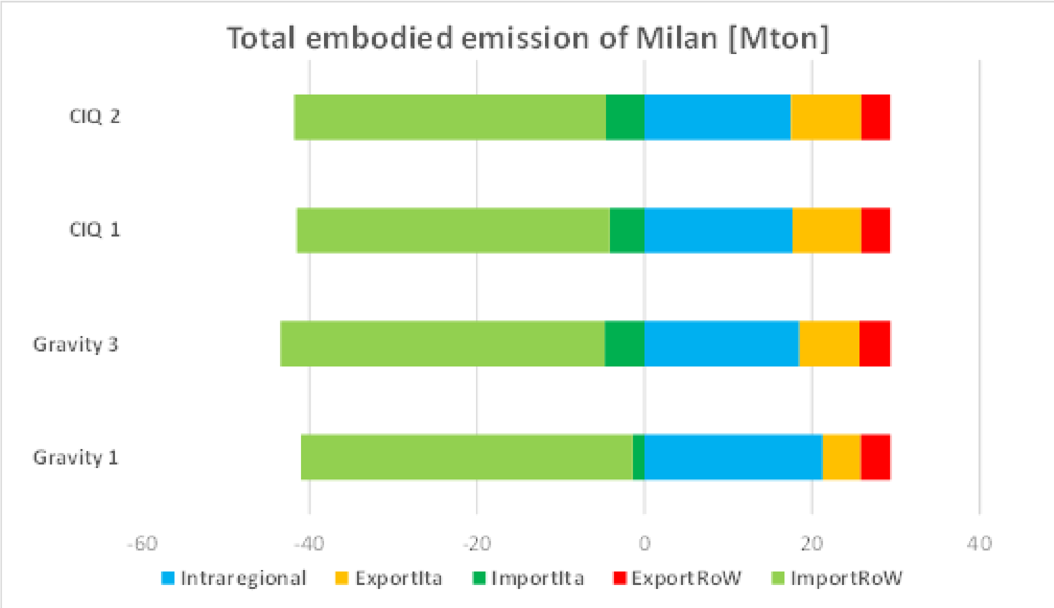


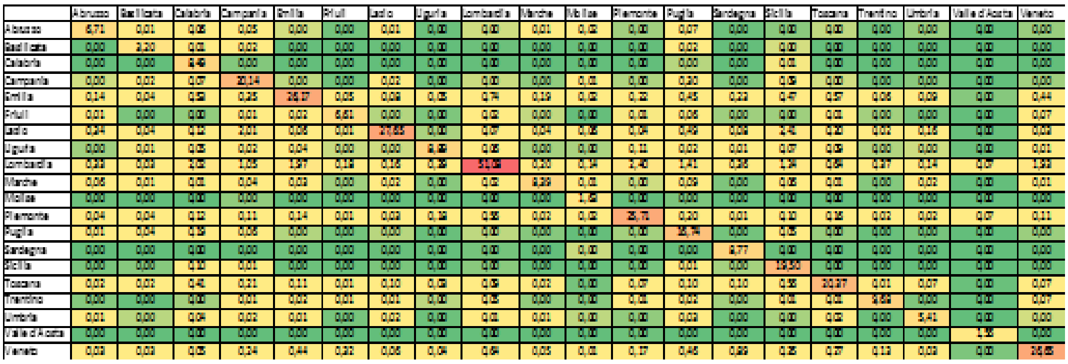
Figure 25. Comparison of Mton of CO_2 emissions embodied in the flows of products for Milan for the five possible configurations of model B.

5.2 Regional and sectoral Carbon Footprint

Heat maps are an efficient way to visualize intra- and interregional carbon flows. Figures 26 and 27 show the respective heat maps of the carbon flows expressed in Mton of CO_2 equivalent for model A and model B. The intensity of the flows is represented using a relative color scale that goes from green (low intensity) to red (high intensity).

region	Central-Northern	Central-Southern	Northern	Sardinia	Sicily	Southern
Central-Northern	26,80	1,39	3,43	0,08	0,52	0,55
Central-Southern	1,02	60,46	4,07	0,09	2,79	4,84
Northern	5,66	7,26	136,31	2,18	3,45	4,96
Sardinia	0,00	0,00	0,03	9,88	0,00	0,03
Sicily	0,01	0,07	0,05	0,01	24,58	0,12
Southern	0,13	1,55	0,99	0,02	1,20	33,68

Figure 26. Heat-map of intra- and interregional carbon flows for model B. Values are expressed in Mton of CO_2 equivalent.



	Abruzzo	Basilicata	Calabria	Campania	Emilia	Friuli	Lazio	Liguria	Lombardia	Marche	Molise	Piemonte	Puglia	Sardegna	Sicilia	Toscana	Trentino	Umbria	Valle d'Aosta	Veneto
Abruzzo	6,71	0,01	0,06	0,05	0,00	0,00	0,01	0,00	0,00	0,01	0,02	0,00	0,07	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Basilicata	0,00	2,20	0,01	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Calabria	0,00	0,00	8,49	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,00
Campania	0,00	0,02	0,07	20,14	0,00	0,00	0,02	0,00	0,00	0,00	0,01	0,00	0,20	0,00	0,09	0,00	0,00	0,00	0,00	0,00
Emilia	0,14	0,04	0,58	0,25	26,17	0,05	0,08	0,05	0,74	0,19	0,02	0,22	0,45	0,22	0,47	0,57	0,06	0,09	0,00	0,44
Friuli	0,01	0,00	0,00	0,01	0,02	6,61	0,00	0,00	0,02	0,00	0,00	0,01	0,06	0,00	0,00	0,01	0,00	0,00	0,00	0,07
Lazio	0,24	0,04	0,12	2,01	0,08	0,01	27,65	0,00	0,07	0,04	0,06	0,04	0,49	0,08	2,41	0,20	0,02	0,16	0,00	0,03
Liguria	0,00	0,01	0,05	0,02	0,04	0,00	0,00	6,89	0,06	0,00	0,00	0,11	0,02	0,01	0,07	0,09	0,00	0,00	0,00	0,01
Lombardia	0,23	0,03	2,08	1,05	1,97	0,18	0,16	0,39	51,08	0,20	0,14	2,40	1,41	0,26	1,34	0,84	0,37	0,14	0,07	1,33
Marche	0,06	0,01	0,01	0,04	0,03	0,00	0,02	0,00	0,02	8,28	0,01	0,00	0,09	0,00	0,06	0,01	0,00	0,02	0,00	0,01
Molise	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,69	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Piemonte	0,04	0,04	0,12	0,11	0,14	0,01	0,03	0,19	0,58	0,02	0,02	25,71	0,20	0,01	0,10	0,16	0,02	0,02	0,07	0,11
Puglia	0,01	0,04	0,19	0,06	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	16,74	0,00	0,05	0,00	0,00	0,00	0,00	0,00
Sardegna	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	6,77	0,00	0,00	0,00	0,00	0,00	0,00
Sicilia	0,00	0,00	0,10	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	19,50	0,00	0,00	0,00	0,00	0,00
Toscana	0,02	0,02	0,41	0,21	0,11	0,01	0,10	0,03	0,09	0,02	0,00	0,07	0,10	0,10	0,58	20,27	0,01	0,07	0,00	0,07
Trentino	0,00	0,00	0,00	0,01	0,02	0,01	0,01	0,00	0,05	0,00	0,00	0,01	0,02	0,00	0,01	0,01	8,68	0,00	0,00	0,07
Umbria	0,01	0,00	0,04	0,02	0,01	0,00	0,02	0,00	0,01	0,01	0,00	0,00	0,03	0,00	0,00	0,03	0,00	5,41	0,00	0,00
Valle d'Aosta	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,58	0,00
Veneto	0,03	0,03	0,05	0,24	0,44	0,22	0,06	0,04	0,69	0,05	0,01	0,17	0,46	0,69	0,26	0,27	0,13	0,03	0,00	26,65

Figure 27. Heat-map of intra- and interregional carbon flows for model A. Values are expressed in Mton of CO_2 equivalent.

The elements on the main diagonal are the intraregional carbon flows, while the extra-diagonal elements represent the interregional carbon flows. In particular, considering a generic region r, the column values are the carbon flows entering inside region r to satisfy its final demand and the row values are the carbon flows outgoing from region r to satisfy the final demand of other regions. Therefore, we can calculate if a region is a net importer or exporter of CO_2 in the Italian context (Table 1 and 3) and in the international context (Table 2 and 4). A region is a net importer of CO_2 when the sum of entering carbon flows is higher than the sum of the outgoing flows, vice versa it is a net exporter.

REGION	Gravity 1	Gravity 3	CIQ 1	CIQ 2	
Central-Northern	-0,86	-1,48	-1,00	-1,50	CO_2 IMPORTER
Central-Southern	2,52	1,85	2,02	1,70	CO_2 EXPORTER
Northern	14,95	13,23	14,29	14,35	CO_2 EXPORTER
Sardinia	-2,30	-1,41	-2,10	-1,71	CO_2 IMPORTER
Sicily	-7,70	-6,73	-7,33	-6,30	CO_2 IMPORTER
Southern	-6,61	-5,47	-5,88	-6,54	CO_2 IMPORTER

Table 1. Net CO_2 importers and exporters in the Italian context for model B.

Considering the model B, the Northern and the Central-Southern regions turn out to be net exporters (considering only the Italian intra-national flows), though the others are net importer. The result is coherent with the production structure of

Italian economy, in which the larger part of goods and services are produced in the northern regions and consumed throughout the country. All these products carry a CO_2 embodied emission, which can be calculated and evaluated only adopting an analytical structure able to account for them, as a MRIO model.

The situation is completely different considering the international flows, indeed all the regions become net importers, due to the fact that imported products from the rest of the world (RoW region) have a higher level of embodied emissions due to the lower level of the average productive technologies around the world with respect to Italy.

REGION	Gravity 1	Gravity 3	CIQ 1	CIQ 2	
Central-Northern	-18,75	-19,21	-20,56	-19,86	CO_2 IMPORTER
Central-Southern	-25,37	-26,17	-27,37	-27,28	CO_2 IMPORTER
Northern	-97,07	-98,16	-95,35	-95,62	CO_2 IMPORTER
Sardinia	-6,57	-5,58	-6,92	-5,77	CO_2 IMPORTER
Sicily	-16,84	-16,55	-16,29	-16,79	CO_2 IMPORTER
Southern	-25,05	-23,86	-23,14	-24,39	CO_2 IMPORTER

Table 2. Net CO_2 importers and exporters in the international context for model B.

Considering model A, the situation is similar: there are four main net CO_2 exporter regions (Lombardy, Lazio, Veneto and Emilia-Romagna) while the others are all net CO_2 importer regions.

REGION	Gravity 1	Gravity 2	Gravity 3	CIQ 1	CIQ 2	
Abruzzo	-0,76	-0,76	-0,76	-0,44	-0,52	CO_2 IMPORTER
Basilicata	-0,26	-0,23	-0,21	0,14	0,04	CO_2 EXPORTER
Calabria	-3,77	-3,65	-3,86	-3,57	-3,47	CO_2 IMPORTER
Campania	-3,68	-3,55	-4,28	-4,63	-4,60	CO_2 IMPORTER
Emilia	1,84	1,33	2,00	1,65	1,44	CO_2 EXPORTER
Friuli	-0,38	-0,40	-0,32	-0,61	-0,78	CO_2 IMPORTER

Lazio	5,67	5,75	4,54	7,39	7,08	CO_2 EXPORTER
Liguria	-0,19	-0,19	-0,22	-0,82	-1,03	CO_2 IMPORTER
Lombardy	12,76	13,24	12,11	18,04	18,73	CO_2 EXPORTER
Marche	-0,14	-0,15	-0,18	-0,35	-0,41	CO_2 IMPORTER
Molise	-0,29	-0,28	-0,33	-0,13	-0,24	CO_2 IMPORTER
Piedmont	-1,08	-1,01	-0,83	-2,52	-2,73	CO_2 IMPORTER
Puglia	-3,36	-3,21	-3,11	-4,66	-4,62	CO_2 IMPORTER
Sardinia	-1,68	-1,42	-1,21	-2,28	-1,98	CO_2 IMPORTER
Sicily	-5,29	-5,28	-5,60	-7,10	-7,00	CO_2 IMPORTER
Tuscany	0,02	-0,25	0,42	0,18	-0,15	CO_2 IMPORTER
Trentino	-0,37	-0,46	0,24	-1,29	-0,63	CO_2 IMPORTER
Umbria	-0,34	-0,38	-0,11	-0,69	-0,63	CO_2 IMPORTER
Valle d'Aosta	-0,14	-0,14	0,02	-0,19	-0,26	CO_2 IMPORTER
Veneto	1,45	1,03	1,69	1,88	1,77	CO_2 EXPORTER

Table 3. Net CO_2 importers and exporters in the Italian context for model A.

After the evaluation of the interconnections between Italian regions and their role in the "Italian carbon map", the analysis of the system moves to a deeper assessment of the composition of regional Carbon Footprint.
The total CO_2 embodied emissions do not allow a significant comparison between regions that are very different in terms of size and population, for this reason, figure 28, 29, 30 and 31 show the specific Carbon Footprint of regions. The first is calculated as the total CO_2 embodied emissions of region divided by its value added to understand how many CO_2 emissions are produced to obtain one million euros of value added. The second specific quantity is calculated as the total CO_2 embodied emissions of region divided by the regional population, in this way it is possible to evaluate how much the final demand of each citizen influences the carbon emissions of the region.

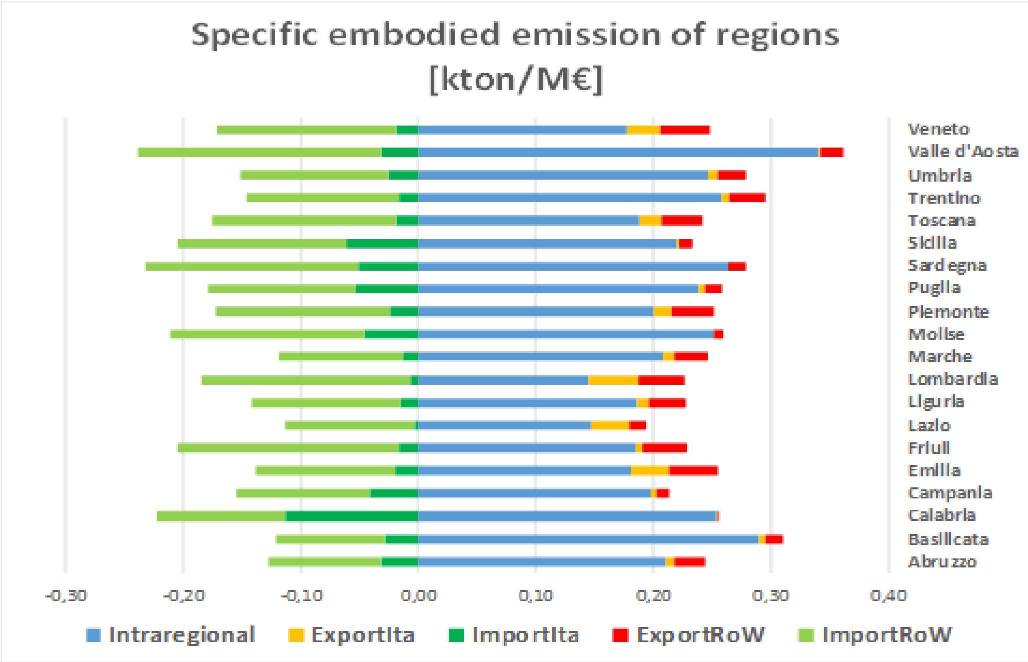


Figure 28. Specific embodied CO_2 emissions of region for model A. The values are expressed in kton per M€ of value-added.

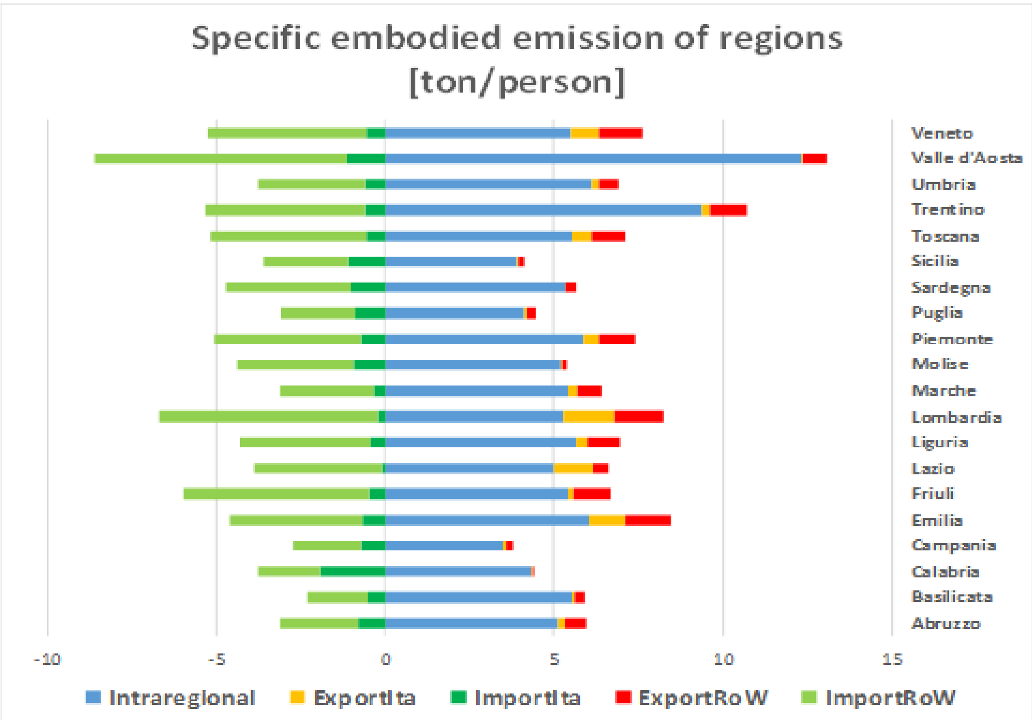


Figure 29. Specific embodied CO_2 emissions of region for model A. The values are expressed in ton per resident.

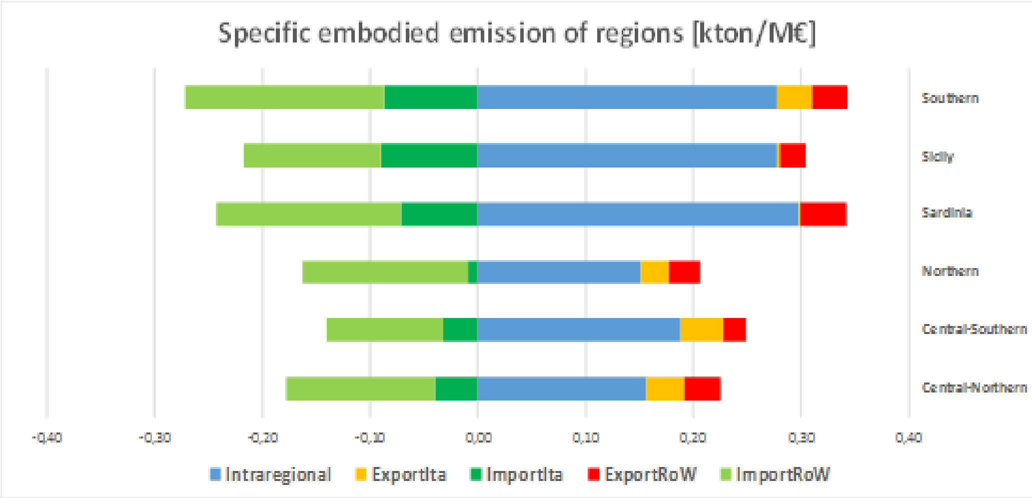


Figure 30. Specific embodied CO_2 emissions of region for model B. The values are expressed in kton per M€ of value-added.

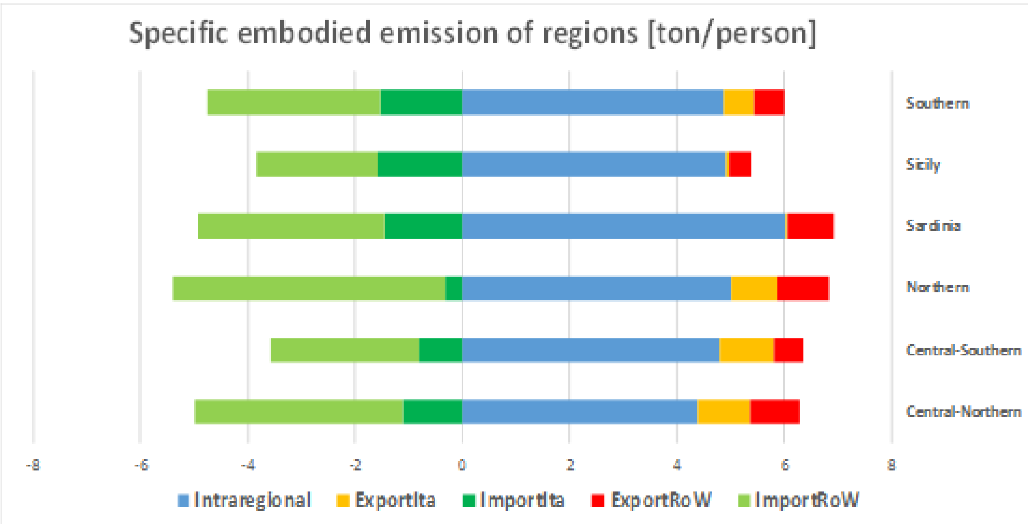


Figure 31. Specific embodied CO_2 emissions of region for model B. The values are expressed in ton per resident.

Considering these results, the 20-region model is the most significant to make a comparison of regional characteristics, thanks to its high level of territorial disaggregation. The analysis of the results points out that Valle d'Aosta is the region with the higher level of specific embodied carbon emissions, while Lombardy, which presents the highest total embodied emissions when considering absolute values, turns out to have low specific carbon emissions.

As explained in previous chapters, Carbon Footprint is usually calculated considering two different logics: Production-Based Accounting (PBA) and Consumption-Based Accounting (CBA). The PBA-Carbon Footprint is the sum of Intraregional, Export Ita and Export RoW carbon emission components, whilst the CBA-Carbon Footprint is the sum of Intraregional, Import Ita and Import RoW carbon emission components. From the previous charts it is possible to calculate both these values for all the regions. For example the PBA-Carbon Footprint of Lombardy is 80,05 Mton of CO_2 equivalent emissions and the CBA-Carbon Footprint is 115,14 Mton of CO_2 equivalent emissions.
The high difference of the reported values, once again, illustrates the importance of using an Input-Output model to study indirect emissions instead of evaluating only direct emissions. All the Italian regions have a CBA-carbon footprint higher than the PBA-carbon footprint, due to the fact that, in an international context, Italian regions are net importers of CO_2, as already shown in table 2.

The analysis of the regional Carbon Footprint is not complete; indeed the Python script permits a further step of disaggregation to evaluate the regional Carbon Footprint at sectoral level and understand which are the most carbon-intensive sectors. In figure 32 is reported, for brevity, only the regional sectoral Carbon Footprint of the Northern region of model B, but this result is obtainable for each region of each model. The region's choice is based on the crucial role of environmental impact of Northern region in the Italian context, while the model's choice is based on the number of higher number of sectors of model B.

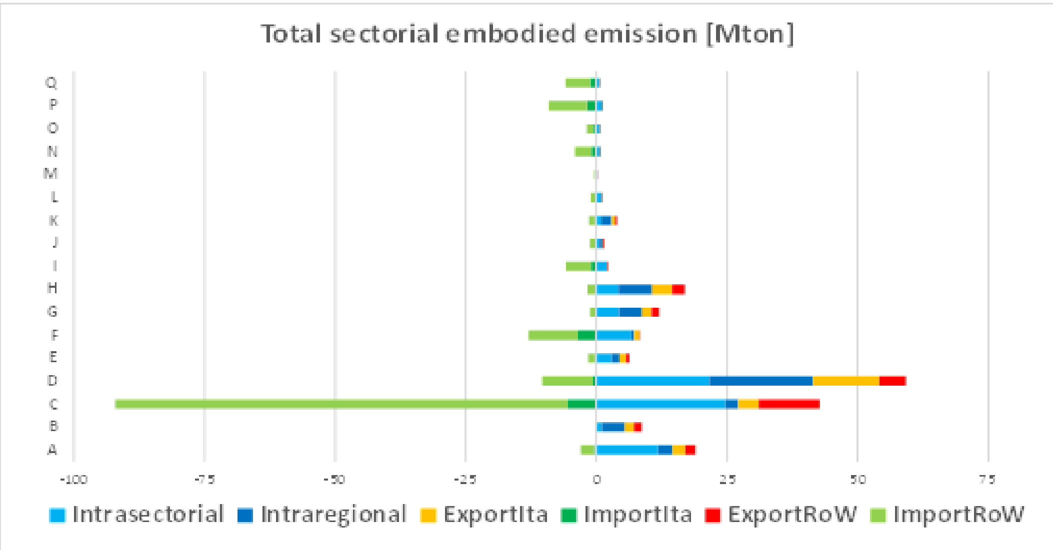


Figure 32. Sectoral CO_2 embodied emissions for Northern region (model B).

Sectoral difference between CBA-Carbon Footprint and PBA-Carbon Footprint is even more emphasized. For example, sector C ("manufacture") has a value of CBA-Carbon Footprint that is more than double of the value of PBA-Carbon Footprint. On the contrary sector H ("transport and warehousing") has a value of CBA-Carbon Footprint lower than the value of PBA-Carbon Footprint. This type of analysis provides quantitative results to policy-makers for a sectoral specific intervention.

The Carbon Footprint is not the only meaningful value of emission obtainable with the environmental extension of the Multiregional Input-Output model, indeed EXIOBASE 3 dataset contains information about other types of resources, wastes and emissions. Thus, it is possible to calculate specific and total sectorial embodied emissions for other pollutants as shown in equation (4.11). The elements of e represent the specific embodied resources/wastes directly and indirectly related to the production of one unit of final demand of each sector and the element of E represent the total embodied resources/wastes directly and indirectly related to the production of the entire final demand for each sector.

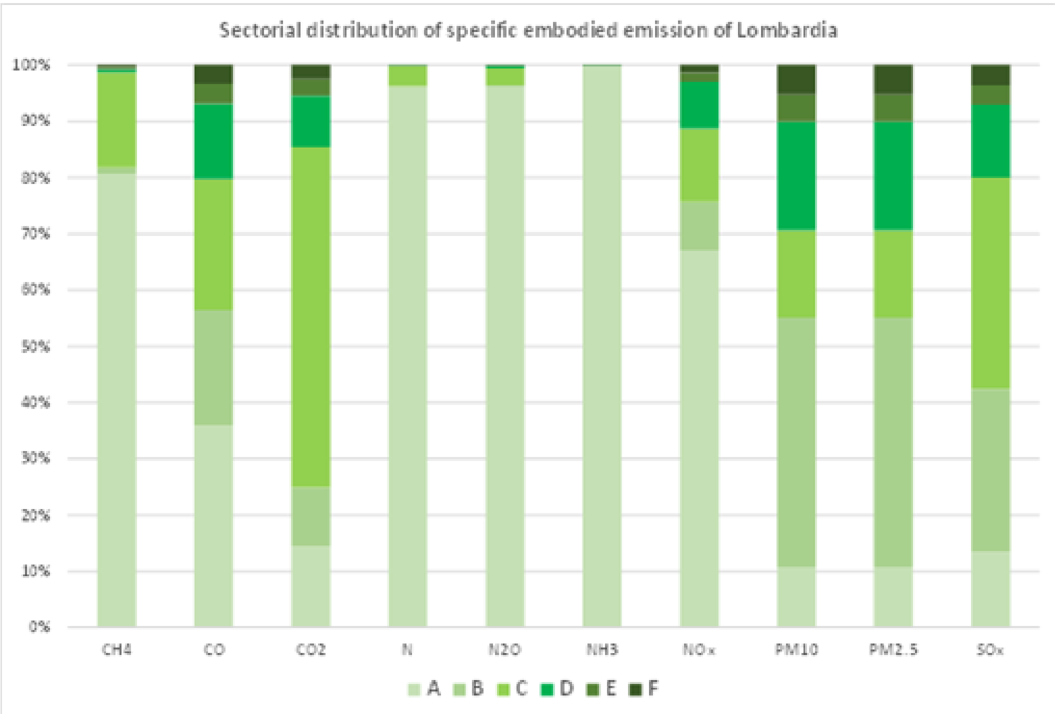


Figure 33. Percentage of specific embodied sectoral emissions for ten pollutants for region Lombardy in model A.

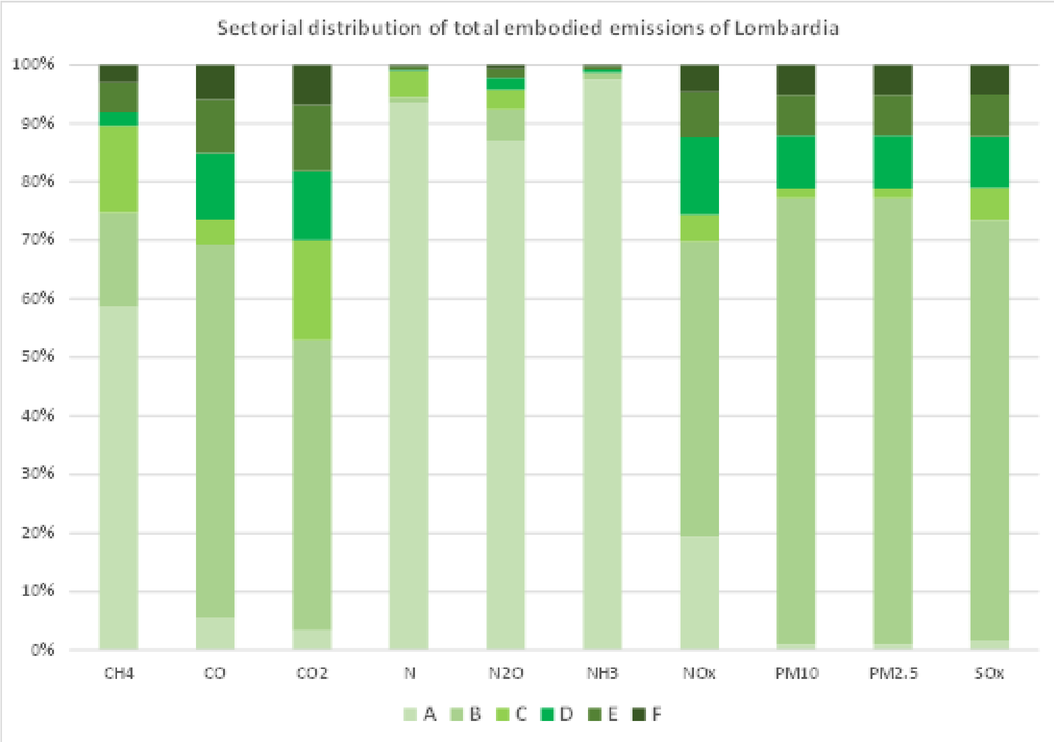


Figure 34. Percentage of total embodied sectoral emissions for ten pollutants for region Lombardy in model A.

The difference between the two figures is evident and it underlines the reason why it is important to consider both specific and total values when analyzing sectoral emissions. For example, considering the particular matters the total embodied emission of sector C ("Supply and Wastes") is more or less null, while the specific emission is more than 15% of the sum of all sectors.

5.3 Milan Carbon Footprint

The focus of the study is on the metropolitan area of Milan and about the difference between the hypothesis and the methods used in scaling and creating the Environmental Extended Multiregional Input-Output Table of Milan. As explained in the first paragraph of this chapter, the number of possible applications and results of the Python script are huge. For the sake of clarity, figure 35 shows only three possible results concerning the total embodied emission of metropolitan area of Milan. The underlying assumption of the three models are:

- CASE A: application of CIQ method using the material flow coefficient for the 20 regions model, scaling the Milan's data from Lombardy.

- CASE B: application of CIQ method using the material flow coefficient for the 6 regions model, scaling the Milan's data from Northern region.

- CASE C: application of CIQ method directly on Italy creating a simple model of 3 regions (Milan, Rest of Italy and Rest of the World).

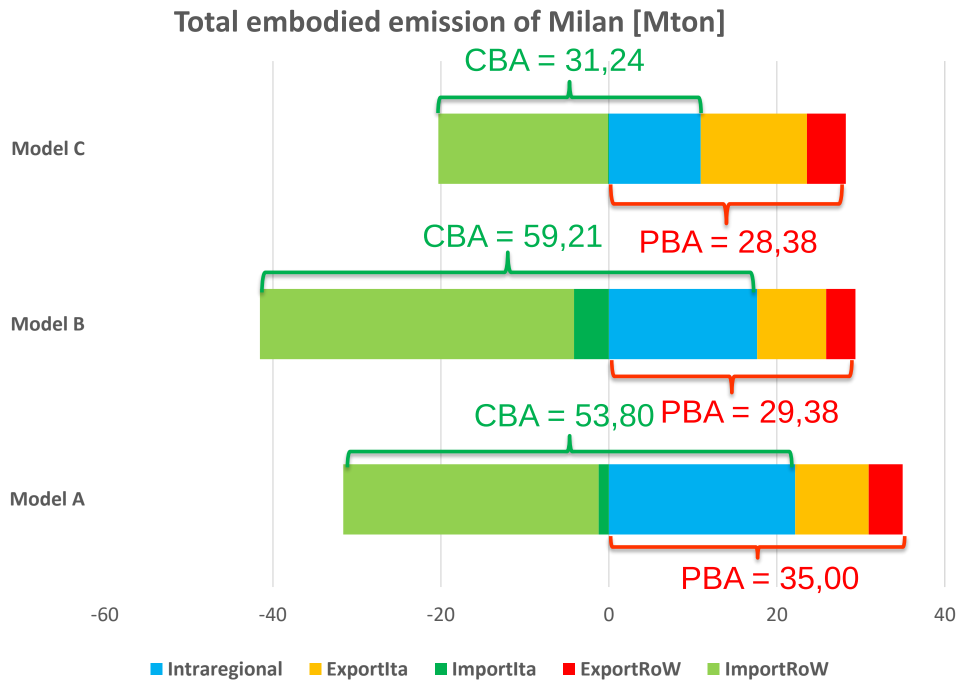


Figure 35. Carbon Footprint of Milan calculated with three different scaling-steps.

These results are very meaningful, thus they show how an intermediate scaling of Italy into regions and an extraction of Milan from region, completely differ from the direct extraction of Milan from Italy. Due to the absence of survey data or previous works regarding interregional carbon flows of Italy, it is impossible to know the correct result among the reported ones, but it is clear that Case 3 underestimate the emissions embodied in import from Rest of Italy and Rest of the World. On the other hand, Case 1 and Case 2 are better aligned with the expected results and with the real structure of Milan's productive system, indeed according to Wiedmann et al. [12] the majority of metropolitan cities have a consumption-based carbon footprint higher than the production-based carbon footprint.

As previously done for the regions, it is possible to calculate the CO_2 embodied emissions in each sector of the production system of the city. In the following figures are reported both the total and value-added specific sectoral embodied carbon emissions of Milan obtained for model B and model C, that are comparable (same number of sectors).

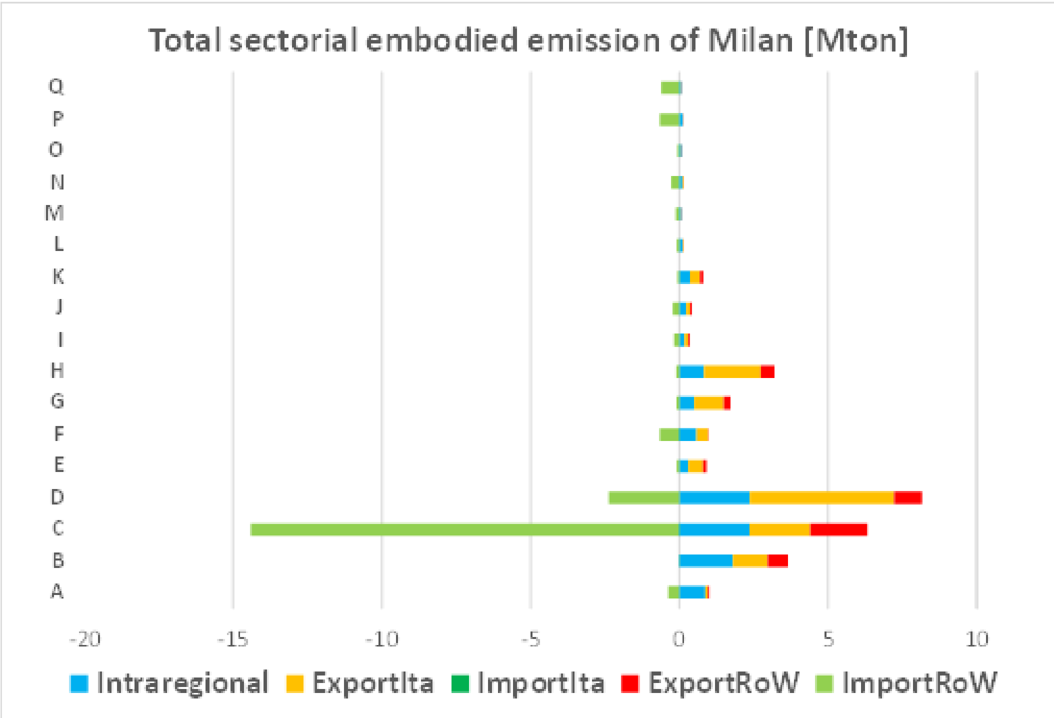


Figure 36. Total sectoral embodied carbon emissions of Milan for model C. Values are expressed in Mton.

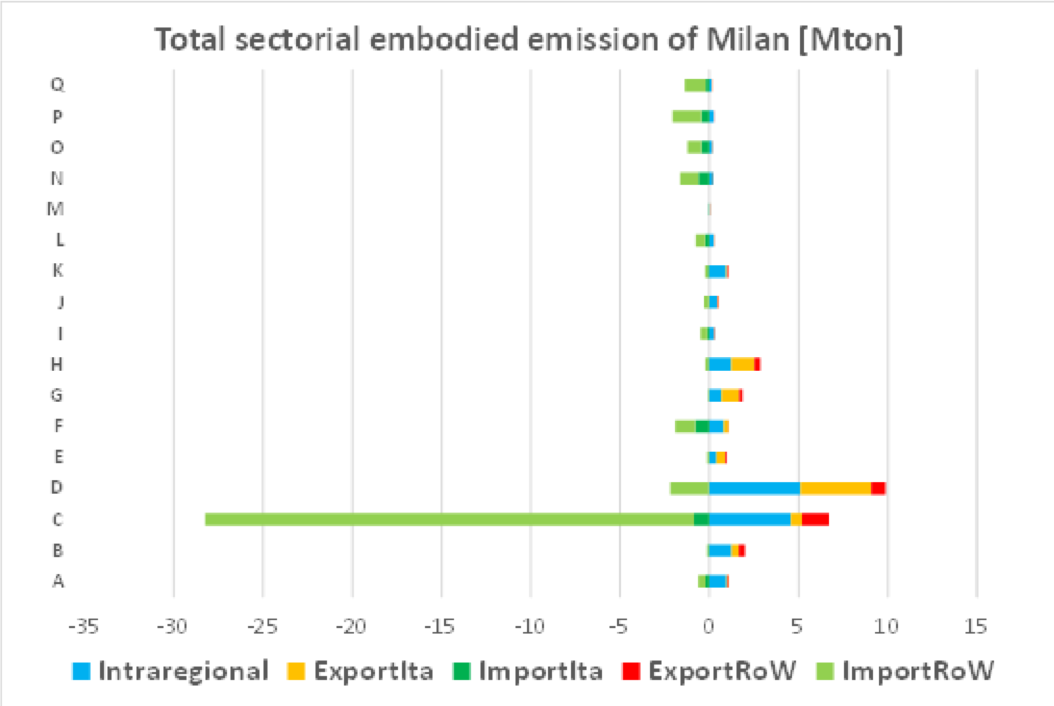


Figure 37. Total sectoral embodied carbon emissions of Milan for model B. Values are expressed in Mton.

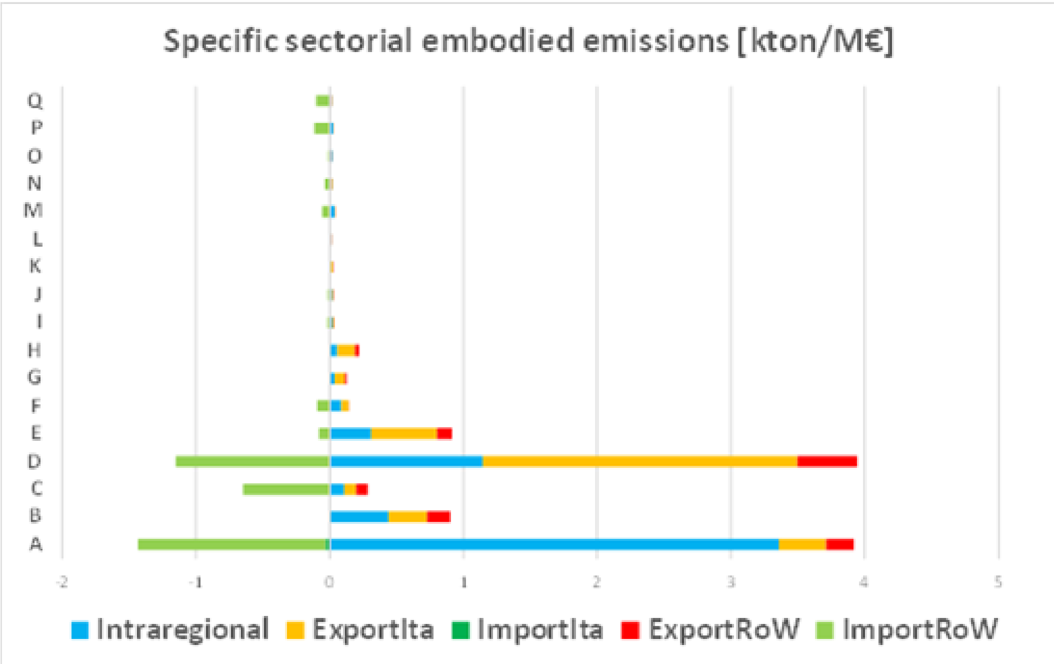


Figure 38. Specific sectoral embodied carbon emissions of Milan for model C. Values are expressed in kton per M€ of value-added.

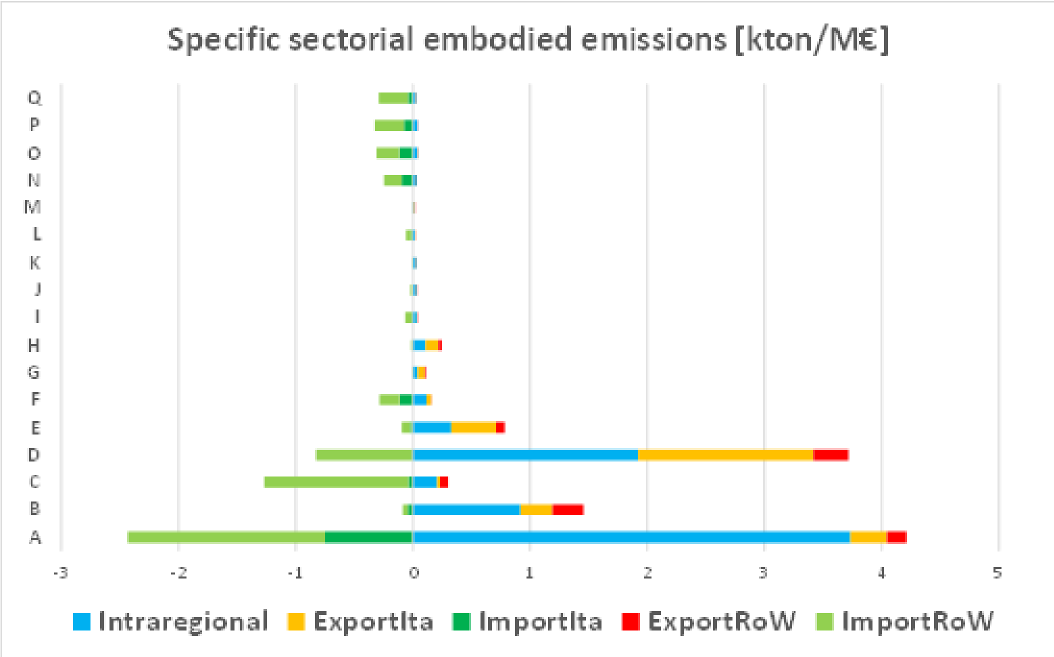


Figure 39. Specific sectoral embodied carbon emissions of Milan for model B. Values are expressed in kton per M€ of value-added.

In conclusion, the implemented tool permits to calculate a large amount of results about the Carbon Footprint at national, regional and urban level, deepening to the sectoral interconnections. Moreover, changing input data, other types of embodied resources and wastes, as well as the structure of other nations, can be estimated.
The following and last chapter of this manuscript explores another possible use of this tool. Indeed, varying the input data in the table, it is possible to simulate national, regional or urban policies and assess their economic and environmental impact at different spatial and sectoral levels.

5.4 Policy assessment

The objective of the paragraph is to identify and analyse the impact associated to the application of the policy concerning the spread of green roofs in the metropolitan area of Milan. This policy assessment is an exemplification of a possible usage of the implemented model and represents one of the scopes of the entire work.

5.4.1 Introduction

Green roof is the name that indicates the roof of a building partially or completely covered with vegetation and a growing medium, planted over a waterproof membrane. Green roofs have been shown to be an excellent technical, economic and environmental solution for energy efficiency of buildings, water management and elimination of heat islands in cities [34], [35]. In particular, energy efficiency and water management are crucial national and international targets in the fight for climate change, therefore it is essential to study the effectiveness of these actions at different spatial levels with an appropriate tool.

The green roofs policy has been included in the new PGT ("Piano di Governo del Territorio") compiled by Comune di Milano and it aims at developing and introducing tax benefits and economic incentives to innovative and performant energy-efficient solutions.

Since 2013 Comune di Milano has developed an analysis of the possible installation sites, thanks to the European project Decumanus, directed by the West England University and by the Spanish society Idra in cooperation with the German space agency Dlr. The analysis pointed out that the hypothetical installable surface is about 13 million square meters, considering the geometrical characteristics of the roofs of Milan's buildings.

In this scenario, the policy assessment is based on a shock analysis, which considers a change in the final demand due to designing, procurement and installation of 1 million square meters of green roofs in the metropolitan area of Milan. The objective is to evaluate the total production change and the total embodied carbon footprint variation due to the new final demand. Moreover, with these data of new production and new carbon footprint, it is possible to provide quantitative estimations to policy-makers, that will evaluate if the policy is effective or not, considering the potential benefits and the expenditures related to the installations of green roofs. The obtained results can be useful also to compare the impact of different policies and to find which can be the best solution considering not only the potential benefits but also the environmental and economic expenditure of the policy.

5.4.2 Shock Analysis

The implemented shock is based on the three following hypotheses:

1. Lack of supply-side constraints on labor, energy or other resources
2. Fixed production technologies (Technical, Leontief and value-added coefficients remains constant)
3. Final demand changes with fixed returns to scale

The change of the final demand can be computed considering a market price value for the turnkey installation of one square meter of green rooftop. The price is strongly influenced by the typology of the installation, the thickness of the green coverage, the geometrical characteristics of the roofs, thus it varies from 35 €/m^2 to 200 €/m^2. The best solution is to consider a mean value which is estimated to be 100 €/m^2 and is comprehensive of all the tangible and intangible goods needed.

The implemented Nested Multiregional Input-Output model allows to distribute the estimated change in final demand both among sectors and regions, therefore is possible to study the impact of the installation on all the production sectors of all the regions of the model. Therefore, is important to use a model with a good level of regional and sectoral disaggregation. The best solution is Model B, which is composed by six regions and seventeen sectors. The sectoral distribution of the costs is summarized in the following table:

Sector Name (Code)	Specific Costs	Change of Final Demand
Agriculture, forestry and fishing (A)	25 €/m2	25 M€
Manufacturing (C)	17 €/m2	17 M€
Construction (F)	15 €/m2	15 M€
Transport and Warehousing (H)	8 €/m2	8 M€
Professional, scientific and technical activities (N)	35 €/m2	35 M€

Table 4. Sectoral distribution of specific and total costs associated to the application of the policy.

The regional distribution of the costs is analysed for three different cases:

Sector Name (Code)	Case 1	Case 2	Case 3
Agriculture, forestry and fishing (A)	Northern	Northern	Milan
Manufacturing (C)	RoW	Northern	Milan
Construction (F)	Northern	Northern	Milan
Transport and Warehousing (H)	Northern	Northern	Milan
Professional, scientific and technical activities (N)	Milan	Milan	Milan

Table 5. Possible regional distributions of the costs associated to the application of the policy.

Three cases are analysed to point out how the origin of final demand supply can influence the environmental and economic impact of the green roofs policy.
The first case is focused on external supply, indeed the entire final demand supply comes from outside of Milan except for sector “Professional, scientific and technical activities”. This sector is one of the excellences of Milan production system and so is correct to consider that designing, structural calculations and engineering are made internally. The final demand of the other sectors is supplied by the “Northern” region, while the supply of manufacture sector comes from the region “Rest of the World”. The second case is similar to the first and is focused on external supply, but it considers that the “Northern” region is able to provide all the necessary external final demand supply. The last case assumes that all the sectoral final demand supplies come from inside the metropolitan area of Milan; this case is the most unlikely, but it is useful to understand if and how the policy can boost the better supply plan.

Once evaluated the final demand change, it is possible to apply the shock analysis. A variation of the final demand implies a change of the total production level.

$$x_1 - x_0 = [(I - A_0)^{-1} f_1] - [(I - A_0)^{-1} f_0] = (I - A_0)^{-1}(f_1 - f_0) \quad (5.1)$$

The shock does not affect the production technology, indeed the technical coefficients matrix does not change ($A_1 = A_0$). Consequently, a total production variation determines an increase or decrease of value added (factors of production) and of exogenous resources or wastes directly consumed or produced.

$$Va_1 - Va_0 = v_0\hat{x}_1 - v_0\hat{x}_0 = v_0(\hat{x}_1 - \hat{x}_0) \quad (5.2)$$

$$R_1 - R_0 = B_0\hat{x}_1 - B_0\hat{x}_0 = B_0(\hat{x}_1 - \hat{x}_0) \quad (5.3)$$

As for technical coefficients matrix, value added coefficients vector and input coefficients matrix are the same before and after the shock (v_1=v_0, $B_1 = B_0$). Therefore, a variation of the final demand level has an impact on the exogenous resources directly and indirectly consumed in order to satisfy the final demand.

$$CF_1 = (\hat{b}_0 L_0)\hat{f}_1 \quad (5.4)$$

Once performed the shock analysis, the different regional distribution assumed in the three cases for the variation of the final demand influences the results, both at global and local level. In table 6 are reported the total production and carbon flow variation of the system for the three different cases.

	Total production variation (M€)	Carbon flow variation (kton)
CASE 1	203,46	57,73
CASE 2	195,54	46,52
CASE 3	219,48	57,12

Table 6. Total production and carbon flow variations in case 1, 2 and 3.

The reported results are not enough to evaluate the effect of the policy on the metropolitan area of Milan; for this reason it is necessary to evaluate both the economic and environmental impact at a sectorial and local level. The economic impact is considered by taking into account the variation of Milan's value added caused by the change in final demand for all the seventeen sectors. Instead, the environmental impact is considered taking into account the variation of consumption-based carbon footprint for all the production sectors of Milan.

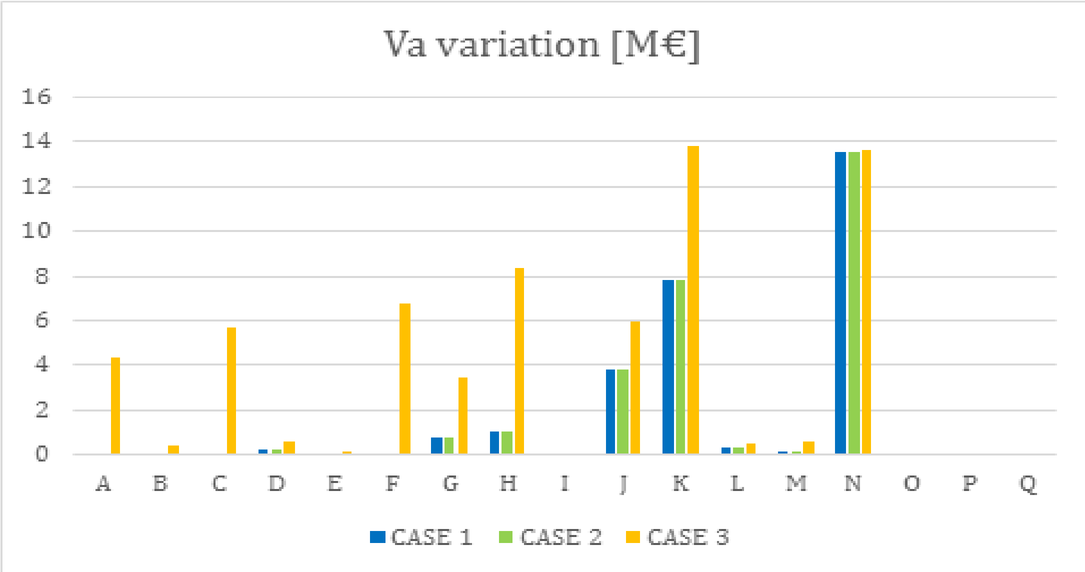


Figure 40. Variation of the sectoral value added of Milan in the three cases. Values are expressed in M€.

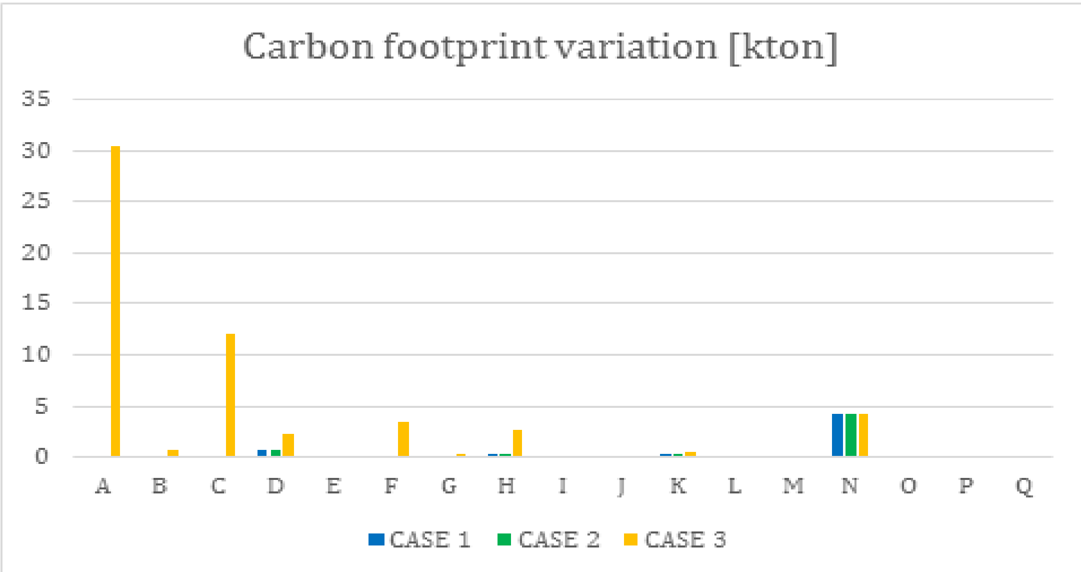


Figure 41. Variation of the sectoral Carbon Footprint of Milan in the three cases. Values are expressed in kton.

The results are very different and strongly influenced by the different hypothesis on which the cases are based. To obtain a better and useful visualization of the results, a specific multidimensional indicator is calculated as the ratio of Carbon Footprint variation and value added for all the sectors.

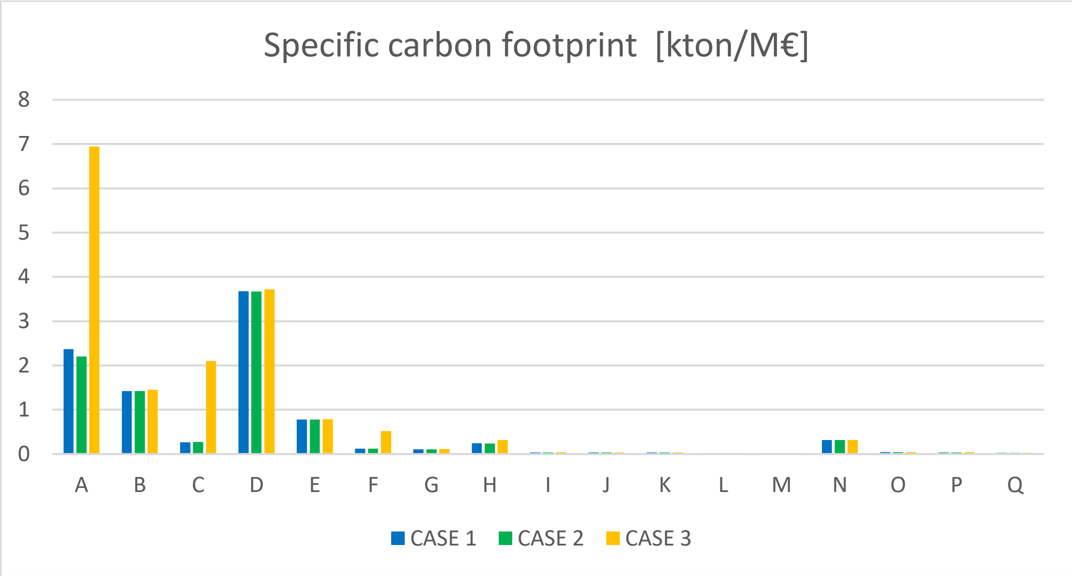


Figure 42. Variation of specific sectoral Carbon Footprint of Milan in the three cases. Values are expressed in kton per M€.

From figure 42 and table 6, it is possible to understand that, between the three hypothetical regional distribution of final demand variation, the second case, in which the final demand is allocated in the "Northern" region, is the less impacting at environmental level and benefits also of a good economic return. The obtained result is coherent with the characteristic of the "Northern" region production system, indeed its level of technological development and efficiency is higher than the international average.

In conclusion, the policy assessment illustrates the environmental and economic impact of the installation of 1 million square meter of green roof in the metropolitan area of Milan. The analysis points out that the best solution for that kind of installation is the CASE 2, with a low range import scheme. For this solution, the total carbon flow variation of the system is 46,52 kton of CO2 equivalent and the specific carbon footprint, at urban sectorial level, maintains the lower value among the three cases. With these results, the policy-makers have a first quantitative assessment to evaluate the effectiveness of the policy considering the potential future benefits and the estimated impact related to the installations of green roofs.

The green roof policy assessment is an example of the possible application of the model and can be further improved with more specific and precise data about final demand variation, but also with a comparison of that policy with other policies with similar purpose to evaluate the best solution between them.

Conclusions

The environmental impact of urban areas is becoming an important issue due to the worldwide growing urbanization trend and the central economic, social and environmental role that cities play. In this context, the understanding and the representation of the urban system complexity is the first key point to implement a specific and effective set of measures. For this reason, it is important to characterize the material and monetary flows entering/exiting into urban area, how they are transformed by different economic activities and how they impact on the environment through their consumption of resources and generation of wastes. Indeed, current local and urban global warming mitigation actions have mainly focused the attention within the jurisdictional boundaries, while the results clearly show how the main sources of carbon emission are outside the local boundaries. The particular structure of the cities implies the necessity of considering a consumption-based accounting (CBA) for the calculation of the Carbon Footprint in addition to a production-based accounting (PBA). In order to implement effective environmental policies, local governments need to recognize that a number of local activities have environmental consequences outside of the local jurisdictions. Considering the CBA perspective, it is possible to study and implement proper and effective policies to reduce the carbon emissions of cities.

The literature review performed in this study points out that the most suitable and used method able to capture all dimensions and sectors of the urban metabolism is the Input-Output Analysis. For this reason, the central purpose of our work is the creation of an Environmental Extended Multiregional Input-Output model, through the scaling of national Input-Output Tables at a regional and urban level.

The implemented model applies well-established methodologies of scaling to describe the urban metabolism of Milan’s metropolitan area and evaluate its economic and environmental interactions with all the Italian regions. The procedure and its application to Italy and Milan’s metropolitan area represents an innovation and a starting point for future developments. For this reason, we have implemented the model using an open source programming language, as Python, and using only public database, thus the procedure is replicable and applicable to other regions or cities and it can be used to account different resources consumption or pollutant emissions.

Considering the regional level, the model points out how the totality of the Italian regions are net importer of embodied carbon emissions, indeed the CBA Carbon Footprint is higher than the PBA Carbon Footprint. These results should induce national policy-makers to address the attention of their policies towards the consumption side rather than the production side.

Considering the urban level, it is interesting to compare the three different scaling procedure for the modeling of Milan's metabolism. The first key aspect is the difference between the two-steps scaling procedures (CASE A and CASE B) presented in paragraph 5.3 and the direct scaling of Milan's data from Italy (CASE C). The urban CBA and PBA Carbon Footprint changes accordingly to the applied procedure, in particular CASE C strongly underestimates the CBA Carbon Footprint (31,24 Mton of CO2 equivalent), while in the others two scaling procedures the resulting values are higher (59,21 Mton of CO2 equivalent for CASE B and 53,80 Mton of CO2 equivalent for CASE A). For this reason, the direct scaling procedure should be avoided in the implementation of urban metabolism model in which the external inputs play a key role, as widely demonstrated in the literature. Comparing the two-step procedures, CASE B maintains a higher sectoral disaggregation at urban level, allowing a more detailed analysis of the sectoral embodied carbon emissions. The sectoral analysis of embodied carbon emission points out that the most important sources of emissions for Milan's metropolitan area are sector C (Manufacture), sector D (Electricity, steam and air conditioning supply) and sector H (Transport and warehousing) considering the total value of Mton of CO2 equivalent, while, considering the specific value of emission for M€ of value added, the most important sources of emission are sector A (Agriculture), sector D (Electricity, steam and air conditioning supply) and sector E (Water supply, drainage, waste treatment).

In the end, the green roof policy assessment is an example of how the model can be useful not only for attributive analysis but also for consequential analysis. The Input-Output framework gives the possibility of performing a shock analysis to evaluate the effects of policies and structural changes. This can be the starting point of future applications and developments of our work, indeed the implemented model offers a number of possible applications to other policy assessments.

The main issue of the model is the absence, or the incompleteness, of regional and local data about sectoral total production and embodied emissions. The further development and implementation of the proposed procedure goes through the usage of new and more detailed local and sectoral data, which would enhance the completeness and the meaningfulness of the analysis of urban and regional activities. Another possible development of the model is the extension of the analysis to other forms of footprint, for example considering the land or water usage. This new development of the model can be useful for policymakers to balance their intervention considering the trade-off between social, economic and multi-perspective environmental impact.

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Appendix A

Regional and sectorial disaggregation of Model A

Region	Sector Code	Sector Name
Abruzzo	A	Agriculture
Basilicata	B	Industry and post-industry
Calabria	C	Supplies and Wastes
Campania	D	Construction
Emilia-Romagna	E	Service
Friuli-Venezia Giulia	F	Activities
Lazio		
Liguria		
Lombardia		
Marche		
Molise		
Piemonte		
Puglia		
Sardegna		
Sicilia		
Toscana		
Trentino Alto Adige		
Umbria		
Valle d'Aosta		
Veneto		
Rest of the World		

Regional and sectorial disaggregation of Model B

Region Name	Corresponding region	Sector Code	Sector Name
Northern	Emilia-Romagna	A	Agriculture
	Friuli-Venezia Giulia	B	Mining and quarrying
	Liguria	C	Manufacture
	Lombardia	D	Electricity, steam and air conditioning supply
	Piemonte	E	Water supply, drainage, waste treatement and reclamation
	Trentino Alto Adige	F	Construction
	Valle d'Aosta	G	Wholesole and retail, car and motorbike maintenance
	Veneto	H	Transport and warehousing
Central-Northern	Marche	I	Lodging and catering
	Toscana	J	Information and communication activities
	Umbria	K	Financial and insurance activities
Central-Southern	Abruzzo	L	Real Estate activities
	Campania	M	Professional and scientific activities
	Lazio	N	Public amministration and defence
Sardinia	Sardegna	O	Education
Sicily	Sicilia	P	Healthcare and social assistance
Southern	Basilicata	Q	Artistic activities, entratainment and other activities
	Calabria		
	Molise		
	Puglia		
Rest of the World	All contries expect Italy		