TESE DE DOUTORAMENTO

DEVELOPING AN INTEGRATED FRAMEWORK TO QUANTIFY SUSTAINABILIY INDICATORS IN THE CONTEXT OF URBAN SYSTEMS

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Prof. Gumersindo Feijoo Costa e Dra. Sara González García

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Abstract

The exponential growth suffered by the global population in recent decades and the current consumption system are two factors responsible for the main environmental problems such as climate change or the overexploitation of natural resources. Hence, it is necessary to take measures and actions in line with sustainable development, to cushion these environmental impacts. Bearing in mind that cities concentrate more than 50% of the world's population, and it is estimated that it will continue to grow in the next decades, urban systems play an essential role in sustainable development. Consequently, the main objective of this thesis is to develop methodologies to quantify the sustainability of urban systems and identify the main deficiencies.

Accordingly, in the first Section, two environmental methodologies that are Life Cycle Assessment (LCA) and Environmentally Extended Input-Output Analysis (EEIOA) were applied and adapted to different case studies. First, the environmental profile of the municipality of Madrid was analyzed through LCA. Second, the carbon footprint (CF) of the city of Cádiz was evaluated by comparing the LCA and EEIOA methodologies. Finally, the CF was determined by means of EEIOA for the cities of Bilbao, Madrid, Santiago de Compostela and Seville and results when compared with those from LCA.

However, within the concept of sustainability of urban systems, social and economic variables must also be considered. For this reason, in the second Section a methodology was developed to analyze the sustainability of urban systems through an index based on a three-letters label, which is the result of the aggregation of social, economic and environmental indicators. This methodology was applied first in 64 municipalities in the region of Galicia (northwest of Spain) and then, in 31 Spanish cities. One of the main challenges in this field of research is the selection of a manageable number of indicators. Hence, from the case study with 31 Spanish cities, the three key indicators that define a city as sustainable were identified. Accordingly, a method was developed to quantify the sustainability of a city using only three indicators but with a high degree of accuracy.

One of the main functions of a city or an urban system is to maintain the quality of life of its citizens. However, some factors such as tourism can affect the way of life. For this reason, considering socio-economic indicators, an assessment method was developed to quantify the impact that tourism creates on the way of life of citizens in a city with a historical heritage. Therefore, the relationship of residents with visitors in Santiago de Compostela was analyzed through a sustainability score.

The methodologies developed in this thesis aim to highlight the main challenges that must be considered to improve the sustainability of an urban system. In this way, help policy makers to take action and create more effective actions to achieve a more sustainable future.

Keywords: Sustainable City; Urban Systems; Life Cycle Assessment; Environmentally Extended Input-Output Analysis; Sustainable Development Indicators; Urban Metabolism.

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Abbreviations and acronyms

AAE	Andalusia Energy Agency
AHP	Analytic Hierarchy Process
ANEFA	National Association of Aggregates Manufacturers
ANFEVI	National Association of Glass Container Manufacturers
BOD_5	Biological Oxygen Demand
BPIA	Bank of Environmental Public Indicators
CART	Classification and Regression Trees
Cat.	Category
CF	Carbon Footprint
CI	Composite Indicator
COD	Chemical Oxygen Demand
Cod.	Code
Cult.	Cultural
DF	Downscaling Factor
EC	European Commission
EEA	Environmental European Agency
EEIOA	Environmentally Extended Input-Output Analysis
EMEP	Evaluation and Monitoring European Program
ENUCAM	Nutrition Survey of the Community of Madrid
EPS	Expanded Polystyrene
ETBE	Ethyl Tert-butyl Ether
ETSI	European Telecommunication Standards Institute
FE	Freshwater Eutrophication
FEGAMP	Galician Federation of Municipalities and Provinces
FET	Freshwater Ecotoxicity
FN	False Negative
FP	False Positive
FPMF	Fine Particulate Matter Formation
FRS	Fossil Resource Scarcity
FU	Functional Unit
GDP	Gross Domestic Product

GDSEC	General Direction of Sustainability and Environmental Control
GHG	Greenhouse Gases
GW	Global Warming
HDPE	High Density Polyethylene
HT	Human Toxicity
IE	Inhabitants Equivalent
IECA	Institute of Statistics and Cartography of Andalusia
IECM	Institute of Statistics of the Community of Madrid
IGE	Galician Statistics Institute
Ind.	Indicator
INE	Statistics National Institute
IO	Input-Output
IOA	Input-Output Analysis
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ITU	Telecommunication Standardization Sector
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low Density Polyethylene
LGP	Liquefied Petroleum Gas
LLDPE	Linear Low-Density Polyethylene
LU	Land Use
MAPA	Ministry of Agriculture, Fisheries and Food
MAPAMA	Ministry of Agriculture, Fisheries, Food and Environment
MFA	Material Flow Analysis
MSW	Municipal Solid Waste
n.e.c.	Not Contemplated Elsewhere
OECD	Organization for Economic Co-operation and Development
PD	Population Density
PET	Polyethylene Terephthalate
PP	Polypropylene
PS	Polystyrene

PUR	Polyurethane
PVC	Polyvinyl Chloride
Resid.	Residential
RF	Random Forest
SDG	Sustainable Development Goals
SDI	Sustainable Development Indicators
SEP	Singular Entities of Population
SOD	Stratospheric Ozone Depletion
SS	Suspended Solids
TA	Terrestrial Acidification
TN	True Negative
TP	True Positive
UM	Urban Metabolism
UNESCO	United Nations Educational, Scientific and Cultural Organization
WC	Water Consumption
WWTP	Wastewater Treatment Plant

Resumo

Nos últimos anos, certos impactos ambientais como o cambio climático, a sobre-explotación de recursos naturais ou a deforestación, veñen cobrando forza e ocupando cada vez máis espazo nos xornais e nos informativos. Algunhas das causas principais de estes impactos son por un lado, o sistema de consumo lineal predominante, e por outro o crecemento da poboación mundial de forma exponencial nas últimas décadas. Considerando que a maior parte desta poboación concéntrase nas cidades, os sistemas urbanos xogan un papel crítico no desenvolvemento sostible. Deste xeito, tomando medidas que melloren a sustentabilidade das cidades, repercutirá de forma importante en todo o planeta.

Esta tese doutoral, céntrase no estudo da sustentabilidade dos sistemas urbanos. Por iso, o seu obxectivo principal é o de desenvolver metodoloxías que permitan cuantificar a sustentabilidade destes, e identificar as principais deficiencias. Para levar isto a cabo, esta tese consta de tres seccións, as cales inclúen os capítulos que se explican a continuación.

Capítulo 1: Estado do arte de Sistemas Urbanos. Este capítulo pretende servir de marco teórico e conceptual do campo de investigación no cal se desenvolve a tese. Polo tanto, partindo da base de que creando cidades máis sostibles conséguese crear un planeta más sostible, é necesario cuantificar a sustentabilidade das cidades e coñecer como poder mellorala. Pero antes diso debemos de intentar responder á pregunta ¿*que é un sistema urbano sostible*?. Existe unha importante falta de consenso á hora de determinar que é un sistema urbano sostible. Por un lado, algúns autores defíneno como aquel sistema urbano que consume recursos naturais e xera residuos a unha velocidade inferior á que a natureza é capaz de producir estes recursos e de asimilar os residuos.

Tendo en conta esta definición, nesta tese utilizáronse as metodoloxías de Análise de Ciclo de Vida (ACV) e Análise Input-Output Ambientalmente Estendida (AIOAE), baseadas no concepto de Metabolismo Urbano (MU) para medir indicadores e impactos ambientais como a pegada de carbono ou o consumo de auga, que nós proporciona información sobre o perfil ambiental dun sistema urbano. A pesares de que ambas metodoloxías foron empregadas en algúns casos de estudo, aínda existen carencias importantes dentro da investigación. Polo tanto, esta tese pretende contribuír ao desenvolvemento destas metodoloxías propoñendo solucións a estas deficiencias metodolóxicas.

Por outro lado, dentro da definición de sistema urbano sostible, algúns autores defenden que ademais de indicadores ambientais, deben ser consideradas variables sociais e económicas. De acordo con isto, existen diferentes estudos que utilizan indicadores e índices para cuantificar a sustentabilidade dun sistema urbano. Sen embargo, existen discrepancias á hora de determinar o número de indicadores a utilizar, e como definir se un sistema urbano é ou non sostible. En consecuencia nesta tese desenvólvense metodoloxías baseadas en índices e indicadores como propostas para avaliar a e definir a sustentabilidade de varios sistemas urbanos.

Capítulo 2: Como medir cargas ambientais en sistemas urbanos? Este capítulo que introduce a primeira sección da tese, describe en detalle as dúas metodoloxía empregadas nesta tese para avaliar ambientalmente sistemas urbanos: Análise de Ciclo de Vida (ACV) e Análise Input-Output Ambientalmente Estendida (AIOAE). O ACV é unha metodoloxía que considera unha perspectiva de ciclo de vida de un produto ou proceso e consta de catro etapas: definición do obxectivo e do alcance, inventario de ciclo de vida, avaliación do impacto de ciclo de vida e interpretación dos resultados. Esta metodoloxía transforma fluxos de materiais e enerxía en impactos ambientais. Sen embargo, non hai un claro consenso en que fluxos se deben considerar, á hora de aplicar ACV a sistemas urbanos. Ademais, os datos dos fluxos necesarios para levar a cabo a análise deben ser datos a escala local, os cales en moitos casos non están disponíbles. Por iso, é necesario facer estimacións e utilizar factores de redución de escala.

Por outro lado, o AIOAE é unha metodoloxía que transforma fluxos monetarios en impactos ambientais. Nesta tese, só se empregou esta metodoloxía para avaliar pegada de carbono (PC), pero ten máis alcance podendo medir consumo de auga ou consumo de materiais. O EIOAE necesita de tres bases de datos principais: As táboas Input-Output, as emisións por cada rama de actividade e o gasto por habitante por cada grupo de gasto. Para levar a cabo a análise é necesario establecer relacións entre os sectores económicos e os grupos de gasto. Establecer estas relacións é un dos principais problemas á hora de desenvolver a análise. Ademais, ao igual co ACV, os datos dispoñibles para levar a cabo AIOAE non están dispoñibles a escala local, polo que se deben utilizar tamén factores de redución de escala. Nesta tese, empregáronse dous factores diferentes ao empregar AIOAE.

Capítulo 3: Avaliación ambiental mediante Análise de Ciclo de Vida do municipio de Madrid. Neste Capítulo analizouse o perfil ambiental do municipio de Madrid mediante o ACV. Os obxectivos deste estudo foron primeiro, o de avaliar os impactos ambientais producidos polas actividades diarias dos cidadáns de Madrid. E segundo, contribuír ao desenvolvemento da metodoloxía aplicada a sistemas urbanos propoñendo solucións ás principais carencias. Os resultados mostraron que os responsables da maior parte dos impactos, son os fluxos asociados ao consumo eléctrico, a produción de manufacturas (como o aceiro ou cemento) e os fluxos de alimentos, maiormente de produtos derivados da gandería. Tendo en conta estes resultados, é posible establecer melloras de cara un municipio más sostible desenvolvendo accións que mitiguen o consumo nos fluxos con máis carga ambiental. Ademais, é importante dispoñer de datos a nivel local para mellorar a calidade deste tipo de análise máis alá dos retos metodolóxicos, para conseguir análises máis fiables, robustos e precisos.

Capítulo 4: Avaliación da Pegada de Carbono a escala cidade: Análise de Ciclo de Vida ou Análise Input-Output Ambientalmente Estendida. O quecemento global é un dos problemas ambientais máis importantes na actualidade. Considerando que as a maior parte das emisións de gases de efecto invernadoiro (GEI) prodúcese nas cidades, estas xogan un rol crítico na loita contra o cambio climático. Por iso, neste capítulo calculouse a PC asociada coas actividades que se levan a cabo na cidade de Cádiz (ao sur da península ibérica) mediante as dúas metodoloxías: ACV e AIOAE. Os obxectivos deste capítulo son, por un lado cuantificar a PC dunha cidade, e por outro lado, comparar ambas metodoloxías. Cando se considerou AIOAE, utilizáronse dous factores de redución de escala DF_1 e DF_2 baseados en datos sobre a renda por habitante e os gastos por habitante respectivamente. Os resultados mostraron unha PC de 5.25 e 3.83 tCO_2-eq·habitante^{-1}·ano^{-1} de acordo cos DF_1 e DF_2 considerando AIOAE, e de 5.43 tCO_2-eq·habitante^{-1}·ano^{-1} utilizando ACV. Como principal conclusión, utilizando o DF_1 a metodoloxía AIOAE chegou a un resultado sen diferencias significativas con respecto ao ACV sinalando que AIOAE é unha alternativa rápida e eficaz ao ACV, e que require menos esforzo. Sen embargo, AIOAE ten más limitacións para identificar os fluxos críticos, mentres que ACV é moito máis potente, neste sentido.

Capítulo 5: Comparación da Pegada de Carbono de diferentes cidades españolas a través da Análise Input-Output Ambientalmente Estendida. Neste capítulo seleccionouse un caso de estudo composto por catro cidades Españolas: Bilbao, Madrid, Santiago de Compostela e Sevilla, para cuantificar a PC mediante a AIOAE. Ademais, a PC destas catro cidades foi previamente analizada noutro estudos mediante ACV. Os principais obxectivos do capítulo foron: avaliar a PC destas cidades, contribuír ao desenvolvemento da metodoloxía EEIOA e comparar os resultados cos obtidos a través de ACV nos outros estudos. Prestando atención aos resultados, obtívose que Madrid foi a cidade con maior PC (5,98 tCO_2-eq·habitante^{-1}·ano^{-1}) seguida de Santiago de Compostela (5,66 tCO_2-eq·habitante^{-1}·ano^{-1}), Bilbao (5,26 tCO_2-eq·habitante^{-1}·ano^{-1}) e Sevilla (5,22 tCO_2-eq·habitante^{-1}·ano^{-1}). Afondando nos sectores cunha maior contribución á PC, estes foron os relacionados cos sectores da alimentación, consumo de electricidade e consumo de combustibles fósiles. Por outra banda, estes resultados difiren de xeito significativo dos obtidos con ACV. Non obstante, en ambas metodoloxías coinciden os principais fluxos que máis afectan á PC. Finalmente, este capítulo tivo como obxectivo final contribuír a establecer a metodoloxía EEIOA como unha metodoloxía robusta e fiable para avaliar a PC das cidades.

Capítulo 6: Analizar a sustentabilidade de sistemas urbanos con indicadores: desenvolvemento da metodoloxía. Neste capítulo, que inicia a segunda sección da tese, desenvolveuse un método baseado nun índice que permite avaliar a sustentabilidade de varios sistemas urbano simultaneamente considerando indicadores sociais, económicos e ambientais. Este índice esta formado por unha etiqueta de tres letras (unha por cada pilar da sustentabilidade: social, económico e ambiental) e a obtención desta etiqueta consta de varias etapas: i) selección de un set representativo de indicadores, ii) normalización dos valores dos indicadores, iii) atribución dos pesos de cada indicador mediante o procesos de xerarquía analítica (PXA), iv) agregación dos indicadores e v) asignación dunha letra (A, B ou C) dependendo do valor obtido por cada indicador composto. De este xeito, cada un dos sistemas urbanos estudados obtén unha letra por cada dimensión da sustentabilidade, é dicir, unha etiqueta con tres letras. O criterio para definir se un sistema urbano é sostible estableceuse segundo a etiqueta de tres letras como un sistema urbano que non teña ningunha C na etiqueta, pero teña ao menos unha A. Polo tanto, para alcanzar a categoría de sistema urbano sostible, é necesario un equilibrio entre as tres dimensións.

Capítulo 7: Aplicación dunha metodoloxía para avaliar a sustentabilidade de municipios en Galicia con diferentes tamaños de poboación. No capítulo anterior estableceuse unha metodoloxía para avaliar a sustentabilidade de sistemas urbanos. Neste capítulo a metodoloxía desenvolvida foi aplicada a un caso de estudo de 64 municipios de Galicia (noroeste de España). Estes municipios foron seleccionados mediante un cribado, para escoller os máis representativos da comunidade tendo en conta diferentes variables sociais e demográficas. Unha vez identificados estes 64 municipios foron clasificados segundo a poboación en tres grupos: municipios de tamaño medio, municipios pequenos e vilas. Con respecto a metodoloxía, adaptouse a metodoloxía desenvolvida no capítulo anterior, e utilizáronse dous métodos de ponderación: os PXA e se consideraron pesos iguais. Os resultados sinalaron que os municipios do norte da rexión, son polo xeral máis sostibles cos do sur. Ademais, o 57 % dos municipios de tamaño medio foron clasificados como sostibles, mentres que para municipios pequenos e vilas so o 45 % foron puntuados como sostibles. Isto podería indicar co tamaño do municipio inflúe na sustentabilidade. Por outro lado, non se encontraron diferencias significativas entre os dous métodos de ponderación. Por último, este caso de estudio mostrou que a metodoloxía pode ser aplicada en municipios de diferentes tamaños, e é robusta á hora de utilizala para avaliar a sustentabilidade dos sistemas urbanos dunha rexión.

Capítulo 8: Avaliación da sustentabilidade de cidades Españolas. Este capítulo é unha continuación do anterior, xa que neste caso, adaptouse a metodoloxía desenvolvida no Capítulo 6 para cuantificar a sustentabilidade de 31 das cidades máis representativas de España. O obxectivo deste capítulo é o de consolidar a metodoloxía de forma que pode ser utilizada para analizar diferentes tipos de sistemas urbanos sen importar o tamaño de poboación nin a localización. Os resultados mostraron unha gran diferencia entre as cidades do norte, as cales resultaron ser máis sostibles, que as cidades do sur, sendo Pamplona e L'Hospitalet de Llobregat as cidades coa puntuación máis alta. Por outro lado, os peores resultados obtivéronos as cidades de Murcia, Xixón, Badaxoz e Huelva. A metodoloxía permite identificar os indicadores nos que peores puntuacións se obtivo, polo que se poden establecer medidas de mellora específicas para alcanzar niveles de sustentabilidade maiores.

Capítulo 9: Tres indicadores clave para o análise da sustentabilidade de sistemas urbanos. Un dos principais retos dentro da investigación dos indicadores de desenvolvemento sostible é a selección de indicadores. Canto maior número de indicadores se utilice, o resultado vai a ser máis preciso e vai conter máis información. Sen embargo, recompilar datos para os indicadores require tempo e recursos, polo que se necesita chegar a un equilibrio onde se obteña o máximo de información coa máxima eficiencia. Neste capítulo desenvolveuse unha metodoloxía que permite coñecer a sustentabilidade dun sistema urbano utilizando tres indicadores. Para isto, aplicáronse dous métodos de regresión sobre o caso de estudo do Capítulo 8: Árbores de regresión e clasificación (ARC) e Random Forest. Estas dúas ferramentas, identificaron os indicadores coa mellor capacidade de predición os cales foron "mulleres desempregadas", "taxa de paro da cidade" e "residuos sólidos urbanos recollidos". Ademais, establecéronse os valores de estes indicadores a partir dos cales unha cidade deixa de ser sostible. De este xeito, creuse un método no cal se unha cidade está dentro dos valores límite destes tres indicadores considérase sostible. De acordo con isto, este novo método foi aplicado a un novo caso de estudo de 32 cidades Españolas. Os resultados de esta aplicación mostran unha vez máis, que as cidades situadas no sur do país teñen xeralmente peores resultados que os obtidos nas cidades máis ao norte. Ademais as cidades que obtiveron mellores resultados foron as más achegadas ás grandes urbes como Madrid e Barcelona. Este método é un método rápido e ten un erro dun 13 % con respecto ao método desenvolvido no Capítulo 6, pero sen embargo, non se pode obter información tan detallada con respecto a metodoloxía que empregan máis indicadores.

Capítulo 10: Cara un turismo sostible: Avaliando o impacto do turismo en Santiago de Compostela. Unha cidade sostible debe posuír determinadas características socioeconómicas que permiten aos cidadáns manter unha certa calidade de vida. Non obstante, o efecto do turismo en algunhas cidades con patrimonio histórico afecta de forma negativa ao desenvolvemento normal da comunidade. Neste capítulo desenvolveuse unha metodoloxía para avaliar como o turismo afecta o modo de vida dos residentes en Santiago de Compostela. Por iso, creouse un conxunto de indicadores baseados en enquisas realizadas entre os tres grupos implicados no sector turístico: cidadáns, comerciantes e visitantes. Finalmente, este conxunto de indicadores agregouse a unha puntuación de sustentabilidade nunha escala de 1 a 10. Os resultados amosan unha puntuación de sustentabilidade de 6,84 e os principais puntos débiles foron a mobilidade da residencia dos cidadáns ás zonas periféricas e o cambio de a oferta polo comercio promovida polo turismo. En consecuencia, esta metodoloxía é útil para os responsables políticos cando toman decisións e propoñen accións para fomentar un turismo sostible

Capítulo 11: Conclusións e futuras perspectivas. Neste capítulo están sinaladas as principais conclusións alcanzadas na tese, e algunhas propostas para futuras investigacións. Con respecto a primeira sección desta tese que abrangue os Capítulos 2, 3, 4 e 5, onde se avaliaron impactos ambientais mediante ACV e AIOAE de diferentes sistemas urbanos, as principais conclusións foron: i) Os principais fluxos que contribúen aos impactos ambientais son a alimentación, o consumo eléctrico e as manufacturas; ii) AIOAE é unha boa alternativa rápida e eficaz a ACV para analizar pegada de carbono; iii) ACV permite unha mellor disgregación para avaliar os fluxos que máis impacto xeran e iv) A non dispoñibilidade de datos locais afecta a precisión dos estudos.

Por outro lado, na segunda sección desta tese, que conforman os capítulos do 6 ao 10, nos que se avaliou mediante indicadores a sustentabilidade de sistemas urbanos, as principais conclusións foron: i) Os índices axudan a interpretar de forma rápida e sinxela valores complexos e ii) As metodoloxías desenvolvidas son robustas, fiables e fáciles de aplicar en novos casos de estudo.

Chapter 1: **State-of-the-Art of Urban Systems**

SUMMARY

The main environmental problems of the last decades are accelerated mainly due to anthropogenic causes. Two of the main factors that cause these problems are the increase in world population and the consumption system. Bearing both issues in mind, a transition towards sustainable development is necessary.

Within this context, cities play an important role in achieving sustainable development since they concentrate most of the world's population, and consequently, they consume most of the natural resources and generate most of the emissions and waste worldwide. Thus, transforming cities into sustainable cities would help create a more sustainable planet. For this, it is necessary to develop tools that allow analyzing the sustainability of cities and identifying the main shortcomings so that policy makers can establish actions for the sustainable development of cities.

This thesis seeks to adapt and develop different methodologies to evaluate the sustainability of different cities. First, adapting well-known and established tools such as Life Cycle Assessment (LCA) and Environmentally Extended Input-Output Analysis (EEIOA) to be applied at a local scale and to quantify and analyze the environmental profile of urban systems. Secondly, analyzing the performance of cities through sustainable development indicators. To do so, in environmental social and economic parameters related with urban systems will be identified and proposed for analysis, developing a specific assessment procedure. In this way, the thesis aims to carry out an in-depth evaluation of the three traditional pillars of sustainability for an urban system.

1.1 INTRODUCTION

In recent years, it can be observed in the news on television, newspapers or even on social networks, how there are a series of environmental problems that are increasingly gaining importance within society: climate change, deforestation, overexploitation of natural resources and the great generation of waste. In addition, these problems not only directly harm society, but the main cause of these is anthropogenic, with people are one of the victims and at the same time the cause (Sulphey and Faisal, 2021). Two of the factors that lead to these environmental situations are: the linear consumption system and the growth of the population at the global level (Ng et al., 2019; Steffen et al., 2015).

Currently the predominant system of consumption is a linear model of "take-made-dispose" as detailed in **Figure 1.1** (Ng et al., 2019). Consequently, the resources necessary to produce household consumer goods are extracted from nature, and then disposed of as waste. However, when the extraction of natural resources exceeds the capacity of nature to regenerate them, it is when the supply is in danger. An example that illustrates this situation could be a product in a supermarket that customers buy at a rate of one unit per minute. If supermarket workers refuel that product at a slower rate, there will come a point where some customers will not be able to purchase it.

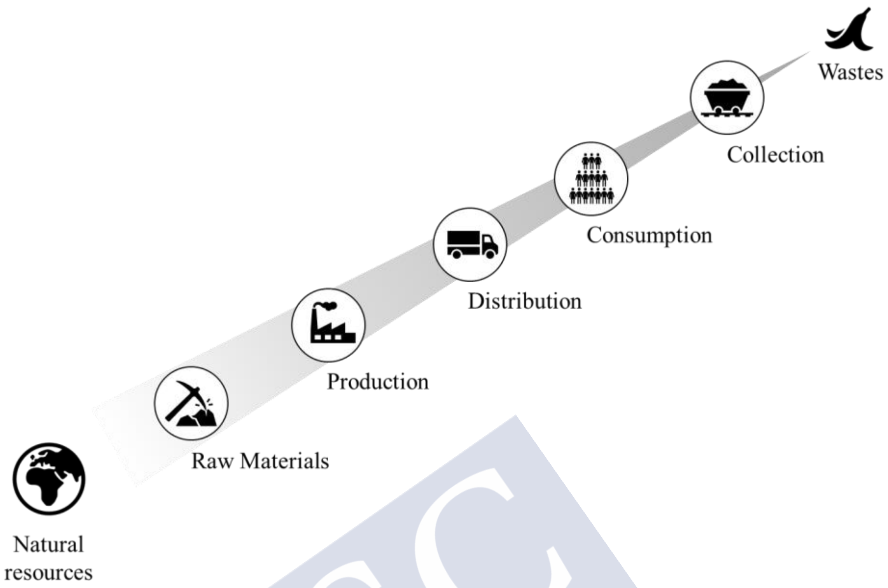

Figure 1.1. Linear model of consumption based on "take-make-dispose".

In addition to the linear consumption system, it must be considered that the world population has been growing exponentially since 1950 (Steffen et al., 2015) and therefore, the demand for natural resources increases proportionally. Therefore, these two factors together contribute synergistically to the environmental problems that currently exist.

Bearing in mind that global population is expected to continue to growth (Steffen et al., 2015), it is necessary to change the predominant linear consumption system for a circular economy model which allows sustainable development and helps reduce the environmental impacts derived from consumption (Bonciu, 2014). Circular economy consists in a circular model of consumption, where raw materials are extracted from the natural resources but after the consumption, the wastes generated are revalorized into a resource and re-integrated into the consumption system through recycling or reuse (**Figure 1.2**). Thus, it is possible to reduce the exploitation of natural resources and mitigate the waste generated (Bonciu, 2014).

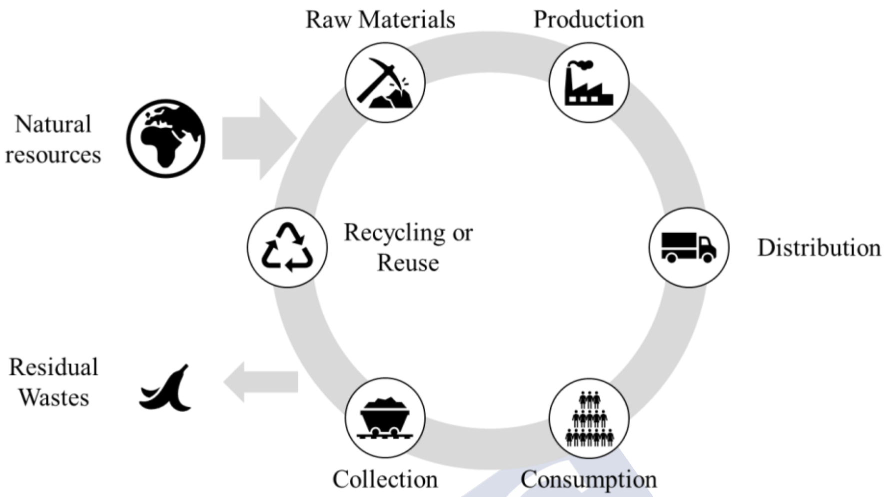

Figure 1.2. Circular economy system scheme adapted from Bonciu (2014).

In this transition for sustainable development, a commitment from society is essential. In these sense, social concern about the environmental problems derived from the massive consumption of natural resources are materialized in the action plan of the 2030 agenda of the United Nations. This action plan consists of 17 Sustainable Development Goals (SDGs) where different objectives are established to achieve in 2030, which face the great environmental but also social and economic challenges worldwide (United Nations, 2015). Therefore, this agreement signed by all the countries that make up the United Nations is a historical fact that reflects the main social concerns.

In this context, cities and urban systems play a critical role when it comes to implementing measures and taking actions towards sustainable development. Currently, more than half of the world's population resides in cities, and it is estimated that in 2050 the urban population will be 66% of the global population (Ibrahim et al., 2018). That is why cities account for 85% of global gross domestic product (GDP) generation (World Bank, 2019), 75% of natural resources demand and 50% of global waste production (Ellen MacArthur

Foundation, 2017). In addition, cities are responsible for the 70% of the global greenhouse gas (GHG) emissions (World Bank, 2019). Therefore, cities and urban systems are essential elements in global performance, and accordingly, developing methodologies to analyze the sustainability of a city is crucial when it comes to know its weaknesses to create plans and actions to improve its sustainability.

1.2 SUSTAINABLE CITY: A COMPLEX CONCEPT

Commonly, the concept of a sustainable city is associated with an environmentally friendly city (Kennedy et al., 2007). In addition, Kennedy et al. (2007) defined a sustainable urban system as one whose extraction of natural resources and waste generation does not exceed the capacity of the environment to regenerate these resources and to assimilate the waste produced. This definition of a sustainable urban system points to the relationship that an urban system has with the environment. Nevertheless, a city that meets the requirements according to this definition, but has one birth out of every four deaths, or has a very poor industry, and 50% of its workforce is unemployed, or has more than half of the population at risk of poverty, despite having an excellent relationship with the environment … *could be considered as a sustainable city?* Therefore, in addition to environmental aspects, to define a sustainable city, social and economic factors must be taken into account (Feleki et al., 2018; Tanguay et al., 2010).

Currently, there is a lack of consensus among researchers on the definition of a sustainable city with respect to what factors should be considered or what are the thresholds from which a city should be considered sustainable or not (Berardi, 2013; Feleki et al., 2018; Tanguay et al., 2010). Consequently, it is necessary to develop methodologies that allow not only evaluating the state of sustainability of a city, but also defining a sustainable city.

Some of the methodologies developed in this field of research (Dias et al., 2018; García-Guaita et al., 2018; Goldstein et al., 2013;

González-García and Dias, 2019) use the urban metabolism (UM) perspective to analyze the sustainability of a city.

1.2.1 Urban Metabolism

A food that is gaining fame among the population is kefir. This food consists of milk fermented by a conglomerate of fungi and bacteria that can be found for sale in many supermarkets but can also be made at home. The process consists of adding a quantity of milk to some granules formed by fungi and bacteria for two or three days at room temperature and in the absence of light. After three days the mixture is filtered, separating the kefir from the granules, the granules are cleaned, and the process is repeated. If favorable conditions are maintained, the granules grow with each cycle. Therefore, the granules need milk from time to time to feed, and they generate kefir because of the consumption of milk by these granules. Urban metabolism considers that a city could behave in the same way as these granules that generate kefir. In other words, a city needs food and water for its inhabitants, materials and energy and the consumption of these produces waste (which can be revalued following the principles of circular economy), emissions and discharges (**Figure 1.3**) and if the conditions of the city are favorable, the city grows just like the granules.

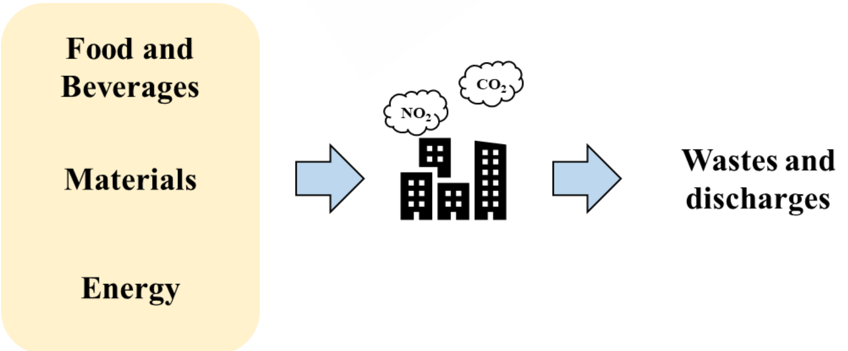

Figure 1.3. Material and energy requirements of a city from the perspective of urban metabolism (UM).

Hence, the sustainability of a city depends considerably on the human activities performed within its system boundaries, involving therefore agricultural, daily life, building, transport and industrial activities (Cui et al., 2019). These activities are addressed in the concept of UM which was introduced by Burgess (1925) to analyze the growth of a city from a sociologist approach. Afterwards, the concept of UM was adapted with the aim of quantifying material and energy flows within the limits of a city (Wolman, 1965). Although the references identifying the first works are documents from several decades ago, the concept of UM, to which socio-economic processes were incorporated into its definition (Kennedy et al., 2007), is still valid today, and thus, a better understanding of the links between societies and the mentioned flows is needed to identify the possibilities of fostering sustainability (Dijst et al., 2018). Moreover, UM approach can be combined with other assessment methodologies to obtain data about the status of an urban area, such as material flow analysis (MFA) – considered as a supporting tool to identify inventory data (mass and energy flows) –, life cycle assessment (LCA), which identifies environmental burdens arising from urban behavior, input-output analysis (IOA), which includes economic parameters, and extended environmentally IOA – to combine both environmental and economic indicators. In this thesis, the LCA and Environmental Extended Input-Output Analysis (EEIOA) methodologies were adopted and applied at the local scale in different case studies to evaluate the environmental profile of urban systems.

However, the concept of sustainability must be developed under three fundamental pillars, considering social, economic and environmental aspects but these methodologies only consider environmental issues, with the exception of IOA which includes economic data, and require additional information in order to contemplate all dimensions of the sustainability (Goldstein et al., 2013).

1.2.2 Sustainable development indicators

The use of indicators and indices to analyze the sustainability of urban systems has intensified since the 1992 Earth Summit in Rio de

Janeiro (Michael et al., 2014). In this sense, ISO 37120 (ISO, 2014) proposes a set of standard indicators that will be used for the assessment of cities, municipalities or local governments. Furthermore, there are different initiatives to define Sustainable Development Indicators (SDI), which consider different approaches such as energy efficiency, optimization of the urban transport system and waste management, among others (Dizdaroglu, 2017). However, the selection and number of potential indicators considered vary substantially according to the point of view of evaluator (Tanguay et al., 2010). Designing a methodology to select the best set of indicators based on all dimensions of sustainability is a challenge, as it may depend on very different factors (i.e., the scale of study and data quality).

A large number of indicators provide more extensive and complementary information than establishing a single value, but the need to collect a large volume of data could complicate the understanding of the results. Thus, the use of indexes or scores (e.g., the air quality index that reports daily air quality by means of six different colors according to the level of health concern) is increasingly recognized as specifically useful for public communications (Feleki et al., 2018; Tanguay et al., 2010). This is the case of developing composite indicators based on the aggregation of different variables or indicators that make easier the understanding of sustainability results and reduce significantly the number of separated indicators (Dizdaroglu, 2017; Riedler and Lang, 2018). Nevertheless, aggregation of data may also imply a lack of valuable information or even the elaboration of simplistic policy conclusions. As a result, it is necessary to develop a methodological framework for selecting and assessing the indicators required to develop sustainable action plans and adequately summarize multi-dimensional issues (Copus et al., 2004).

A sustainability index is also based on the aggregation of selected indicators. The selection of the indicators set is a critical step in the sustainability assessment. There are different international standard organizations, such as ISO, European Telecommunication Standards

Institute (ETSI) and Telecommunication Standardization Sector (ITU), which provide and recommend different indicators to assess the sustainability of urban systems (ISO, 2014). These recommended indicators could be considered as a starting point, which, according to the needs of each city, include a more manageable set that provides the information required for the city under study (Huovila et al., 2019). However, the most common application is the comparison between cities in terms of sustainability (Tanguay et al., 2010). Accordingly, if each study considers different indicators for evaluation, such comparison will not be possible. In this sense, it is necessary to develop methodologies focused on the selection of potential indicators to assess the sustainability of cities in a more holistic and systematic way (Feleki et al., 2018).

In addition, the comparative analysis between cities provides information on the shortcomings of cities with lower indicator values and, on the other hand, makes it possible to identify the cities with better results, which are usually linked to sustainability policies (Rozhenkova et al., 2019). For example, if one city has an unemployment rate of around 20% but another city in the same country has around 10%, this implies that the policy makers of the first city must orient their employment policies and strategies according to those of the second city. The main difference between comparative and individual analysis is that in the latter it is difficult to know whether 20% of the unemployment rate, following the example, is a bad or a good value. In this way, reference values or thresholds could be calculated and established in the comparative analysis within a sample of the cities studied. Moreover, the threshold may help to define the criteria under which a city is established whether or not it is considered sustainable (González-García et al., 2019). However, the comparative analysis of cities requires an exhaustive compilation of data. It is therefore necessary to collect information at city level for all selected indicators.

In this context, some authors developed and applied different methodologies to evaluate the sustainability of cities using indicators. Some studies proposed a set of indicators taking into account the specific characteristics of the case study, such as the study of peripheral informal settlements in Latin American cities (Montoya et al., 2020), or the study of the strengths and weaknesses of a specific area (Hély and Antoni, 2019) or even the study of some characteristic sector, such as tourism (Biagi et al., 2020). However, the number of indicators could be low (no more than 10) and very specific to the case study. In this regard, there are other studies in which the selection of the set of indicators was first introduced based on databases, regardless of the characteristics of the urban system. It is necessary to incorporate screening methods to identify indicators that are representative of each case study in order to establish specific criteria for the selection of key indicators (Bienvenido-Huertas et al., 2020; Chen and Zhang, 2021; González-García et al., 2019; Karji et al., 2019). Consequently, the set of indicators identified in these studies can be easily adapted and used in the analysis of other case studies (Rama et al., 2020). However, despite reducing the number of indicators, these studies required a large amount of data to be compiled, which requires time and resources.

Therefore, this thesis intends to propose solutions to the main deficiencies within this field of research regarding the selection of indicators and the definition of sustainability.

1.3 OBJECTIVES AND STRUCTURE OF THE THESIS

The main objective of this thesis is to develop tools that allow evaluating the sustainability of urban systems and identifying the main deficiencies. For this purpose, the thesis was structured in three sections. The first section is made up of 4 chapters and the second section of five chapters. Finally, Section 3 includes Chapter 11 with the main conclusions and future perspectives of the thesis were summarized.

Section 1: Relationship of urban systems with the environment. In this section, the environmental assessment tools LCA and Environmentally Extended Input-Output Analysis (EEIOA) were used to analyze the environmental profile and in special, carbon footprint of different urban systems. This section is composed of Chapter 2, in which the methodological tools used are introduced; Chapter 3, in which the case study of the municipality of Madrid is analyzed through LCA; Chapter 4 where the LCA and EEIOA methodologies are compared as tools to analyze the carbon footprint of the city of Cádiz; and finally, Chapter 5 in which the carbon footprint of different cities is analyzed using the EEIOA methodology.

Section 2: Sustainability indices of urban systems. In this section, social, economic and environmental indicators were used to assess the sustainability of different urban systems. In Chapter 6, a methodology is developed that defines a sustainable city through a three-letter index. To do this, a set of indicators is selected and the normalization, weighting, aggregation methods and the thresholds that define the index are defined. After this, in Chapters 7 and 8, this methodology is applied in 64 municipalities in Galicia (Chapter 7) and in 31 Spanish cities (Chapter 8). In Chapter 9 the three key indicators of the methodology developed in Chapter 6 are identified and a criterion to define sustainability based on them is developed. On the other hand, in Chapter 10, a series of indicators are established to analyze the sustainability of a tourist city, evaluating the case of Santiago de Compostela. Thus, Chapters 6 to 9 focus on a methodology that seeks to analyze several cities, and Chapter 10 focuses on a particular case study.

Section 3: Conclusions. This section details the main conclusions obtained in this thesis as well as what are the future perspectives within this field of research.

1.4 REFERENCES

Berardi, U., 2013. Sustainability assessment of urban communities through rating systems 1573–1591. https://doi.org/10.1007/s10668-013-9462-0

Biagi, B., Ladu, M.G., Meleddu, M., Royuela, V., 2020. Tourism and the city: The impact on residents' quality of life. Int. J. Tour. Res.

22, 168–181. https://doi.org/10.1002/jtr.2326

Bienvenido-Huertas, D., Farinha, F., Oliveira, M.J., Silva, E.M.J., Lança, R., 2020. Comparison of artificial intelligence algorithms to estimate sustainability indicators. Sustain. Cities Soc. 63. https://doi.org/10.1016/j.scs.2020.102430

Bonciu, F., 2014. The European economy: From a linear to a circular economy. Rom. J. Eur. Aff. 14, 78–91.

Burgess, E.W., 1925. The Growth of the City: An Introduction to a Research Project. Urban Ecol. An Int. Perspect. Interact. Between Humans Nat. XVIII, 71–78. https://doi.org/10.1007/978-0-387-73412-5_5

Chen, Y., Zhang, D., 2021. Evaluation and driving factors of city sustainability in Northeast China: An analysis based on interaction among multiple indicators. Sustain. Cities Soc. 102721. https://doi.org/10.1016/j.scs.2021.102721

Copus, A., Smith, J., Lloyd, J., Zografos, C., 2004. Study on indicators of sustainable development at the local level.

Cui, X., Wang, X., Feng, Y., 2019. Examining urban metabolism: A material flow perspective on cities and their sustainability. J. Clean. Prod. 214, 767–781. https://doi.org/10.1016/j.jclepro.2019.01.021

Dias, A., Lemos, D., Gabarrell, X., Arroja, L., 2018. Comparison of tools for quantifying the environmental performance of an urban territory. J. Ind. Ecol. 22, 868–880. https://doi.org/10.1111/jiec.12614

Dijst, M., Worrell, E., Böcker, L., Brunner, P., Davoudi, S., Geertman, S., Harmsen, R., Helbich, M., Holtslag, A.A.M., Kwan, M.P., Lenz, B., Lyons, G., Mokhtarian, P.L., Newman, P., Perrels, A., Ribeiro, A.P., Rosales Carreón, J., Thomson, G., Urge-Vorsatz, D., Zeyringer, M., 2018. Exploring urban metabolism—Towards an interdisciplinary perspective. Resour. Conserv. Recycl. 132, 190–203. https://doi.org/10.1016/j.resconrec.2017.09.014

Dizdaroglu, D., 2017. The Role of Indicator-Based Sustainability Assessment in Policy and the Decision-Making Process : A Review and Outlook. https://doi.org/10.3390/su9061018

Ellen MacArthur Foundation, 2017. Cities in the circular economy: an initial exploration. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Cities-in-the-CE_An-Initial-Exploration.pdf (accessed May 2021)

Feleki, E., Vlachokostas, C., Moussiopoulos, N., 2018. Characterisation of sustainability in urban areas: An analysis of assessment tools with emphasis on European cities. Sustain. Cities Soc. 43, 563–577. https://doi.org/10.1016/j.scs.2018.08.025

García-Guaita, F., González-García, S., Villanueva-Rey, P., Moreira, M.T., Feijoo, G., 2018. Integrating Urban Metabolism, Material Flow Analysis and Life Cycle Assessment in the environmental evaluation of Santiago de Compostela. Sustain. Cities Soc. 40, 569–580. ttps://doi.org/https://doi.org/10.1016/j.scs.2018.04.027

Goldstein, B., Birkved, M., Quitzau, M.B., Hauschild, M., 2013. Quantification of urban metabolism through coupling with the life cycle assessment framework: Concept development and case study. Environ. Res. Lett. 8. https://doi.org/10.1088/1748-9326/8/3/035024

González-García, S., Dias, A.C., 2019. Integrating lifecycle assessment and urban metabolism at city level: Comparison between Spanish cities. J. Ind. Ecol. 23, 1062–1076. https://doi.org/10.1111/jiec.12844

González-García, S., Rama, M., Cortés, A., García-Guaita, F., Núñez, A., Louro, L.G., Moreira, M.T., Feijoo, G., 2019. Embedding environmental, economic and social indicators in the evaluation of the sustainability of the municipalities of Galicia (northwest of Spain). J. Clean. Prod. 234, 27–42. https://doi.org/10.1016/j.jclepro.2019.06.158

Hély, V., Antoni, J.P., 2019. Combining indicators for decision making in planning issues: A theoretical approach to perform sustainability assessment. Sustain. Cities Soc. 44, 844–854. https://doi.org/10.1016/j.scs.2018.10.035

Huovila, A., Bosch, P., Airaksinen, M., 2019. Comparative analysis of standardized indicators for Smart sustainable cities : What indicators and standards to use and when ? Cities 89, 141–153. https://doi.org/10.1016/j.cities.2019.01.029

Ibrahim, M., El-Zaart, A., Adams, C., 2018. Smart sustainable cities roadmap: Readiness for transformation towards urban sustainability. Sustain. Cities Soc. 37, 530–540. https://doi.org/10.1016/j.scs.2017.10.008

ISO, 2014. International Organization for Standarization. 37120 Sustainable development in communities : City indicators for service delivery and quality of life.

Karji, A., Woldesenbet, A., Khanzadi, M., Tafazzoli, M., 2019. Assessment of Social Sustainability Indicators in Mass Housing Construction: A Case Study of Mehr Housing Project. Sustain. Cities Soc. 50, 101697. https://doi.org/10.1016/j.scs.2019.101697

Kennedy, C., Cuddihy, J., Engel-yan, J., 2007. The Changing Metabolism of Cities. https://doi.org/10.1007/s00125-014-3420-8

Michael, F.L., Zainon, Z., Figueroa, M.J., 2014. Review of urban sustainability indicators assessment e Case study between Asian countries. Habitat Int. 44, 491–500. https://doi.org/10.1016/j.habitatint.2014.09.006

Montoya, J., Cartes, I., Zumelzu, A., 2020. Indicators for evaluating sustainability in Bogota's informal settlements: Definition and validation. Sustain. Cities Soc. 53. https://doi.org/10.1016/j.scs.2019.101896

Ng, K.S., Yang, A., Yakovleva, N., 2019. Sustainable waste management through synergistic utilisation of commercial and domestic organic waste for efficient resource recovery and valorisation in the UK. J. Clean. Prod. 227, 248–262. https://doi.org/10.1016/j.jclepro.2019.04.136

Rama, M., González-García, S., Andrade, E., Moreira, M.T., Feijoo, G., 2020. Assessing the sustainability dimension at local scale: Case study of Spanish cities. Ecol. Indic. 117, 106687. https://doi.org/10.1016/j.ecolind.2020.106687

Riedler, B., Lang, S., 2018. A spatially explicit patch model of habitat quality , integrating spatio- structural indicators. Ecol. Indic. 94, 128–141. https://doi.org/10.1016/j.ecolind.2017.04.027

Rozhenkova, V., Allmang, S., Ly, S., Franken, D., Heymann, J., Sdg, U., 2019. The role of comparative city policy data in assessing progress toward the urban SDG targets. Cities 95, 102357. https://doi.org/10.1016/j.cities.2019.05.026

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C., 2015. The trajectory of the anthropocene: The great acceleration. Anthr. Rev. 2, 81–98. https://doi.org/10.1177/2053019614564785

Sulphey, M.M., Faisal, S., 2021. Connectedness to nature and environmental concern as antecedents of commitment to environmental sustainability. Int. J. Energy Econ. Policy 11, 208–219. https://doi.org/10.32479/ijeep.10803

Tanguay, G.A., Rajaonson, J., Lanoie, P., 2010. Measuring the sustainability of cities : An analysis of the use of local indicators. Ecol. Indic. 10, 407–418. https://doi.org/10.1016/j.ecolind.2009.07.013

United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. https://sdgs.un.org/2030agenda (accessed May 2021)

Wolman, A., 1965. The Metabolism of Cities. Sci. Am. 213, 178–190. https://doi.org/10.1038/scientificamerican0965-178

World Bank, 2019. Urban development overview.

https://www.worldbank.org/en/topic/urbandevelopment/overview (accessed May 2021)

RELATIONSHIP OF URBAN SYSTEMS WITH THE ENVIRONMENT

Chapter 2: **How to measure environmental burdens in urban systems?**

SUMMARY

Urban systems generate impacts on the environment since the inhabitants consume natural resources and generate waste, emissions and discharges. There are methodologies that allow to identify and quantify these impacts. In this chapter, two methodologies that evaluate the environmental impacts of urban systems which were used in the following chapters of this doctoral thesis were detailed in depth: Life Cycle Assessment (LCA) and Environmentally Extended Input-Output Analysis (EEIOA). The application of these methodologies on urban systems at a local scale is very recent, so there are still many challenges when it comes to their application. The quantification of these impacts is important when obtaining information to reduce them and thus establish actions for future more sustainable urban systems.

2.1 INTRODUCTION

The urban metabolism perspective perceives a city as a living organism that needs energy and materials (food, manufacturing, fossil fuels) to grow and maintain itself and generates waste. Thus, from the UM approach urban systems are in contact with the environment through the input flows of materials and energy extracted from natural sources and the output flows of wastes and emissions. In these sense, urban systems are related to the environment, and have an impact on it. Consequently, so that this relationship is sustainable over time, it is essential that these impacts are assumable by nature (Kennedy et al., 2007a). Hence, that is why it is necessary to be able to quantify these impacts, to be able to take measures to reduce environmental loads so that urban systems are as harmless as possible for the environment.

The assessment of the environmental impacts derived from the urban systems requires the use of tools and methodologies that allow these impacts to be measured and quantified. The most commonly methodology employed in order to measure the environmental burdens is Life Cycle Assessment (LCA) (Ghaemi and Smith, 2020; Parkes et al., 2015). This methodology quantifies the environmental impacts associated with a product or process, in indicators such as the carbon footprint (CF), fossil fuel depletion or water consumption. Recently, LCA has been adapted to analyze urban systems in some case studies (Goldstein et al., 2013). However, there are still some shortcomings regarding its application on a local scale, mainly due to the availability of data.

On the other hand, another methodology that allows quantifying the CF of a city is the Environmentally Extended Input-Output Analysis (EEIOA) (Dias et al., 2014). This methodology transforms economic data from expenses of the citizens in kilograms of equivalent carbon dioxide (kg CO_2-eq). However, research at the local scale is still in its infancy and there are many gaps in the application of this methodology in cities (Dias et al., 2014; Dias et al., 2018; Rama et al., 2021).

In this first section of this doctoral thesis, the application of the LCA and EEIOA in different case studies was studied, to analyze the environmental profile of cities. Furthermore, these methodologies were compared to evaluate the advantages and disadvantages of one over the other. To understand the methodological framework, this chapter addressed in depth the foundations of the methodologies of LCA and EEIOA and their use to analyze the environmental profile of urban systems.

2.2 LIFE CYCLE ASSESSMENT

2.2.1 Introduction to LCA

A citizen of Spain in a market wants to buy avocados but finds that he/she has two options to buy: avocados from Spain, and others from Chile and both have a similar price. After thinking for a while, the citizen considers that the Spanish avocado is the best option because it is closer, so the transportation needed to take it to that market is less and therefore its contribution to climate change is also less. In this whole process of analysis that the citizen in this example encountered, it could be said that he/she evaluated a product (an avocado) from a life cycle perspective, assessed the environmental impacts derived from the whole process that took the product from its production to the point of purchase, and decided on the basis of the conclusions reached.

In this way, Life Cycle Assessment (LCA) methodology allows to identify and quantify the environmental impacts associated to a product, process or system considering all energy and materials flows implicit in the life cycle (cradle-to-grave) (Arvanitoyannis, 2008). This methodology is normalized by ISO 14040 (2006) and consists in four steps:

i) Goal and scope definition: the system boundaries are identified. Therefore, Following the previous example, the system has a cradle-to-gate perspective, that is, all material and energy flows are considered in the production and transport of the avocado to the supermarket. Moreover, in this stage the function or the purpose of the system is also defined, e.g., considering that the main objective of all the process could be the avocado production, the functional unit (FU) could be 1 avocado. It is important to define the FU correctly, because it is what can make it possible to compare the impacts of different products or processes. If in the previous example the FU identified were grams of avocado, and the avocado originating from Chile had more weight, the decision-making of the citizen would require a more in-depth analysis.

ii) Life Cycle Inventory (LCI): In this step, the material and energy flows were identified and quantified. This stage is the one that requires the most time because all the data of the flows considered must be collected. There are databases considered in LCA as Ecoinvent® 3.5 database (Moreno Ruiz et al., 2018) and Agri-footprint database (Blonk Agri-footprint BV, 2015) that consider products and processes from a life cycle perspective.

iii) Life cycle impact assessment (LCIA): The mass and energy flows collected in the previous stage are transformed into environmental impacts considering the characterization factors. There are different methods which calculate these factors. One of the most commonly used characterization methods is the ReCiPe v.1.1 Midpoint (Huijbregts et al., 2017; Jungbluth, 2019). The hierarchy perspective was assumed, as it is based on the most common policy principles. Currently, there are software such as SimaPro, Air.e or GaBi that allow LCA to be carried out, and which have different databases and characterization methods incorporated.

iv) Interpretation of the results: Once the environmental burdens derived from each flow were calculated, the socio-economic flows mainly responsible for the impacts were identified and to provide decision makers with comprehensive and clear information.

2.2.2 Application of LCA to urban systems

In this doctoral thesis, the LCA methodology was used to analyze the environmental impacts of urban systems. As mentioned previously

LCA is an environmental methodology that, through the quantification of the inventory data from direct and indirect flows, makes it possible to estimate the associated impacts (Chester et al., 2012), which in the particular case of the urban metabolism of a city takes into account supply chains and waste management (Goldstein et al., 2013; Pincetl et al., 2012). Considering the need for a large number of data for the modelling of the city, the concept of urban metabolism (UM) (Wolman, 1965) adapted by several authors (Kennedy et al., 2007; Zhang, 2013) makes it possible to consider the city as the whole of all its flows to maintain the daily life of its citizens. The collection of high quality data arises as a major challenge due to the scarcity of information and the difficulty of tracking unregulated flows (Currie et al., 2017), which can lead to the underestimation of the final environmental impacts (Goldstein et al., 2013). Some authors have combined environmental assessment methods (footprint, input/output, network analysis or LCA) with accounting tools (Goldstein et al., 2013; Lopes Silva et al., 2015; Nakem et al., 2016)– i.e. flow and energy assessment methods such as Material Flow Analysis (MFA) (Kalbar et al., 2016). The tools listed here have been used, separately or combined, in UM studies (Beloin-Saint-Pierre et al., 2017; González-García and Dias, 2019; Rosado et al., 2014; Sahely et al., 2003). However, accounting methods often need to be complemented with estimates to address missing data by applying certain criteria, such as apparent consumption (Li et al., 2018; Rosado et al., 2016) or by simplifying according to the downscaling strategy (Courtonne et al., 2015; Dias et al., 2014; González-García and Dias, 2019).

Accordingly, the steps considered by (ISO 14040, 2006) detailed in Section 2.2.1 the LCIA and Interpretation of the results stages are transversal to any LCA, however the Goal and Scope definition and LCI stages depend on the system and the process being analyzed, so in the LCA of urban systems these two stages must be adapted.

2.2.2.1 Goal and Scope definition

System boundaries in urban system were the limits of the city, municipality or town studied. Therefore, considering the UM approach, the flows of materials and energy that were consumed by the citizens of an urban system were considered as inputs, and the waste generated by the citizens as the outputs, as shown in **Figure 2.1**.

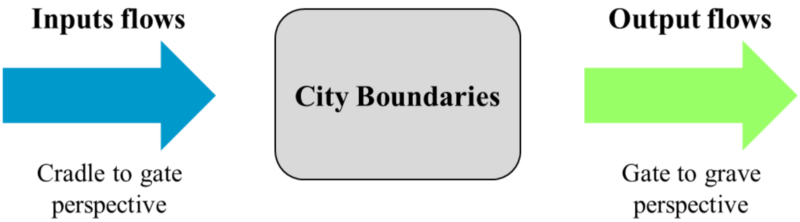

Figure 2.1. Flow scheme considered in LCA applied to urban systems.

On the other hand, to establish the FU, it must be taken into account that the function of a urban system is to maintain the quality of life of its citizens, as well as other geographical areas that depend directly or indirectly on its socio-economic factors, and to support people with different cultures, habits, diets, etc. (Goldstein et al., 2013). In this sense, the most common in the bibliography is to consider one inhabitant and one year as a functional unit (Goldstein et al., 2013; González-García and Dias, 2019). However, other authors (García-Guaita et al., 2018; González-García et al., 2021) consider the equivalent inhabitant, i.e., considering also the non-resident population in the city (students who are not registered in the census, and workers who live in other urban systems and tourists.

2.2.2.2 Life Cycle Inventory

In this stage, the flows of materials and energy that were consumed in the urban system under study were identified and quantified. It is the most time-consuming stage, and it was also the stage in which the most important research challenges were encountered. This is due to the fact that there is no clear consensus on which flows must be considered (García-Guaita et al., 2018; Goldstein et al., 2013; González-García and Dias, 2019). In addition, the lack of data at the local level makes it necessary to perform downscaling.

In LCA studies of urban systems, a series of general flows were defined. **Table 2.1** shows the main flows considered.

Table 2.1. Main flows considered in LCA of urban systems.

Input Flows	Output Flows
Food and drinks	Wastewater
Manufactures	Municipal Solid Wastes
Energy	
Fossil Fuels	

All food and drinks (water included) consumed by citizens within the limits of the system were taken into account. These data are available at the regional level, however, depending on the case study, the data sources may be different. Therefore, within this flow were considered the quantity of tomatoes, meat, fish etc. that each inhabitant consumes. In Manufactures, building materials (such as cement, sand, steel, etc.), the consumption of paper, cardboard, glass and plastics were included. On the other hand, in Energy the electricity consumed was considered, and the Fossil Fuels considered the consumption of gas, natural gas, diesel, carbon etc. in households, transport and industry. In addition, the treatment of the municipal solid waste and wastewater was also considered in LCA studies as Outputs flows.

In this sense, consumption data per person were collected for each flow. On the other hand, to maintain the life cycle approach, background data must also be considered. These data were associated with each product and they were the data of the materials and energy necessary to produce each product and its transport to the system (cradle-to-gate). Therefore, in addition to considering the grams of avocado consumed, for example, the amount of water used to grow the avocado, the hectares of cultivated land, transportation, etc. must be considered. There are databases that compile background data for many processes and products such as those mentioned above, i.e., Ecoinvent® 3.5 database (Moreno Ruiz et al., 2018) or Agri-footprint database (Blonk Agri-footprint BV, 2015).

Once all the flows were quantified, the environmental impacts were determined using the characterization models. Consequently, depending on the characterization method, these impacts were calculated in indicators such as the carbon footprint (CF), or water consumption, which were called impact categories. Therefore, it is possible to determine which flows contribute the most within each category of impact. For example, the electricity consumption from thermal power plants was a flow with an important contribution within the CF impact category. In this way, results were obtained from which measures can be taken to mitigate environmental impacts and achieve more sustainable urban systems.

2.3 ENVIRONMENTALLY EXTENDED INPUT-OUTPUT ANALYSIS

Environmentally Extended Input-Output Analysis (EEIOA) is based on the economic data provided by the Input-Output tables which reflect the monetary transactions between the different industrial sectors (Leontief, 1936), which are associated with their corresponding environmental burdens (GHG emissions, water consumption, land use, etc.) (Bertram et al., 2019; Dias et al., 2014; Dias et al., 2018). Thus, EEIOA transforms the money spent per inhabitant or household during a period (usually one year), into CO_2-eq units. Different environmental footprints as those related to water-scarcity (Ridoutt et al., 2018), land and material (Bertram et al., 2019) can be calculated considering EEIOA and depending on the environmental impact data provided and recorded by each country for all economic sectors (e.g., greenhouse gases (GHG) emission and water consumption by sector) (Bertram et al., 2019; Dias et al., 2014). Similarly, CF can be evaluated at country level (Bertram et al., 2019), at regional level (Roibás et al., 2017) or at city level (Dias et al., 2014) taking into account the expenditures of the inhabitants or households of the country, region or city, respectively.

When the CF was estimated considering EEOIA, the procedure reported by Dias et al. (2014) was followed in detail, although incorporating some modifications in order to adapt the methodology to the case studies. A detailed description of the procedure and the information required was summarized below.

2.3.1 Data requirements

EEIOA mainly required three data sources as a starting point, which are IO tables, GHG emission per Branches of Activity and the expenditures of the households per group. Accordingly, some transformations were necessary. The IO tables provide information regarding the monetary interactions between economic sectors which are symmetrically distributed in the table in form of rows and columns. Therefore, each row indicates the revenues that each sector receives from each of the sectors located in each column. The same sectors are considered in the rows as in the columns, so the IO table is a square matrix.

In contrast, if the table is read vertically, each column indicates the expenditures that each sector has from the sectors of the corresponding rows (Leontief, 1936). To conduct an EEIOA it was necessary to transform the IO table into the inverse Leontief matrix $(I-A)^{-1}$; where I was the identity matrix and A was the matrix resulting from dividing the values of the IO table by the gross domestic product (GDP) of the corresponding sector (Dias et al., 2014). In this thesis, this methodology was applied to case studies within Spain, therefore, it has been used the total IO table from Spain (INE, 2015b), which considered 64 economic sectors and was elaborated according to Regulation (EU) nº 549/2013 (European Union, 2013). This regulation indicates that the data from the IO table must be updated every 5 years since 2010. This is why the year selected to conduct this study was 2015, rather than another, more up-to-date period. In addition, this data source provided, in addition to the total IO table, the domestic IO table, the importations IO table and the corresponding inverse Leontief matrices (INE, 2015b).

GHG emission data by Branch of Activity are available at the national level from the National Statistics Institute (INE, 2015a). This source reports the GHG emissions for each of the 64 different

Branches of activity according to the National Classification of Economic Activities established in the Regulation (EC) No 1893/2006 (European Commission, 2006). These GHG emission flows are provided in tons of CO_2-eq; however, to calculate the CF it was necessary to divide each value by the GDP of the corresponding Branch of activity, i.e., the emissions associated with the "*manufacture of food, beverages and tobacco products*" must be divided by the GDP of the same activity "*manufacture of food, beverages and tobacco products*". As a result, the GHG emission intensity in tons of $CO_2\text{-eq}\cdot€^{-1}$ was obtained.

Finally, data on household expenditure per group are available at a regional level with a four-digit level of disaggregation, corresponding to different expenditure groups (INE, 2021). Moreover, data is available from different consumption sources such as average expenditure per person, per household or per consumption unit. However, in Spain each autonomous community or region has a statistical institute, which can account for different groups of expenditure depending on the region. Therefore, if the number of expenditure groups considered in the statistical institute of a region is different from those considered by the national statistics institute, the results obtained from some data or others will be different.

The lack of data at the city level made it necessary to transform some required data by means of downscaling factors (Shafie et al., 2013). Thus, these factors must be based on other variables with data available at different scales (Courtonne et al., 2015). Hence, two downscaling factors (DF) have been proposed which were: i) DF_1 considering the average level of income per household in a city and the average level of income in the region of this city and ii) DF_2 based on the average expenditures per person in a city and in the region of the city. In this sense, **Equation 2.1** and **Equation 2.2** show the how to estimate both downscaling factors.

$$DF_1 = \frac{Incomes\ per\ household\ in\ City}{Incomes\ per\ household\ in\ Region} \quad \textbf{(Equation 2.1)}$$

$$DF_2 = \frac{Expenditures\ per\ person\ in\ City}{Expenditures\ per\ person\ in\ Region} \quad \textbf{(Equation 2.2)}$$

2.3.2 Equivalences between expenditures groups and economic sectors of the IO table.

One of the most important points of the EEIOA was to establish the equivalences between the expenditures groups, the 64 Branches of activity and the 64 economic sectors of the IO table. The relationship between Branches of activity and Economic sectors was evident, since each branch of activity corresponds to a specific economic sector. However, for the expenditures groups, relationships were established between each of the expenditure groups and the economic sectors, in such a way that several expenditure groups can belong to the same sector. To determine these relationships, this study used the Regulation (EC) No 1893/2006 (European Commission, 2006), which provides a breakdown of economic sectors, thus facilitating the establishment of equivalencies. **Figure 2.2** shows the case of the economic sector "*Products of agriculture, hunting and related services*", which is related to the branch of activity "*Crop and animal production, hunting and related service activities*" and to the expenditure groups "*Meat*" and "*Fruits*".

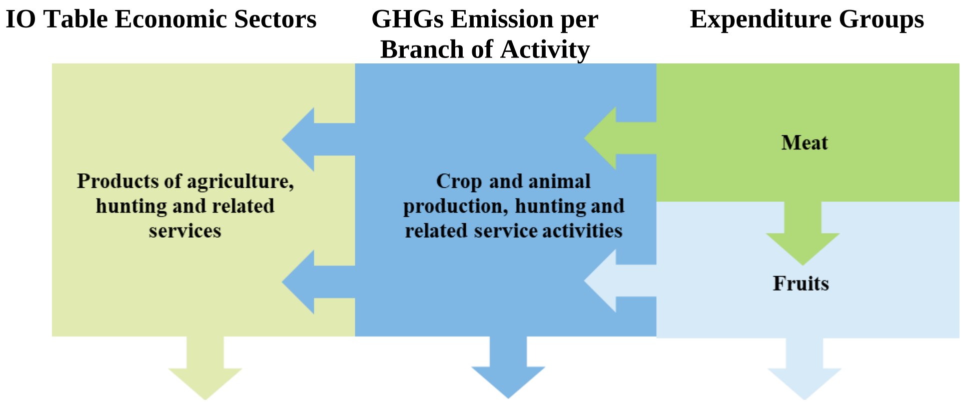

Figure 2.2. Equivalences between Branches of activities, Economic sectors of the Input-Output (IO) table and Expenditure groups corresponding to the first economic sector considered "Products of agriculture, hunting and related services".

Hence, expenditure on "*Products of agriculture, hunting and related services*" has been calculated as the sum of the expenditure per person on "*Meat*" and "*Fruits*". In this way, the expenditure groups were classified into *n* economic sectors. However, in the IO table, other economic sectors were considered that do not have a direct relation with the expenditure groups, such as "*Mining and quarrying*", "*Coke and refined petroleum products*" or "*Chemicals and chemical products*". Thus, these sectors did not directly affect the everyday life of citizens, but rather indirectly. For example, a family buys a car, this expense is associated with the economic sector "*Motor vehicles, trailers and semi-trailers*", but the manufacture of the car requires other sectors such as "*Mining and quarrying*", "*Fabricated metal products, except machinery and equipment* "or" *Rubber and plastics products* ".

2.3.3 Carbon Footprint calculation

EEIOA consists of transforming economic data into environmental impacts. Thus, in this study the CF was calculated by transforming the expenditures (in €) of the citizens of Cadiz in tons of CO_2-eq, following the methodology described by Dias et al. (2014).

Consequently, this calculation was based on the three main databases that consist basically of a matrix ($(I-A)^{-1}$) and two vectors (Y and Z):

$$(I-A)^{-1} = \begin{pmatrix} c_{1,1} & \cdots & c_{1,n} \\ \vdots & \ddots & \vdots \\ c_{64,1} & \cdots & c_{64,n} \end{pmatrix}$$ (Inverse Leontief matrix)

$$Y = \begin{pmatrix} y_1 & \cdots & y_n \end{pmatrix}$$ (Expenditures by economic sector vector)

$$Z = \begin{pmatrix} z_1 \\ \vdots \\ z_{64} \end{pmatrix}$$ (GHG emission vector)

The inverse Leontief matrix ($(I\text{-}A)^{-1}$) was composed of the coefficients $c_{i,j}$ distributed in 64 rows according to the number of economic sectors, and *n* columns corresponding to the economic sectors related to the expenditure groups. The expenditures by economic sector vector (*Y*) were made up by the expenditure groups classified in the *n* economic sectors in accordance with Section 2.3.2 considering the downscaling factors.

Finally, in the GHG emission vector (*Z*), it was considered the emissions from the 64 economic sectors in tons of $CO_2\text{-eq}\cdot€^{-1}$, resulting from dividing the emissions of each branch of activity by the GDP as specified in Section 2.3.1.

According to these parameters and the mentioned nomenclature, **Equation 3** shows the procedure for estimating the CF according to the EEIOA methodology.

$$CF = \sum_{j=1}^{n} \sum_{i=1}^{64} c_{ij} \cdot y_j \cdot z_i$$ (**Equation 2.3**)

Where *i* corresponded with each of the 64 economic sectors and *j* with the *n* economic sectors related with the expenditure groups. Therefore, the CF for a city was calculated. Moreover, EEIOA allows to identify the contribution of the different economic sector on CF in a similar way to LCA. Consequently, it is possible identify the key sectors to mitigate the contribution of the urban system to climate change.

2.4 CONCLUSIONS

In this chapter, two methodologies for analyzing the environmental impacts of urban systems were detailed. The application of these methodologies at the local level is very recent in research, with which there are several challenges to consider. One of them is the lack of data at a local scale, which implies developing downscaling techniques to obtain the minimum possible error in the results and maximum reliability. Furthermore, there are methodological lacks such as the lack of a consensus when it comes to identifying the necessary flows in LCA or the criteria for relating expenditure groups with economic sectors with respect to EEIOA. Therefore, in the next chapters of this thesis, these methodologies were applied to different case studies, to know the main environmental impacts of these case studies, and also contribute to the development of these methodologies and their application.

2.5 REFERENCES

Arvanitoyannis, I.S., 2008. Waste Management for the Food Industries, Journal of Chemical Information and Modeling.

Beloin-Saint-Pierre, D., Rugani, B., Lasvaux, S., Mailhac, A., Popovici, E., Sibiude, G., Benetto, E., Schiopu, N., 2017. A review of urban metabolism studies to identify key methodological choices for future harmonization and implementation. J. Clean. Prod. 163, S223–S240. https://doi.org/10.1016/j.jclepro.2016.09.014

Bertram, F. de B., Rogrigues, J.F.D., Tukker, A., 2019. Modeling reductions in the environmental footprints embodied in European Union's imports through source shifting. Ecol. Econ. 164.

https://doi.org/10.1016/j.ecolecon.2019.04.012

Blonk Agri-footprint BV, 2015. Agri-footprint - Part 2 - Description of Data. Gouda, the Nederlands BSI. (2012). PAS 2050-1: 2012 Assessment of life cycle greenhouse gas emissions from horticultural products. BSI.

Chester, M., Pincetl, S., Allenby, B., 2012. Avoiding unintended tradeoffs by integrating life-cycle impact assessment with urban metabolism. Curr. Opin. Environ. Sustain. 4, 451–457. https://doi.org/10.1016/j.cosust.2012.08.004

Courtonne, J.Y., Alapetite, J., Longaretti, P.Y., Dupré, D., Prados, E., 2015. Downscaling material flow analysis: The case of the cereal supply chain in France. Ecol. Econ. 118, 67–80. https://doi.org/10.1016/j.ecolecon.2015.07.007

Currie, P.K., Musango, J.K., May, N.D., 2017. Urban metabolism: A review with reference to Cape Town. Cities 70, 91–110. https://doi.org/10.1016/j.cities.2017.06.005

Dias, A., Lemos, D., Gabarrell, X., Arroja, L., 2018. Comparison of tools for quantifying the environmental performance of an urban territory. J. Ind. Ecol. 22, 868–880. https://doi.org/10.1111/jiec.12614

Dias, A.C., Lemos, D., Gabarrell, X., Arroja, L., 2014. Environmentally extended input-output analysis on a city scale - Application to Aveiro (Portugal). J. Clean. Prod. 75, 118–129. https://doi.org/10.1016/j.jclepro.2014.04.012

European Commission, 2006. Regulation (EC) No 1893/2006 of the Eurpean Parliament and of the Council of 20 December 2006.

European Union, 2013. Regulation (EU) No 549/2013 of the European Parliament and of the Council of 21 May 2013 2013.

García-Guaita, F., González-García, S., Villanueva-Rey, P., Moreira, M.T., Feijoo, G., 2018. Integrating Urban Metabolism, Material Flow Analysis and Life Cycle Assessment in the environmental evaluation of Santiago de Compostela. Sustain. Cities Soc. 40, 569–580. https://doi.org/10.1016/j.scs.2018.04.027

Ghaemi, Z., Smith, A.D., 2020. A review on the quantification of life cycle greenhouse gas emissions at urban scale. J. Clean. Prod. 252, 119634. https://doi.org/10.1016/j.jclepro.2019.119634

Goldstein, B., Birkved, M., Quitzau, M.B., Hauschild, M., 2013. Quantification of urban metabolism through coupling with the life cycle assessment framework: Concept development and case study. Environ. Res. Lett. 8. https://doi.org/10.1088/1748-9326/8/3/035024

González-García, S., Caamaño, M.R., Moreira, M.T., Feijoo, G., 2021. Environmental profile of the municipality of Madrid through the methodologies of Urban Metabolism and Life Cycle Analysis. Sustain. Cities Soc. 64. https://doi.org/10.1016/ j.scs.2020.102546

González-García, S., Dias, A.C., 2019. Integrating lifecycle assessment and urban metabolism at city level: Comparison between Spanish cities. J. Ind. Ecol. 23, 1062–1076. https://doi.org/10.1111/jiec.12844

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M.D.M., Hollander, A., Zijp, M., van Zelm, R., 2017. ReCiPe 2016 v1.1.

INE, 2021. Statistics National Institute. Total expenditure, average expenditure and distribution of household expenditure (in Spanish). https://www.ine.es/ (accessed May 2021)

INE, 2015a. National annual accounting of Spain: Input-Output tables. National Statistical Institute (in Spanish). https://www.ine.es/dyngs/INEbase/es/ (accessed May 2021)

INE, 2015b. Air emissions accounts by branches of activity (CNAE 2009). National Statistical Institute (in Spanish). https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736176941&menu=ultiDatos&idp=1254735976

603 (accessed May 2021)

ISO 14040, 2006. International Organization for Standardization, ISO 14040. Environmental Management-Life Cycle Assessment - Principles and Framework, Geneve.

Jungbluth, N., 2019. Recommendations for calculation of the global warming potential of aviation including the radiative forcing index 404–411.

Kalbar, P.P., Birkved, M., Kabins, S., Nygaard, S.E., 2016. Personal Metabolism (PM) coupled with Life Cycle Assessment (LCA) model: Danish Case Study. Environ. Int. 91, 168–179. https://doi.org/10.1016/j.envint.2016.02.032

Kennedy, C., Cuddihy, J., Engel-yan, J., 2007a. The Changing Metabolism of Cities 11.

Kennedy, C., Cuddihy, J., Engel-yan, J., 2007b. The Changing Metabolism of Cities 11. https://doi.org/10.1007/s00125-014-3420-8

Leontief, W.W., 1936. Quantitative Input and Output Relations in the Economic Systems of the United States. Rev. Econ. Stat. 18, 105–125.

Li, Y., Wang, X., Tian, X., Zhang, Y., 2018. Understanding the mechanism of urban material metabolism with ecological network analysis: An experimental study of Wuxi, China. Ecol. Modell. 367, 58–67. https://doi.org/10.1016/j.ecolmodel.2017.09.007

Lopes Silva, D.A., De Oliveira, J.A., Saavedra, Y.M.B., Ometto, A.R., Rieradevall I Pons, J., Gabarrell Durany, X., 2015. Combined MFA and LCA approach to evaluate the metabolism of service polygons: A case study on a university campus. Resour. Conserv. Recycl. 94, 157–168. https://doi.org/10.1016/j.resconrec.2014.11.001

Moreno Ruiz, E., Valsasina, L., Brunner, F., Symeonidis, A., FitzGerald, D., Treyer, K., Bourgault, G., Wernet, G., 2018. Documentation of changes implemented in ecoinvent database v3.5. Ecoinvent, Zürich, Switzerland. 5, 1–97.

Nakem, S., Pipatanatornkul, J., Papong, S., Rodcharoen, T., Nithitanakul, M., Malakul, P., 2016. Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) Study for Sustainable Management of PVC Wastes in Thailand, in: Computer Aided Chemical Engineering. pp. 1689–1694. https://doi.org/10.1016/B978-0-444-63428-3.50286-1

Parkes, O., Lettieri, P., Bogle, I.D.L., 2015. Life cycle assessment of integrated waste management systems for alternative legacy scenarios of the London Olympic Park. Waste Manag. 40, 157–166. https://doi.org/10.1016/j.wasman.2015.03.017

Pincetl, S., Bunje, P., Holmes, T., 2012. An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes. Landsc. Urban Plan. 107, 193–202. https://doi.org/10.1016/j.landurbplan.2012.06.006

Rama, M., Entrena-Barbero, E., Dias, A.C., Moreira, M.T., Feijoo, G., González-García, S., 2021. Evaluating the carbon footprint of a Spanish city through environmentally extended input output analysis and comparison with life cycle assessment. Sci. Total Environ. 762, 143133. https://doi.org/10.1016/j.scitotenv.2020.143133

Ridoutt, B.G., Hadjikakou, M., Nolan, M., Bryan, B.A., 2018. From Water-Use to Water-Scarcity Footprinting in Environmentally Extended Input-Output Analysis. Environ. Sci. Technol. 52, 6761–6770. https://doi.org/10.1021/acs.est.8b00416

Rosado, L., Kalmykova, Y., Patrício, J., 2016. Urban metabolism profiles. An empirical analysis of the material flow characteristics of three metropolitan areas in Sweden. J. Clean. Prod. 163, 254–266. https://doi.org/10.1016/j.jclepro.2017.05.143

Rosado, L., Niza, S., Ferrao, P., 2014. A Material Flow Accounting Case Study of the Lisbon Metropolitan Area using the Urban Metabolism Analyst Model. J. Ind. Ecol. 18, 84–101. https://doi.org/10.1111/jiec.12083

Sahely, H., Dudding, S., Kennedy, C., 2003. Estimating the Urban Metabolism of Canadian cities: Greater Toronto area case study. Can. J. Civ. Eng. 30, 468–483.

Shafie, F.A., Omar, D., Karupannan, S., Gabarrell, X., 2013. Urban metabolism using economic input-output analysis for the city of Barcelona. WIT Trans. Ecol. Environ. 179, 27–37. https://doi.org/10.2495/SC130031

Wolman, A., 1965. The Metabolism of Cities. Sci. Am. 213, 178–190. https://doi.org/10.1038/scientificamerican0965-178

Zhang, Y., 2013. Urban metabolism: A review of research methodologies. Environ. Pollut. 178, 463–473. https://doi.org/10.1016/j.envpol.2013.03.052

Chapter 3: **Environmental evaluation through Life Cycle Assessment of the municipality of Madrid**[1]

SUMMARY

In this chapter, a Life Cycle Assessment approach was conducted for the municipality of Madrid, the most populated city of Spain, with the aim of analysing the environmental profile of the municipality and contribute to the development of this methodology for the evaluation of urban systems. The results show that most of the impacts were associated to the consumption of electrical energy, manufactures products such as steel or cement, and food, especially meat products. The findings in this chapter allow performing a sustainability diagnosis of a large city such as Madrid, identifying energy needs, food consumption and manufactures as environmental hotspots. By approaching the comprehensive analysis of available data, important constraints arise, such as access to valuable data. To this end, not only the development of precise estimation tools to quantify these flows, but also greater transparency of data sources, were fundamental elements in the study of the impact categories studied in this chapter.

[1] Based on the study: González-García, S., Caamaño, M.R., Moreira, M.T., Feijoo, G. (2021). Environmental profile of the municipality of Madrid through the methodologies of Urban Metabolism and Life Cycle Analysis. Sustainable Cities and Society, 64: 102546. https://doi.org/10.1016/j.scs.2020.102546.

3.1 INTRODUCTION

Urban systems are the cause of environmental impacts derived from the consumption of goods and services by their inhabitants (Goldstein et al., 2013). In the context of a large city such as Madrid (capital and the most populated city Spain), the urban environment is not only limited to the urban nucleus itself. The City of Madrid has been solving its continuous and growing demands for urban land in the neighbouring locations, those of the municipality itself, but also those bordering. The current urban model in Madrid presents a change from a compact and multifunctional city to a diffuse city model that has grown by adsorbing neighbouring population. In this way, not only a greater use of land is observed, but also an increase in the energy costs linked to motorized mobility, as well as all the other flows required covering the daily needs of the population.

In terms of emissions, the city of Madrid carries out a rigorous record of its atmospheric emissions following the guidance of the Evaluation and Monitoring European Program of the Environmental European Agency (EMEP/EEA) (Ntziachristos et al., 2014), and has developed policies and improvement measures over the years (Andrade et al., 2018). However, the EMEP/EEA methodology only considers emissions that take place within the city limits. Consequently, the emission of atmospheric pollutants released by the production of energy to satisfy the demand of Madrid was not accounted for, so the final impacts associated with these emissions were not quantified. In the case of water and soil pollutants, only domestic production of emissions is considered and, therefore, some challenges arise related to ensuring the effectiveness of regional environmental policies capable of achieving an absolute reduction of impacts (Barrett et al., 2013).

In Chapter 2, Life Cycle Assessment (LCA) was presented as a methodology which could be used to evaluate the environmental impacts derived of an urban system. In this chapter, LCA was applied in the city of Madrid to analyze the environmental profile of the municipality and to contribute to develop this methodology on a local scale. Therefore, the four LCA stages established by ISO 14040, (2006a) and described in Chapter 2 were followed. In the Materials and Methods section, stages 1 to 3 were detailed and, in the Results and Discussion sections the last stage was developed.

3.2 MATERIALS AND METHODS

3.2.1 Goal and Scope definition: Municipality of Madrid

The limits of the system established in the study carried out in this chapter were the municipal limits of Madrid. The city is the administrative and financial capital of Spain. As indicated by the IECM, (2021a), it is also the most populated city in the country (3,334,730 inhabitants registered in 2020) and the first in urban area (604.66 km^2). Furthermore, its capital and historical-artistic heritage make this city a top-level tourist centre, as evidenced by the number of travellers that overnighted in Madrid: 8,384,306 in 2014 (City Council of Madrid, 2018a). The fact that the metropolitan area hosts many "dormitory cities" around the capital makes Madrid a municipality with a large floating population. This result in an extensive transport infrastructure, including several stations for short, medium and long-distance trains, an international airport, more than 10 subway lines and a dense road network. The intense traffic registered in the municipality is partly responsible for high pollution peaks, which forced to restrict traffic in 2017 (City Council of Madrid. GDSEC, 2017). The characteristic climate of Madrid does not help either, as both wind and rain are scarce throughout the year, although their incidence increases in winter (Climate-Data, 2018), so episodes of atmospheric pollution remain for days or weeks.

In terms of economic indicators, Madrid plays a major role in both the regional and national context. The aspects that characterize Madrid are the influence of the capital on the location of companies, its economic structure characterized by a high degree of atomization, the higher level of income of the municipality compared to the national average, the significant dependence of the local economy on the public sector and as negative features, the high price of land and the congestion of the municipality that limits the level of growth of new establishments. In relative figures, Madrid's heavy dependence on the service sector represents 90% of the total Gross Domestic Product (GDP) of the municipality in 2016. Within this area, administrative and financial companies represent 51% of GDP, compared to 25% of distribution and tourism and 24% of other services. The secondary sector accounts for 10% of GDP, with 60% coming from mining and industry and 40% from construction (IECM, 2021b). In a municipality of these characteristics, the primary sector, as we understand it in terms of agricultural and livestock farms for food production, is reduced to testimonial levels of urban agriculture, so that food inputs come from other geographical areas (IECM, 2021b).

3.2.1.1 Functional Unit

The functional unit is the quantified performance of a product system used as a reference unit (ISO 14040, 2006). As cities are complex organisms, it is common to express all results in units per capita (Dias et al., 2014; Goldstein et al., 2013; González-García and Dias, 2019). This practice has the added advantage of allowing comparison among cities with different populations. It should be borne in mind that the values of the census population represent a fraction of the total number of inhabitants, as it was necessary to consider not only the influence of the visiting population, mainly tourists, but also the population living in the metropolitan area and working in Madrid, so they need to travel daily.

Therefore, the 'inhabitant-equivalent' unit was defined as the amount of permanent population (i.e., living in Madrid most of the year) that consumes the same amount of resources as the floating population (García-Guaita et al., 2018) taking into account visitors, workers who move to the municipality every day, and students who live in the municipality only during the academic year. In the case of visitors, both the number of tourists and the average duration of their visit has been taken from the information available in periodic reports of the Madrid City Council (2018a). Therefore, the value of inhabitants-equivalent due to tourism was calculated by **Equation 3.1**.

$$\mathrm{IE} = \frac{VT}{\mathrm{PPT}} * Number\ of\ tourists \quad \textbf{(Equation 3.1)}$$

Where IE was the number of inhabitants-equivalent associated with tourism; VT was the average time visitors spent in the municipality (2.06 days) and PPT was the average residence time of the permanent population (typically 365 days).

In the case of the floating population working in the municipality, an 8-hour working day was estimated. The number of inhabitants-equivalent was calculated according to **Equation 3.2**. Regarding the number of workers, this data was available from the Instituto de Estadística de la Comunidad de Madrid (IECM, 2021c).

$$\mathrm{IE} = \frac{WT}{\mathrm{PPT}} * Number\ of\ workers \quad \textbf{(Equation 3.2)}$$

Where IE was the number of inhabitants-equivalent associated with workers; WT was the corresponding time (in days) that workers spent in the municipality and was calculated by taking into account the number of working days in a year, i.e. discounting holidays (22 days), bank holidays (14 days) and weekends (104 days) from the annual period and multiplying the result by the ratio that a worker spent per day (on average): 8 h of daily working day/24 h and 0.56 h of travel time (INE, 2021); PPT was the average residence time of the permanent population (typically 365 days).

For students, the inhabitants-equivalent was calculated according to **Equation 3.3**. To do so, the duration of an academic year (AY) of 220 days (García-Guaita et al., 2018) and the mentioned PPT (365 days) were considered. When calculating the number of students which only live in Madrid during the academic year, foreign non-university students (City Council of Madrid, 2018b) and foreign university students (Universidad Autónoma de Madrid, 2017; Universidad Complutense de Madrid, 2016; Universidad Politécnica de Madrid, 2017) were counted due to the limited information available. Only in the case of the Universidad Autónoma de Madrid has it been possible to consider the number of Spanish students who live in Madrid during the academic year.

$$\mathrm{IE} = \frac{AY}{\mathrm{PPT}} * Number\ of\ students \quad \textbf{(Equation 3.3)}$$

Bearing in mind the abovementioned inhabitant-equivalent estimates and the inhabitants registered in the census which were 3,182,981 in 2017 (INE, 2020), the final population considered for the municipality was 3,402,134 inhabitants-equivalent in 2017.

Although data were available for certain flows that correspond to more than 15 years, from 2000 to 2017, most data were only available for the years 2014 to 2017, with only a few exceptions (plastics, cement, steel and glass). Therefore, it was decided to consider the time series between 2014 and 2017, assuming that the consumption of resources would be the same for these years. Thus, the impacts were calculated per inhabitant-equivalent and year between 2014 and 2017.

3.2.2 Life Cycle Inventory (LCI)

In order to include in the calculations a sufficient number of valid and representative material flows to carry out the analysis of the metabolism of the municipality of Madrid, seven general streams have been considered (**Figure 3.1**), whose selection has been carried out according to the approach developed in other studies (Dias et al., 2018, 2014; Goldstein et al., 2013). Thus, **Figure 3.1** shows the different flows (transport, energy, food and drinks, manufacturing, municipal solid waste, water and wastewater), and the process for each flow considered. Considering the LCA approach, the background processes involved in the production of all municipality inputs (i.e., raw material extraction), as well as solid waste and wastewater management, have been considered within the boundaries of analysis.

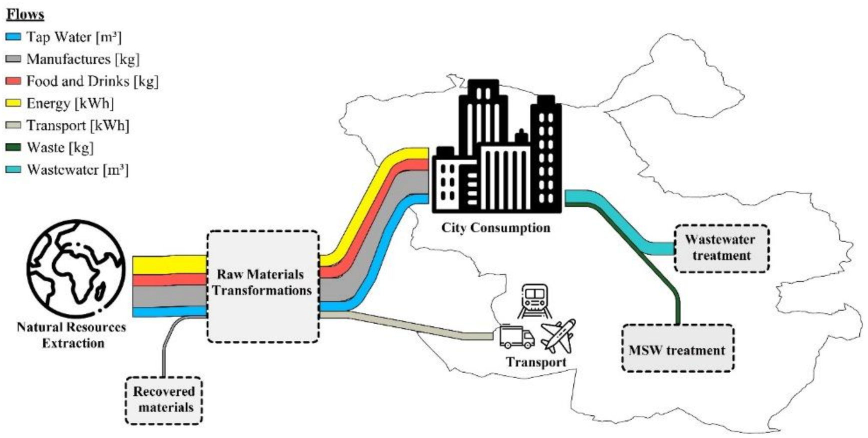

Figure 3.1. Schematic representation of the flows considered in the LCA of the municipality of Madrid.

Some data were only available at regional (Autonomous Community of Madrid) or even national (Spain) scale. Therefore, it was necessary to downscale these data. For this purpose, a ratio of the population at each level was applied according to **Equation 3.4**.

$$X_{i,L} = X_{i,U} \frac{P_L}{P_U} \qquad \textbf{(Equation 3.4)}$$

Where X_i was the datum of interest; P the population; and U and L represent the upper and lower levels, respectively. Therefore, **Table 3.1** shows the values considered.

Table 3.1. Information used for downscaling. All data correspond to year 2017.

	Inhabitants
Population at the regional level	6,507,184
Population at the local level	3,402,134
Population at the national level	46,572,184
Ratio (P_L/P_U) of population regional-local	0.523
Ratio (P_L/P_U) of population national-local	0.073

In other cases, data were available but not disaggregated – i.e., only the consumption of big groups comprehending several flows. There, it was assumed that the tendency of consumption remains equal at all levels. This means that, if a certain percentage of all building materials correspond to wood in Spain, the same percentage will be observed at local scale. This assumption allows disaggregating the information at local scale into its different flows.

Background (outside the municipality limits) data have been taken from Ecoinvent® 3.5 database (Moreno Ruiz et al., 2018) or from peer-review scientific papers when necessary, as detailed in the corresponding cases.

3.2.2.1 Energy and Transport

Energy and transport data were available at local scale and it were composed of electricity, fossil fuels for heating and renewable sources (Fundación para el Fomento de la Innovación Industrial, 2016) – see **Table 3.2**, which presents data on energy consumption of dwellings, shops and industries located in the municipality in 2016. It was important to bear in mind that 93% of total GDP of the municipality of Madrid in 2018 was associated with financial services and tourism (IECM, 2021b). Therefore, it has been considered that all goods consumed in the municipality were imported, avoiding double counting.

On the other hand, data on fuel consumption in 2016 for transport were shown in **Table 3.2**, as road transport and other means of transport. In addition, traffic statistics (e.g. number of vehicles per type) were available online (Directorate General of Traffic, 2016). In transport were included cars, motorbikes, lorries and vans and buses. Metro transport has been estimated from electricity consumption data. The production and maintenance of the vehicles used in Madrid were included in the system boundaries.

Table 3.2. Fuels and electricity consumption data used in dwellings, shops, industry and transport in kWh·inhab-eq^{-1}·year^{-1}.

Flow	Dwellings and shops	Industry	Road transport	Other means of transport	Total
Biomass	22.3				22.3
Natural gas	2,194	311	121		2,626
LPG	89.9	5.0	16.5		111
Petrol			766		766
Diesel	512	26.3	2,244	82.0	2,782
Fuel oil		1.3			1.3
Kerosene				561	561
ETBE[2]			74.7		74.7
Biodiesel			103		103
Bioethanol			0		0.0
Electricity	3,187	213	0.1	301	3,701
Coal	71.0				71.0
Solar	44.2				44.2
Geothermal	0.9				0.9

3.2.2.2 Water

Water consumption included tap water (for cleaning, drinking and cooking), as well as that for irrigation and cleaning public spaces and consumed water by industry. Data were available at a regional level and highly disaggregated at industrial and domestic levels for year 2016 (IECM, 2021d) – see **Table 3.3**.

[2] Ethyl Tert-butyl Ether

Table 3.3. Water consumption data.

Units	Total	Domestic use	Industrial use	Others
$m^3 \cdot inhab\text{-}eq^{-1} \cdot year^{-1}$	59.9	44.8	11.1	4.0

3.2.2.3 Food and beverages

All food and beverage consumption data were available at regional level per capita and day and were taken directly from literature for year 2015 (ENUCAM, 2015; MAPA, 2020). Average food intake values per inhabitant were assumed. A detailed description of the inventory data and data sources for food consumption rates classified by food groups (vegetables, fruits, meat, fish, seafood and other food) was given in **Table 3.4**. Moreover, **Table 3.5** displays the consumption rates of beverages.

Table 3.4. Food consumption data.

Flow	**Consumption ($kg·inhab\text{-}eq^{-1}year^{-1}$)**	**Data source**	**Source of background data**
		Vegetables	
Fresh potatoes	25.2	(ENUCAM, 2015)	Ecoinvent®
Onion	22.2	(ENUCAM, 2015)	Ecoinvent®
Lettuce	18.2	(ENUCAM, 2015)	Ecoinvent®
Tomato	32.9	(ENUCAM, 2015)	Ecoinvent®
Chickpea	2.3	(ENUCAM, 2015)	(Blonk Agri-footprint BV, 2015)
Beans	1.8	(ENUCAM, 2015)	(Blonk Agri-footprint BV, 2015)
Lentil	2.6	(ENUCAM, 2015)	(Blonk Agri-footprint BV, 2015)
Total	105		
		Fruits	
Citrus	46.4	(ENUCAM, 2015)	(Blonk Agri-footprint BV, 2015)
Apple	28.2	(ENUCAM, 2015)	(Blonk Agri-footprint BV, 2015)
Melon	26.0	(ENUCAM, 2015)	(Blonk Agri-footprint BV, 2015)
Total	100		
		Meat	
Beef	14.2	(ENUCAM, 2015)	Ecoinvent®
Lamb	3.7	(ENUCAM, 2015)	Ecoinvent®
Chicken	16.2	(ENUCAM, 2015)	Ecoinvent®
Pig	11.1	(ENUCAM, 2015)	(Noya et al., 2017)
Total	45.3		

Table 3.4 (cont.). Food consumption data.

Flow	**Consumption ($kg·inhab-eq^{-1}year^{-1}$)**	**Data source**	**Source of background data**
	Fresh Fish		
Tuna (fresh)	2.2	(ENUCAM, 2015)	(Vázquez-Rowe et al., 2011)
Blue fish	11.5	(ENUCAM, 2015)	(Vázquez-Rowe et al., 2011)
White fish	21.7	(ENUCAM, 2015)	(Vázquez-Rowe et al., 2011)
Canned tuna	5.5	(ENUCAM, 2015)	(Vázquez-Rowe et al., 2011)
Total	40.9		
	Frozen Fish		
Blue fish	0.1	(MAPA, 2020)	(Vázquez-Rowe et al., 2011)
White fish	1.3	(MAPA, 2020)	(Vázquez-Rowe et al., 2011)
Total	1.4		
	Seafood		
Mussel	5.6	(ENUCAM, 2015)	(Vázquez-Rowe et al., 2016)
Lobster	2.4	(ENUCAM, 2015)	(Vázquez-Rowe et al., 2016)
Total	8.0		
	Other food		
Eggs	9.5	(ENUCAM, 2015)	Ecoinvent®
Rice	3.4	(ENUCAM, 2015)	Ecoinvent®
Bread	33.9	(ENUCAM, 2015)	Ecoinvent®
Cereals	2.7	(ENUCAM, 2015)	Ecoinvent®
Pasta	6.2	(ENUCAM, 2015)	Ecoinvent®
Milk	110	(ENUCAM, 2015)	Ecoinvent®
Yogurt	27.9	(ENUCAM, 2015)	Ecoinvent®
Sugar	2.5	(ENUCAM, 2015)	Ecoinvent®
Honey	1.2	(ENUCAM, 2015)	(Postacchini et al., 2018)
Other oils	0.4	(ENUCAM, 2015)	Ecoinvent®
Olive oil	10.3	(ENUCAM, 2015)	(Tsarouhas et al., 2015)
Butter	0.5	(ENUCAM, 2015)	(Blonk Agri-footprint BV, 2015)

Table 3.5. Beverages consumption data.

Flow	Consumption (L·inhab-eq^{-1}·year^{-1})	Data source	Source of background data
Bottled water	483	(ENUCAM, 2015)	(Garfí et al., 2016)
Soft drinks	62	(ENUCAM, 2015)	(Amienyo et al., 2013)
Citric juice	16	(ENUCAM, 2015)	Ecoinvent®
Beer	29	(ENUCAM, 2015)	(Cordella et al., 2008)
Wine	7.3	(ENUCAM, 2015)	(Villanueva-Rey et al., 2014)

3.2.2.4 Manufactures

Within Manufactures was considered fertilizers, plastics, glass, paper and cardboard and building materials. Local consumption of fertilizers (e.g. for gardening activities) has been estimated on the basis of regional data (MAPA, 2017) classified by the type of fertilizer (nitrogen, phosphate and potassium based fertilizer). In the case of plastics or glass, a similar approach has been followed considering that data are available at national level (Plastics Europe, 2017; Regueiro, 2000). As far as plastics were concerned, data were classified by high density polyethylene (HDPE), low density polyethylene (LDPE), linear low-density polyethylene (LLDPE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyurethane (PUR) and others. The consumption of paper and cardboard has been estimated by means of downscaling data at national level taken from the Spanish Association of Pulp, Paper and Cardboard Manufacturers (ASPAPEL, 2015).

Andrade et al. (2018) provided data on cement and steel (building materials), while information on sand and gravel was available at regional level (ANEFA, 2016) and has been downscaled considering the target population. Wood input was considered as a construction material in the form of board and sawn wood (MAPA, 2016). Detailed inventory data of manufactures were given in **Table 3.6**.

Table 3.6. Manufactures consumption data.

Flow	Consumption	Units
Glass	45.3	kg·inhab-eq^{-1}·year^{-1}
Plastics		
HDPE	9.46	kg·inhab-eq^{-1}·year^{-1}
LDPE+LLDPE	13.5	kg·inhab-eq^{-1}·year^{-1}
PP	14.8	kg·inhab-eq^{-1}·year^{-1}
PVC	7.69	kg·inhab-eq^{-1}·year^{-1}
PS + EPS	5.15	kg·inhab-eq^{-1}·year^{-1}
PET	5.69	kg·inhab-eq^{-1}·year^{-1}
PUR	5.77	kg·inhab-eq^{-1}·year^{-1}
Others	14.8	kg·inhab-eq^{-1}·year^{-1}
Paper/Cardboard		
Cardboard	233	kg·inhab-eq^{-1}·year^{-1}
Paper	82.6	kg·inhab-eq^{-1}·year^{-1}
Fertilizers		
Nitrogen Fertilizer	0.946	kg·inhab-eq^{-1}·year^{-1}
Phosphate Fertilizer	0.387	kg·inhab-eq^{-1}·year^{-1}
Potassium Fertilizer	0.201	kg·inhab-eq^{-1}·year^{-1}
Building Materials		
Sawn wood (softwood)	$1.63\cdot10^{-2}$	m^{3}·inhab-eq^{-1}·year^{-1}
Sawn wood (hardwood)	$4.02\cdot10^{-2}$	m^{3}·inhab-eq^{-1}·year^{-1}
Board (softwood)	$1.78\cdot10^{-2}$	m^{3}·inhab-eq^{-1}·year^{-1}
Board (hardwood)	$3.61\cdot10^{-2}$	m^{3}·inhab-eq^{-1}·year^{-1}
Cement	508	kg·inhab-eq^{-1}·year^{-1}
Steel	278	kg·inhab-eq^{-1}·year^{-1}
Sand	1,067	kg·inhab-eq^{-1}·year^{-1}

3.2.2.5 Municipal Solid Wastes

Solid waste generated in the municipality of Madrid is transported to the Treatment Center of Valdemín Gómez for recycling, incineration and final disposal. The composition of waste collected from dwellings in the municipality of Madrid was 27.2% plastics, 25.2% organic matter, 17.2% paper and cardboard, 7.2% metals, 4.4%

tetra bricks, 3.1% glass and 15.8% other wastes, which included electronics and clothing, among others. Moreover, glass, paper and cardboard from separated collection were also included. Only data on the composition of collected and recovered materials was available in the data sources. Therefore, the total waste incinerated and disposed of consists of a mixture of waste.The data on a local level can be found in City Council of Madrid (2014) and were summarized in **Table 3.7**. There was no data on metals collected disaggregated by type and it was considered that the organic matter was recovered as compost (except the part which was to landfill disposal and incineration).

Table 3.7. Wastes generation data in kg·inhab-eq^{-1}·year^{-1}.

	Collected	Recovered	Landfill	Incineration
Plastics	97.6	5.44	-	-
Iron	25.8	4.76	-	-
Iron Burned		1.33	-	-
Aluminum		0.30	-	-
Other Metals		0.26	-	-
Paper and Cardboard	61.7	7.82	-	-
Glass	11.1	0.21	-	-
Organic matter/Compost	90.5	4.26	-	-
Other wastes	72.3		-	-
Total	359	20.9	247	91.3

3.2.2.6 *Wastewater*

Madrid has eight wastewater treatment plants (WWTP) – see **Table 3.8** and **Table 3.9**, with more than 5,000 km of sewerage network satisfying the needs of more than 4 million inhabitants. In general, primary and secondary biological treatment is the technology used in most WWTP. Moreover, the plants of Viveros de la Villa, La Gavia and La China have a tertiary treatment. These three plants, together with that of Rejas, produce regenerated water for irrigation that can be used in the green zones and gardens of the municipality (City Council of Madrid, 2018c). Once again, data are available at municipality level (City Council of Madrid, 2018d). The electrical consumption of the WWTPs, the construction processes and other background data were considered from the Ecoinvent® 3.5 database (Moreno Ruiz et al., 2018) for WWTP of a similar size to those in Madrid.

Table 3.8. Wastewater emission data.

WWTP	Flow treated ($m^3 \cdot year^{-1}$)	BOD_5[3] ($mg \cdot l^{-1}$)	SS[4] ($mg \cdot l^{-1}$)	COD[5] ($mg \cdot l^{-1}$)	P ($mg \cdot l^{-1}$)	N ($mg \cdot l^{-1}$)
Butarque	$3.71 \cdot 10^7$	12	10.7	47.1	0.48	-
La China	$4.69 \cdot 10^7$	7	5.3	31.2	0.53	-
La Gavia	$3.14 \cdot 10^7$	5.3	6.6	28.1	0.65	7.9
Rejas	$2.01 \cdot 10^7$	9.3	13.8	47.3	0.69	-
Sur	$8.20 \cdot 10^7$	8.8	10.8	42.5	0.81	-
Valdebebas	$1.13 \cdot 10^7$	13.1	17	49.7	0.79	-
Viveros de la Villa	$2.73 \cdot 10^7$	5.2	4.5	23.9	0.67	11.2
Sur Oriental	$9.13 \cdot 10^6$	5.4	9.3	27.5	0.65	10.2
Total	$2.65 \cdot 10^9$					

Table 3.9. Sludge, biogas, energy and regenerated water produced in WWTP.

WWTP	Sludge t	Biogas m^3	Energy GWh	Regenerated Water m^3
Butarque	$3.15 \cdot 10^4$	$6.07 \cdot 10^6$	13.3	-
La China	$3.83 \cdot 10^4$	$7.30 \cdot 10^6$	15.5	$2{,}51 \cdot 10^6$
La Gavia	$2.38 \cdot 10^4$	$3.19 \cdot 10^6$	6.10	$3.85 \cdot 10^5$
Rejas	$1.52 \cdot 10^4$	$2.25 \cdot 10^6$	3.92	$1.77 \cdot 10^6$
Sur	$7.61 \cdot 10^4$	$1.23 \cdot 10^7$	23.7	-
Valdebebas	$8.07 \cdot 10^3$	$1.35 \cdot 10^6$	2.71	-
Viveros de la Villa	$2.08 \cdot 10^4$	$3.70 \cdot 10^6$	7.84	$1.68 \cdot 10^6$
Total	$2.20 \cdot 10^5$	$3.70 \cdot 10^7$	74.9	$6.34 \cdot 10^6$

[3] Biological Oxygen Demand.
[4] Suspended Solids
[5] Chemical Oxygen Demand

3.2.3 Life Cycle Impact Assessment

Continuing with the steps described in Chapter 2, to carry out a LCA it is necessary to use a characterization model to transform the flows of mass and energy collected in the LCI into different categories of impact. The method chosen for this chapter was the ReCiPe v.1.1 Midpoint (Huijbregts et al., 2017; Jungbluth, 2019) – default model of the most recent and harmonized approach in LCA. This method has been chosen because it is commonly used by other authors in the analysis of urban systems (e.g., Goldstein et al., 2013; González-García et al., 2018; González-García and Dias, 2019), which facilitates the subsequent comparison with other similar studies.

The environmental profile of the municipality was characterized by 10 impact categories, which were selected on the basis of their relevance in the evaluation of cities and urban systems (Goldstein et al., 2013; González-García et al., 2018; González-García and Dias, 2019): Global Warming (GW), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Human Toxicity - carcinogenic (HT), Fine Particulate Matter Formation (FPMF), Freshwater Ecotoxicity (FET), Land Use (LU), Water Consumption (WC) and Fossil Resource Scarcity (FRS).

3.3 RESULTS AND DISCUSSION

3.3.1 Overall environmental performance

LCA results were presented in **Table 3.10** per inhabitant-equivalent unit, considering the flows from the consumption of goods and services of the citizens of the municipality of Madrid. Total GHG emissions were 7.49 tCO_2-eq· inhab-eq^{-1}·year^{-1} between 2014 and 2017. In addition, the results for the other 9 impact categories were also shown.

Table 3.10. LCA results per inhab-eq and year for Madrid.

	Units	Total
GW	t CO_2 eq	7.49
SOD	g CFC-11 eq	11.7
TA	kg SO_2 eq	30.3
FE	kg P eq	2.01
HT	kg 1.4-DB eq	625
FPMF	kg $PM_{2.5}$ eq	13.3
FET	kg 1.4-DB eq	348
LU	m^2a crop eq	1,677
WC	m^3	292
FRS	t oil eq	1.79

Fundamentally, there were three flows whose impacts were notable with respect to the others: energy, manufactures and food and beverages. Direct energy requirements were mainly responsible for freshwater ecotoxicity (33.6%) and fossil resource scarcity (35.6%) mainly due to electricity consumption. In addition, energy requirements had a great contribution in global warming (30%), terrestrial acidification (30%) and freshwater eutrophication (31.3%) Consumption of food and beverages played a key role in categories such as stratospheric ozone depletion (77%), land use (75%) and water consumption (68%), mostly due to agricultural activities specifically related to animal feed production. On the other hand, requirement of manufactures had the largest contribution in the categories of global warming (31%), freshwater eutrophication (39.8%), human toxicity (81%) and fine particulate matter formation (47%), mainly due to construction materials. Regarding freshwater ecotoxicity, MSW had a significant impact value of 30%, associated with waste management and landfilling. Finally, the impacts linked to transport activities were relevant in global warming (15.3%) and fossil resource scarcity (22.2%) due to the need for fossil fuels and derived tailpipe emissions.

There were relative contributions with negative values associated with positive impacts (environmental credits) in **Figure 3.2**, which correspond to the treatment of MSW. The rationale behind this environmental credit was linked to the recycling process.

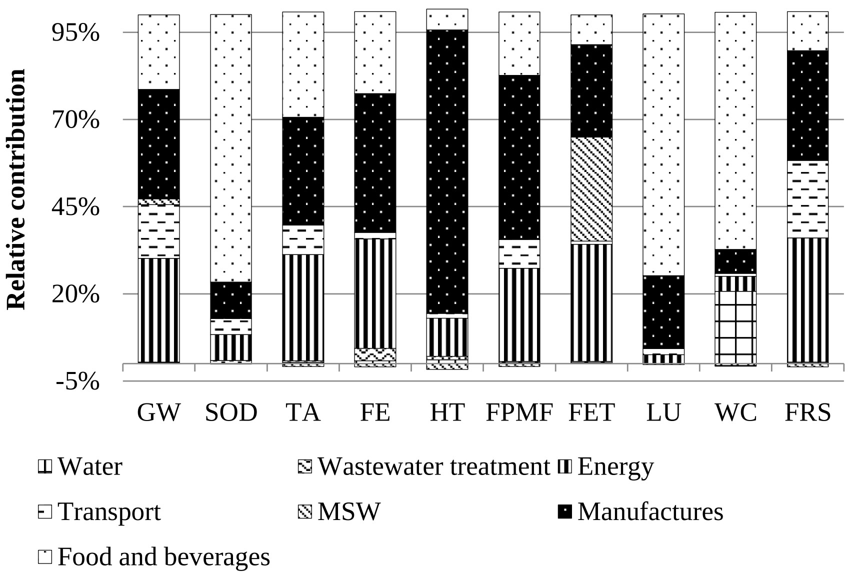

Figure 3.2. Distribution of environmental burdens from the main flows considered in the study per impact category. Acronyms: GW – Global Warming, SOD – Stratospheric Ozone Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity - carcinogenic, FPMF – Fine Particulate Matter Formation, FET – Freshwater Ecotoxicity, LU – Land Use, WC – Water Consumption, FRS –Fossil Resource Scarcity, MSW – Municipal Solid Waste management.

3.3.2 Assessment per contributing flow

This section describes in detail the rationale behind the environmental impacts of each flow, except for municipal solid waste management and water consumption (tap water and irrigation and, cleaning water), as they have a low global impact, but are significant in individual categories such as freshwater ecotoxicity and water depletion, which is not surprising given the consumption associated with a population of more than 3 million people.

3.3.2.1 Energy

Figure 3.3 presents the distribution of environmental burdens of the energy by impact category, considering their origin.

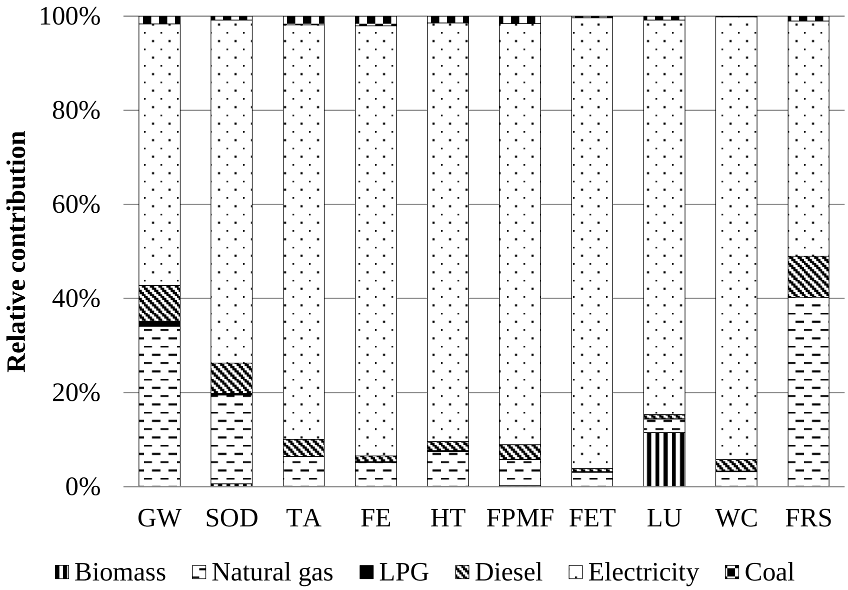

Figure 3.3. Distribution of environmental burdens derived from the production of energy requirements per impact category. Acronyms: GW – Global Warming, SOD – Stratospheric Ozone Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity - carcinogenic, FPMF – Fine Particulate Matter Formation, FET – Freshwater Ecotoxicity, LU – Land Use, WC – Water Consumption, FRS –Fossil Resource Scarcity, LPG – Liquefied Petroleum Gas.

The production of electricity requirements had an environmental impact of more than 50% in all the categories studied. The environmental profile of electricity in each region will depend on the use of fossil fuels as well as renewable energy sources. Madrid is a highly urbanized settlement, so the direct use of fossil fuels was expected to be high. However, some consumption rates can be surprising. This was the case of coal, traditionally a major contributor to climate change and terrestrial acidification (Munawer, 2018), which has a negligible impact on the profile due to its limited use in comparison with the one corresponding to other urbanized Spanish cities such as Bilbao (González-García and Dias, 2019). Nevertheless, coal was implicit in electricity production according to the electric profile of Madrid (Fundación para el Fomento de la Innovación Industrial, 2016), and its derived GHG emissions reach up to 73% of total electricity. Coal (within electricity production) also contributed significantly to terrestrial acidification (88%), freshwater eutrophication (92%), human toxicity (89%), water consumption (94%) and fossil resource scarcity (50%). Natural gas was the most common fossil fuel for domestic use (hot water and cooking), which explains its high effect on global warming (34%), stratospheric ozone depletion (19%) and fossil resource scarcity (40%). Although natural gas was also used in electricity production, its impact was limited compared to coal and fuel oil. Biomass and, in particular, solar energy and liquefied petroleum gas (LPG) had negligible impact compared to other energy sources.

3.3.2.2 Transport

Transport was assessed in detail in **Figure 3.4**. Emissions from diesel combustion in cars were the main contributor, regardless of the category to which they belong, followed by those from diesel and gasoline combustion in lorries and vans. In accordance with energy balance of Madrid (Fundación para el Fomento de la Innovación Industrial, 2016) and municipal traffic statistics (Directorate General of Traffic, 2016), diesel cars were the most commonly used. In Spain around 57% of all registered cars were powered with this fossil fuel. **Figure 3.4** shows the relative impact by fuel type and vehicle.

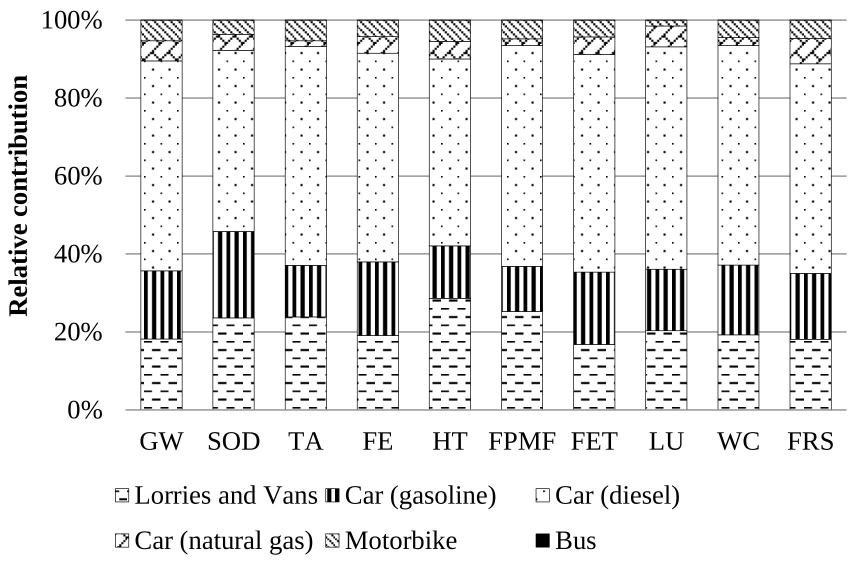

Figure 3.4. Distribution of environmental burdens arising from the production and use of transport fuels per vehicle type. Acronyms: GW – Global Warming, SOD – Stratospheric Ozone Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity - carcinogenic, FPMF – Fine Particulate Matter Formation, FET – Freshwater Ecotoxicity, LU – Land Use, WC – Water Consumption, FRS –Fossil Resource Scarcity.

3.3.2.3 Food and beverages

Figure 3.5 presents the distribution of environmental impacts derived from the demand of food. The relative impact of beverages was irrelevant (less than 2% in all impact categories) within the food chain, in line with trends observed in other studies (Andrade et al., 2018; González-García and Dias, 2019; Kalbar et al., 2016). Livestock products (meat and dairy products) were the main contributors in all impact categories which reach a value of 80% in the land use category.

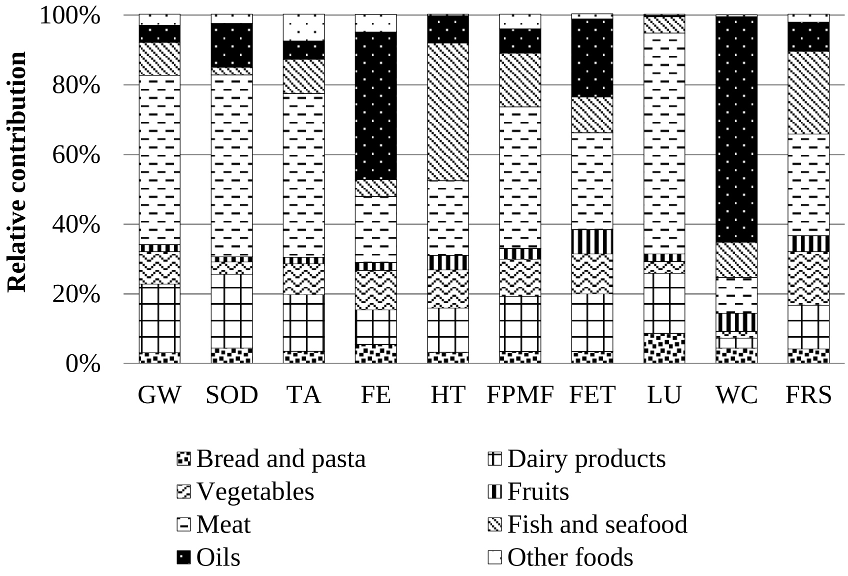

Figure 3.5. Distribution of environmental burdens arising from the production and consumption of food. Other foods include nuts, chocolate and eggs. Acronyms: GW – Global Warming, SOD – Stratospheric Ozone Depletion, TA – Terrestrial Acidification, FE – Freshwater Ecotoxicity, LU – Land Use, WC – Water Consumption, FRS –Fossil Resource Scarcity.

Not all the livestock sources (pork, cow, poultry …) contributed equally so cow derived products presented the largest environmental impacts in terms of GW (Hylan et al., 2017). **Figure 3.6** shows the contributions of the livestock products in the different impact categories studied. The sum of beef and dairy products were the main contributors in all categories. The rationale behind this was mainly related to the animal metabolism of cattle and the emission of methane by enteric fermentation in ruminants. Moreover, the environmental impacts derived from the processes behind the production of these flows (e.g., cultivation for animal feeding) were also considered as background processes. In this way, the treatment of slurry and manure, cultivation for the animal feeding which involve a large need for land farming, were also outstanding in livestock products in general.

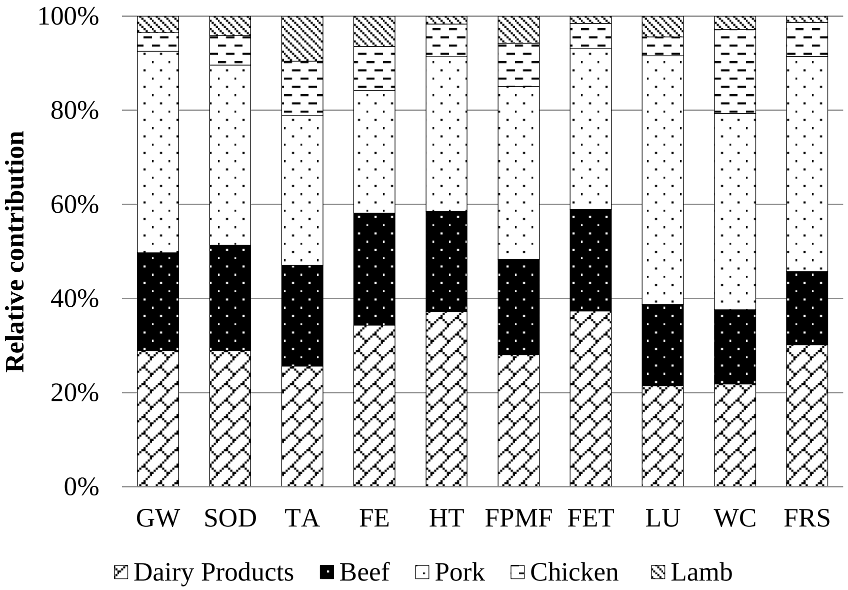

Figure 3.6. Distribution of environmental burdens arising from livestock products. Acronyms: GW – Global Warming, SOD – Stratospheric Ozone Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity - carcinogenic, FPMF – Fine Particulate Matter Formation, FET – Freshwater Ecotoxicity, LU – Land Use, WC – Water Consumption, FRS –Fossil Resource Scarcity.

However, **Figure 3.5** also shows how the vegetable oils, including sunflower and olive oil, had a large contribution in FE (57%), and WC (68%) mainly due to the high consumption of water and fertilizers during the cultivation and production stages of olive oil (Wernet et al., 2016). The wastewater associated with this process has a high phosphorus load, which had a direct effect on FE. Other foods of agricultural origin affected the eutrophication of freshwater due to the use of fertilizers in their farming activities, as well as the rest of impact categories due to energy requirements and other background processes, such as the consumption of fuels for transport.

3.3.2.4 Manufactures

The highest contribution ratios associated with manufacturing, regardless of the impact category, correspond to the production of construction materials required in the municipality, except in terms of land use, as shown in **Figure 3.7**. The rationale behind these results was the background activities involved in the production of steel requirements and, above all, the notable energy consumption associated with construction. As far as LU was concerned, background activities related to the production of wood materials such as panels, paper and sawn timber were the ones that contribute most to this. The justification for this effect was associated with the need for forest area for the production of the raw material, even taking into account the recycling rate. The contribution of fertilizers was negligible regardless the impact category, except in terms of SOD as shown in **Figure 3.7**, which was mainly associated to the consumption of nitrogen-based fertilizers and the corresponding background processes. The impacts generated by the plastics requirement were negligible regardless of the impact category. The lowest consumption rate of plastics per inhabitant compared to other manufacturing materials such as cement, steel or sand was the cause of the negligible effect mentioned (see **Table 3.6**).

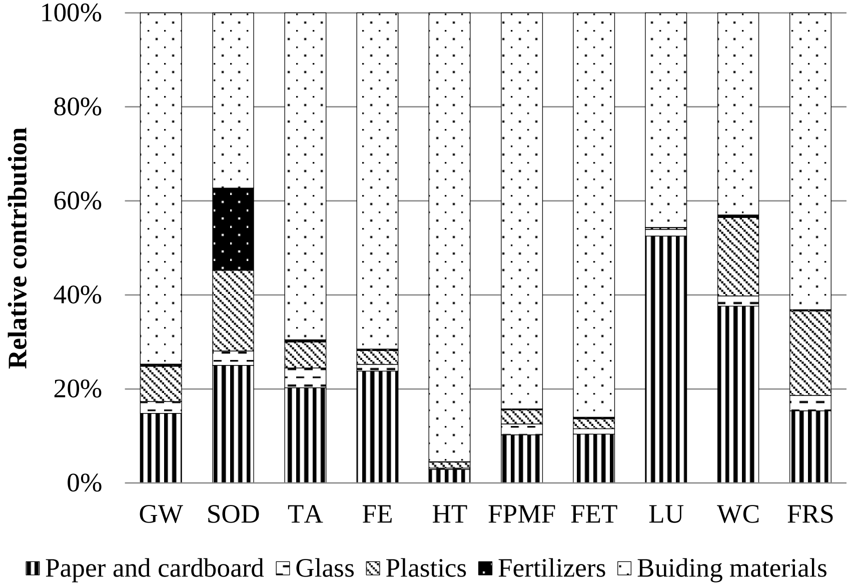

Figure 3.7. Distribution of environmental burdens arising from the demand of manufactures. Acronyms: GW – Global Warming, SOD – Stratospheric Ozone Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity - carcinogenic, FPMF – Fine Particulate Matter Formation, FET – Freshwater Ecotoxicity, LU – Land Use, WC – Water Consumption, FRS –Fossil Resource Scarcity.

3.3.2.5 Wastewater treatment

As shown in **Figure 3.2**, wastewater treatment reported a negligible contribution to the global environmental profile when considering the metabolism of Madrid as a whole, although its contribution rises to 3.7% in terms of FE. The reasons were the direct emissions to water associated with the discharge of treated effluents. Although the composition of the treated effluents strictly complies with the discharge requirements established by legislation (European Union, 1991), the treated stream contains phosphorus, nitrogen and other eutrophication agents, taking into account the water specifications available in the sources consulted.

3.3.3 Comparison with other studies

The present study established GHG emissions of Madrid at 7.49 tCO_2-eq per capita and year between 2014 and 2017. Another UM study on Madrid was performed by Gonzalez-García et al. (2018). There, GHG emissions were estimated at 6.48 tCO_2-eq per capita. Electricity, tap water, MSW and paper were considered responsible factors, as were CO_2 emissions from the municipality's metabolic activities, but not from food since this flow was excluded from the analysis. As reported in our study, food contributes significantly to global warming (22% of total), which is in line with other studies (Goldstein et al., 2013; González-García and Dias, 2019). The exclusion of food from system boundaries also affects the results for the other impact categories, specifically in terms of land use, water consumption and stratospheric ozone depletion (see **Figure 3.2**). It is important to note that, unlike Gonzalez-García et al. (2018), where sustainability (including the three pillars) was assessed, this study considers an inventory matrix based on the extensive collection of material and energy flows (tap water, manufactures, food and drinks, energy, transport, waste and wastewater), lacking social and economic indicators, since the scope is focused on the environmental sustainability according to several impact categories.

In the present study, an update of ReCiPe method (Huijbregts et al., 2017; Jungbluth, 2019) for environmental profile estimation has been considered. As a result, some impact categories as well as their reference units and contributing substances have been modified, making it difficult to directly compare the results with previous studies. In this sense, a direct comparison can be performed in terms of global warming, human toxicity, freshwater ecotoxicity, land use, water consumption, stratospheric ozone depletion, fossil resource scarcity, freshwater eutrophication and terrestrial acidification with some studies available in the literature. An independent research institute (Análisis e Investigación, 2012) evaluated the environmental sustainability of 25 Spanish cities, including Madrid. The authors considered energy, industrial processes, product use, agriculture and livestock farming and wastes to be the most relevant indicators. The results reported in this study in terms of GHG was 2.3 tCO_2-eq per capita and year, a much lower level than other studies for Spanish cities. This underestimation of impacts was associated with the fact that the methodology followed was based on a revision of the data available in official inventories, considering only the direct values of the materials, but not the life cycle perspective, i.e., the basic processes involved in the production of these products or main flows were excluded from the analysis.

In the comparative framework of this study with other similar ones, it is significant that the result obtained for Madrid in terms of GW was lower than the data reported by González-García and Dias (2019) for Bilbao (11.5 tCO_2-eq·inhab^{-1}·year^{-1}) but in line with that of Seville (7.10 tCO_2-eq·inhab^{-1}·year^{-1}), two internationally recognized Spanish cities. The reason for the difference in carbon footprint is mainly associated with different assumptions (e.g., a downscaling approach based on the gross domestic product was used by González-García and Dias (2019), on lifestyle of their inhabitants. In addition, the different climatic characteristics play an important role in terms of global warming (González-García and Dias, 2019), due to the heat requirements or electricity for air conditioning. In this sense, attention should be paid to the characteristics of cities, such as cultural, economic and climatic characteristics, aspects that imply demand for very different flows (e.g., fossil fuels for heating).

When other impact categories were compared, significant differences were observed for Bilbao, a city with considerably lower impacts than Madrid, except in terms of FE and HT, where they were similar. On the contrary, there was a higher level of coincidence with the Seville values except in FRS (lower in Madrid). The rationale behind these differences should be associated with the different mentioned downscaling adopted and other assumptions, as well as data quality, which depend mainly on the availability of the data and the scale at which they are available (city, region or nation scale). Moreover, the system boundaries considered should be considered, since this study focuses on the municipality of Madrid, and Gonzalez-García and Dias (2019) focus their study at the city level.

The bibliographic review of other studies carried out on large cities provides additional information for comparison. Goldstein et al. (2013) assessed the consequences of the metabolism of five major cities (Beijing, Cape Town, Hong Kong, London and Toronto) on climate change, freshwater ecotoxicity and agricultural land occupation. Of this sample, Cape Town (around 3,040,000 inhabitants) and Toronto (5,070,000 inhabitants) are the cities with the closest population to Madrid (3,402,134 inhab-eq). It was surprising that after considering similar flows to those selected in this paper, the results obtained reveal significant discrepancies, with Toronto reaching 18.0 tCO_2-eq per capita (climate change) and around 50 kg 1,4-DB-eq per capita (freshwater ecotoxicity), whereas Cape Town registered even higher values: 11.2 tCO_2-eq per capita and 60 kg 1,4-DB-eq per capita. However, beyond the observed divergences for GHG emissions, other indicators such as the impact of ecotoxicity in freshwater were especially high for Madrid (348 kg 1,4-DB-eq), even surpassing the value reported for Beijing (170 kg 1,4-DB-eq), whose population is more than five times that of Madrid. It was especially significant that in other studies, several Spanish cities report higher freshwater ecotoxicity emissions than Goldstein's study (Gonzalez-Garcia et al., 2018). Once again, quality of data sources and databases could be behind these differences.

Concerning agricultural land occupation, large differences can be identified between the results obtained in the present study and those of Goldstein et al. (2013). The estimated impact of Madrid reaches 1,673 m^2 crop eq per year and values of around 3,300 $m^2 \cdot year^{-1}$ and 2,200 $m^2 \cdot year^{-1}$ were reported for London and Hong Kong, respectively. These differences could be mainly associated with the inherent food ingestion rates associated with the different lifestyles, specifically in terms of livestock products (e.g., meat and dairy products which are consumed in larger amounts in UK in comparison with Spain). Regarding particulate matter formation also considered in the analysis by Goldstein et al. (2013) and González-García et al. (2018), the new definition for this impact category changes not only the reference unit for reporting the results (kg $PM_{2.5}$-eq vs kg PM_{10}-eq) but also the contributing substances (e.g., nitrate and sulphur trioxide emissions into air were not considered in the outdated version of this method), making it impossible a comparison of the results for this category.

3.3.4 Improvement measures

The lack of consensus among researchers to define the concept of sustainable municipality (or city) and the threshold criteria above which an urban area can be considered sustainable (or not), is a major drawback when it comes to classifying and comparing sustainability results in the urban sphere (Feleki et al., 2018; Tanguay et al., 2010). In this report, the proposed methodologies provide information that can be useful to implement improvement actions towards environmental benefits for the municipality.

Thus, the LCA results allow identifying the critical points of the environment and, therefore, the first "problems" to be tackled. Local decision-makers should focus on reducing electricity consumption by adopting certain policies aimed at designing the municipality with energy saving and bioclimatic criteria, reducing energy needs to achieve thermal comfort in official buildings, increasing municipal production of energy from renewable sources and promoting the option of purchasing efficient appliances. Transport has little relative effect on the environment compared to energy and manufacturing, but several measures can be implemented at the local level that makes this flow attractive to decision-makers. Various municipal actions are aimed at reducing motorized mobility, especially private, while recovering the municipality for pedestrians. As an example, the successive expansions of the public transport network, but also the Regulated Parking Service in the central districts, which is estimated to dissuade from entering the municipality more than 100,000 private vehicles per day. Today, Madrid has a shared public car service and a bicycle service.

Although the former has become a success, the latter has little demand in comparison. The most common complaint is that the municipality of Madrid offers few possibilities for cyclists, as most roads have dense traffic and there are no separate areas for bicycles.

Public transport (bus, metro and short-distance train) works well, although gasoline and diesel for buses could be replaced by cleaner fuels or hybrid technology (La Picirelli de Souza et al., 2018). The option of electric cars is an interesting one, but it requires investment in infrastructure, for example, to install sufficient charging points. In addition, the City Council of Madrid has adopted restrictions on private vehicle traffic in the city's central district, reducing nitrogen oxide emissions in one of the areas with the highest levels of air pollution (Romero et al., 2019). In addition to reducing tailpipe emissions, CO_2 collection methods could be considered. In this sense, actions focused on planting trees in urban areas could be promoted, as well as increasing vertical green areas, avoiding urban sprawl.

Food and beverages also contribute greatly to the global environmental impact. Improvements should focus on optimizing industrial food and beverage processing. However, it is possible to put pressure on industry by demanding that products carry the green label. Manufacturers owe their environmental impact primarily to production processes. Therefore, decision-makers should therefore seek to reduce demand for such products. Awareness campaigns can be useful, especially those focusing on recycling. In addition, more containers should be installed, preferably equipped with anti-theft devices. In conclusion, improvements should be considered by the citizen, ensuring a more responsible consumption, as by the producers, who should take advantage of cleaner production technologies.

3.3.5 Limitations

The lack of data made it necessary to make some estimates and assumptions in order to obtain representative flows from the system. Although this drawback is common in UM studies (Schwab et al., 2017), it may lead to uncertainty regarding the representativeness of the results. The current study considered many flows in order not to underestimate the contribution of the different inputs and outputs, but it still needs to be contrasted with other UM works to check its validity. On the other hand, the fact that certain data are only available on a larger scale (national or regional) requires certain assumptions that allow the estimation of certain variables. Although it is possible to associate a certain level of uncertainty to the temporal variable, most of the information (including energy and food, two of the most polluting flows) corresponds to the year 2017, so that the uncertainty associated with data of a not so updated current scenario may be of less relevance (García-Guaita et al., 2018).

As already indicated in previous sections, it is necessary to modify and update the number of inhabitants considered as a reference framework, including both the floating population living in the metropolitan area and the influx of tourists arriving in Madrid, in increasing numbers, which still show a seasonal trend, clearly associated with the holiday period.

3.4 CONCLUSIONS

As the core of human activities, cities are also sources of emissions and pollution, which often affect the health of their inhabitants. However, as mentioned above, most of the actual emissions due to citizens' demands occur outside municipality limits. Therefore, the Life Cycle perspective becomes imperative to obtain complete information on the environmental behavior of urban metabolism. This perspective makes it possible to develop a strategic plan from an integrated point of view, i.e., taking into account not only the local impacts of the consumption of the flows, but also the previous consequences. To ensure study quality, local data were selected whenever possible. If none were available, then assumptions were made to estimate the flows in and out of the municipality. The need for assumptions, while common to most UM-LCA studies, leads to uncertainty. However, the results were not far removed from those of similar documents, both emission values and taxpayers. Energy (direct and indirect demand, as it is consumed in all other flows), manufactures (where construction materials stand out) and food (especially products of animal origin) were the main flow of pollutants. These three flows together represent more than 75% of the total impact in all categories studied, except in the case of freshwater ecotoxicity, where the MSW had an important contribution to impact.

The city council of Madrid, together with the environmental measures currently being implemented, could focus its efforts in the short and medium term on the points of conflict identified in this study in order to integrate additional strategies to improve its sustainability. In this sense, strategies should consider: i) increasing the use of renewable energies, ii), promoting the use of ecological materials in construction activities, iii) raising awareness for a more responsible consumption of livestock products and iv) improving the municipal solid waste system; all of them are essential to achieve a more sustainable municipality. Therefore, the Madrid City Council can consider some specific actions to achieve these objectives, for example, launching a communication campaign to inform citizens about how to follow a sustainable diet, or encourage the use of solar panels through financial aid for their installation. In this sense, small and specific actions are carried out, to achieve the accomplishment of sustainability objectives within the municipality. Future research must address the drawbacks of data availability, both through the development of accurate 'estimation tools' and through the demand for greater transparency of data sources. In addition, policies should be established to provide more disaggregated data so that greater traceability of the municipality's consumption and environmental impacts is possible.

3.5 References

Amienyo, D., Gujba, H., Stichnothe, H., Azapagic, A., 2013. Life cycle environmental impacts of carbonated soft drinks. Int. J. Life Cycle Assess. 18, 77–92. https://doi.org/10.1007/s11367-012-0459-y

Análisis e Investigación, 2012. 25 Ciudades Españolas Sostenibles.

Andrade, J.C.S., Dameno, A., Pérez, J., de Andrés Almeida, J.M., Lumbreras, J., 2018. Implementing city-level carbon accounting: A comparison between Madrid and London. J. Clean. Prod. 172, 795–804. https://doi.org/10.1016/j.jclepro.2017.10.163

ANEFA, 2016. Statistics. Consumption of sand per Autonomous Community (in Spanish). http://www.aridos.org/estadisticas/ (accessed May 2021).

ASPAPEL, 2015. Annual Statistical Report and the Updating of the Sustainability Report of the Paper Sector (in Spanish). http://www.aspapel.es/content/la-producci-n-de-papel-crece-el-26-y-el-consumo-el-56-en-2015 (accessed May 2021)

Barrett, J., Peters, G., Wiedmann, T., Scott, K., Lenzen, M., Roelich, K., Le Quéré, C., 2013. Consumption-based GHG emission accounting: a UK case study. Clim. Policy 13, 451–470. https://doi.org/10.1080/14693062.2013.788858

Blonk Agri-footprint BV, 2015. Agri-footprint - Part 2 - Description of Data. Gouda, the Nederlands BSI. (2012). PAS 2050-1: 2012 Assessment of life cycle greenhouse gas emissions from horticultural products. BSI.

City Council of Madrid. GDSEC, 2017. General Direction of Sustainability and Environmental Control. Air Quality (in Spanish).

City Council of Madrid, 2018a. Tourism Statistics (in Spanish). https://www.madrid.es/portales/munimadrid/es/Estadistica/Areas-de-Informacion-Estadistica/Turismo-y-eventos?vgnextfmt=detNavegacion&vgnextchannel=6930c7edcd025210VgnVCM2000000c205a0aRCRD (accessed May 2021)

City Council of Madrid, 2018b. General Education (in Spanish). https://www.madrid.es/portales/munimadrid/es/Inicio/El-Ayuntamiento/Estadistica/Areas-de-informacion-estadistica/Areas-de-informacion-estadistica/?vgnextfmt=default&vgnextoid=9023c9fa0b23a210VgnVCM2000000c205a0aRCRD&vgnextchannel=b65ef78526674210VgnVCM1000000b205a0aRCRD (accessed May 2021)

City Council of Madrid, 2018c. Sewage System in Madrid (in Spanish). https://www.madrid.es/portales/

munimadrid/es/Inicio/Medio-ambiente/Agua/Sistemas-de-depuracion-de-aguas-residuales-en-Madrid/ (accessed March 2019)

City Council of Madrid, 2014. Technological Park of Valdemin Gómez (in Spanish). https://www.madrid.es/portales/munimadrid/es/Inicio/El-Ayuntamiento/Medio-ambiente/Residuos-y-limpieza-urbana/Parque-Tecnologico-de-Valdemingomez/(accessed March 2019).

Climate-Data, 2018. Climate: Madrid. https://es.climate-data.org/europe/espana/comunidad-de-madrid/ (accessed March 2019)

Cordella, M., Tugnoli, A., Spadoni, G., Santarelli, F., Zangrando, T., 2008. LCA of an Italian lager beer. Int. J. Life Cycle Assess. 13, 133–139. https://doi.org/10.1065/lca2007.02.306

Dias, A., Lemos, D., Gabarrell, X., Arroja, L., 2018. Comparison of tools for quantifying the environmental performance of an urban territory. J. Ind. Ecol. 22, 868–880. https://doi.org/10.1111/jiec.12614

Dias, A.C., Lemos, D., Gabarrell, X., Arroja, L., 2014. Environmentally extended input-output analysis on a city scale - Application to Aveiro (Portugal). J. Clean. Prod. 75, 118–129. https://doi.org/10.1016/j.jclepro.2014.04.012

Directorate General of Traffic, 2016. Vehicle fleet (in Spanish). https://www.dgt.es/es/seguridad-vial/estadisticas-e-indicadores/parque-vehiculos/ (accessed May 2021)

ENUCAM, 2015. Survey on nutrition of the Autonomous Community of Madrid 2014 (in Spanish). Tech. Doc. Public Heal. D137, 1–104.

European Union, 1991. Directive 91/271/CEE of the Council, 21st may of 1991, about urban wastewater treatment. European Union.

Feleki, E., Vlachokostas, C., Moussiopoulos, N., 2018. Characterisation of sustainability in urban areas: An analysis of assessment tools with emphasis on European cities. Sustain. Cities Soc. 43, 563–577. https://doi.org/10.1016/j.scs.2018.08.025

Fundación para el Fomento de la Innovación Industrial; Escuela Técnica Superior de Ingenieros Industriales de la Universidad Politécnica de Madrid, 2016. Energy Balance of the Council of Madrid (in Spanish).

Fundación para el Fomento de la Innovación Industrial; Escuela Técnica Superior de Ingenieros Industriales de la Universidad Politécnica de Madrid, 2015. Inventory of Madrid City Air Pollutants Emissions 2016 Directorate General for Sustainability and Environmental Control.

García-Guaita, F., González-García, S., Villanueva-Rey, P., Moreira, M.T., Feijoo, G., 2018. Integrating Urban Metabolism, Material Flow Analysis and Life Cycle Assessment in the environmental evaluation of Santiago de Compostela. Sustain. Cities Soc. 40, 569–580. https://doi.org/10.1016/j.scs.2018.04.027

Garfí, M., Cadena, E., Sanchez-Ramos, D., Ferrer, I., 2016. Life cycle assessment of drinking water: Comparing conventional water treatment, reverse osmosis and mineral water in glass and plastic bottles. J. Clean. Prod. 137, 997–1003. https://doi.org/10.1016/j.jclepro.2016.07.218

Goldstein, B., Birkved, M., Quitzau, M.B., Hauschild, M., 2013. Quantification of urban metabolism through coupling with the life cycle assessment framework: Concept development and case study. Environ. Res. Lett. 8. https://doi.org/10.1088/1748-9326/8/3/035024

González-García, S., Dias, A.C., 2019. Integrating lifecycle assessment and urban metabolism at city level Comparison between Spanish cities. Ind. Ecol. 1–15. https://doi.org/10.1111/jiec.12844

González-García, S., Dias, A.C., 2019. Integrating lifecycle assessment and urban metabolism at city level: Comparison between Spanish cities. J. Ind. Ecol. 23, 1062–1076. https://doi.org/10.1111/jiec.12844

Gonzalez-Garcia, S., Manteiga, R., Moreira, M.T., Feijoo, G., 2018. Assessing the sustainability of Spanish cities considering environmental and socio-economic indicators. J. Clean. Prod. 178, 599–610. https://doi.org/10.1016/j.jclepro.2018.01.056

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M.D.M., Hollander, A., Zijp, M., van Zelm, R., 2017. ReCiPe 2016 v1.1.

IECM, 2021a. Institute of Statistics of the Community of Madrid. Demographic Statistics: surface, density and population (in Spanish). http://www.madrid.org/iestadis/ (accessed May 2021)

IECM, 2021b. Institute of Statistics of the Community of Madrid. Distribution of GDP by statistical zones and by municipalities according to branches of activity (in Spanish). http://www.madrid.org/iestadis/fijas/estructu/ economicas/contabilidad/ (accessed May 2021)

IECM, 2021c. Institute of Statistics of the Community of Madrid. Atlas of work-residence mobility in the Community of Madrid (in Spanish). http://www.madrid.org/iestadis/ fijas/estructu/general/territorio/atlasmovilidad2017/ (accessed May 2021)

IECM, 2021d. Institute of Statistics of the Community of Madrid. Water supply and sanitation (in Spanish). http://www.madrid.org/iestadis/fijas/estructu/sociales/(accessed May 2021).

INE, 2021. Statistics National Institute. Indicator of paid and unpaid hours of work by type of working day. Work Conditions Survey 2015 (hours / week). https://www.ine.es/ (accessed May 2021)

INE, 2020. Statistics National Institute. Official population figures resulting from the revision of the Municipal Register as of January 1 (in Spanish). https://www.ine.es/ dynt3/inebase/es/ (accessed May 2021)

ISO 14040, 2006. International Organization for Standardization, ISO 14040. Environmental Management-Life Cycle Assessment - Principles and Framework, Geneve.

Jungbluth, N., 2019. Recommendations for calculation of the global warming potential of aviation including the radiative forcing index 404–411.

Kalbar, P.P., Birkved, M., Kabins, S., Nygaard, S.E., 2016. Personal Metabolism (PM) coupled with Life Cycle Assessment (LCA) model: Danish Case Study. Environ. Int. 91, 168–179. https://doi.org/10.1016/j.envint.2016.02.032

La Picirelli de Souza, L., Silva Lora, E.E., Escobar Palacio, J.C., Henrique Rocha, M., Grillo Renó, M.L., Venturini, O.J., 2018. Comparative environmental life cycle assessment of conventional vehicles with different fuel options, plug-in hybrid and electric vehicles for a sustainable transportation system in Brazil. J. Clean. Prod. 203, 444–468. https://doi.org/10.1016/ j.jclepro.2018.08.236

MAPA, 2020. Ministry of Agriculture, Fisheries and Food. Food consumption data (in Spanish). https://www.mapa.gob.es/va/alimentacion/temas/consumo-tendencias/panel-de-consumo-alimentario/series-anuales/ (accessed May 2021)

MAPA, 2017. Ministry of Agriculture, Fisheries and Food. Monthly statistics on fertilizer consumption in agriculture (in Spanish). https://www.mapa.gob.es/es/estadistica/ temas/estadisticas-agrarias/agricultura/estadisticas-medios-produccion/fertilizantes.aspx (accessed May 2021)

MAPA, 2016. Wood National Balance (in Spanish). https://www.mapa.gob.es/es/desarrollo-rural/

estadisticas/forestal_balance_nacional_madera.aspx (accessed March 2019)

Moreno Ruiz, E., Valsasina, L., Brunner, F., Symeonidis, A., FitzGerald, D., Treyer, K., Bourgault, G., Wernet, G., 2018. Documentation of changes implemented in ecoinvent database v3.5. Ecoinvent, Zürich, Switzerland. 5, 1–97.

Munawer, M.E., 2018. Human health and environmental impacts of coal combustion and post-combustion wastes. J. Sustain. Min. https://doi.org/10.1016/j.jsm.2017.12.007

Noya, I., Villanueva-Rey, P., González-García, S., Fernandez, M.D., Rodriguez, M.R., Moreira, M.T., 2017. Life Cycle Assessment of pig production: A case study in Galicia. J. Clean. Prod. 142, 4327–4338. https://doi.org/10.1016/j.jclepro.2016.11.160

Ntziachristos, L., Samaras, Z., Kouridis, C., Samaras, C., Hassel, D., Mellios, G., Mccrae, I., Zierock, K., Keller, M., Rexeis, M., Andre, M., Winther, M., Pastramas, N., Gorissen, N., Boulter, P., Katsis, P., Joumard, R., Geivanidis, S., Hausberger, S., 2014. EMEP/EEA air pollutant emission inventory guidebook 2013. EEA Publ. 158. https://doi.org/10.2800/92722

Plastics Europe, 2017. Plásticos –Situation 2017. Plast. Facts 2017 50.

Postacchini, L., Mazzuto, G., Paciarotti, C., Ciarapica, F.E., 2018. Reuse of honey jars for healthier bees: Developing a sustainable honey jars supply chain through the use of LCA. J. Clean. Prod. 177, 573–588. https://doi.org/10.1016/j.jclepro.2017.12.240

Regueiro, M., 2000. Ceramic industry in Spain. Madrid.

Romero, F., Gomez, J., Rangel, T., Vassallo, J.M., 2019. Impact of restrictions to tackle high pollution episodes in Madrid : Modal share change in commuting corridors. Transp. Res. Part D 77, 77–91. https://doi.org/10.1016/j.trd.2019.10.021

Schwab, O., Zoboli, O., Rechberger, H., 2017. A Data Characterization Framework for Material Flow Analysis. J. Ind.

Ecol. 21, 16–25. https://doi.org/10.1111/jiec.12399

Tanguay, G.A., Rajaonson, J., Lanoie, P., 2010. Measuring the sustainability of cities : An analysis of the use of local indicators. Ecol. Indic. 10, 407–418. https://doi.org/10.1016/j.ecolind.2009.07.013

Tsarouhas, P., Achillas, C., Aidonis, D., Folinas, D., Maslis, V., 2015. Life Cycle Assessment of olive oil production in Greece. J. Clean. Prod. 93, 75–83. https://doi.org/10.1016/j.jclepro.2015.01.042

Universidad Autónoma de Madrid, 2017. Foreing Students (in Spanish). https://www.uam.es/UAM/ Estudios-y-Estudiantes/ (accessed March 2019)

Universidad Complutense de Madrid, 2016. Foreing Students by degree and Nationalit. https://www.ucm.es/ estudiantes-2016-2017 (accessed March 2019)

Universidad Politécnica de Madrid, 2017. The UPM in Figures. http://www.upm.es/UPM/UPMCifras (accessed March 2019)

Vázquez-Rowe, I., Moreira, M.T., Feijoo, G., 2011. Life Cycle Assessment of fresh hake fillets captured by the Galician fleet in the Northern Stock. Fish. Res. 110, 128–135. https://doi.org/10.1016/j.fishres.2011.03.022

Vázquez-Rowe, I., Villanueva-Rey, P., Moreira, M.T., Feijoo, G., 2016. Opportunities and challenges of implementing life cycle assessment in seafood certification: a case study for Spain. Int. J. Life Cycle Assess. 21, 451–464. https://doi.org/10.1007/s11367-016-1043-7

Villanueva-Rey, P., Vázquez-Rowe, I., Moreira, M.T., Feijoo, G., 2014. Comparative life cycle assessment in the wine sector: Biodynamic vs. conventional viticulture activities in NW Spain. J. Clean. Prod. 65, 330–341. https://doi.org/10.1016/j.jclepro.2013.08.026

Chapter 4: **Evaluation of the Carbon Footprint at city scale: Life Cycle Assessment or Environmentally Extended Input-Output Analysis**[6]

SUMMARY

Currently, global warming is one of the most important challenges in the society. Bearing in mind that most of the greenhouse gas (GHG) emissions are attributed to cities, they play an important role in the mitigation of the climate change. In this chapter the carbon footprint (CF) associated with the activities developed in the city of Cadiz (Southwest of Spain) was quantified using the two methodologies described in Chapter 2: Environmentally Extended Input-Output Analysis (EEIOA) and Life Cycle assessment (LCA). When EEIOA is considered, two downscaling factors were proposed for the analysis due to the nature of the data handled (monetary data), based on the incomes (DF_1) and expenditures (DF_2) per inhabitant at city level. The CF scores identified were 5.25 and 3.83 tCO_2-eq·inhabitant^{-1}·year^{-1} for DF_1 and DF_2 respectively, according to EEIOA, and 5.43 tCO_2-eq·inhabitant^{-1}·year^{-1}, considering LCA. Considering the results, the downscaling procedure based on income per inhabitant should be preferred, pointing to EEIOA as a good alternative to LCA for evaluating the CF at city level, requiring less time and effort. In contrast, EEIOA reports more limitations when critical flows were identified, which LCA can solve. Finally, the results obtained in this study could be of interest to policy makers to develop new policies and city models for reducing GHG emission and addressing climate change.

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[6] Based on the study: Rama, M., Entrena-Barbero, E., Dias, A.C., Moreira, M.T., Feijoo, G., González-García, S. (2021). Evaluating the carbon footprint of a Spanish city through environmentally extended input output analysis and comparison with life cycle assessment. Science of the Total Environment, 762, 143133. https://doi.org/10.1016/j.scitotenv.2020.143133

4.1 INTRODUCTION

Greenhouse Gases (GHGs) emission has increased exponentially since 1950 and, as a result, this fact has led to an acceleration of climate change (Steffen et al., 2015). Different impacts on the natural environment derive from global warming, such as i) alteration of hydrological systems, ii) change in both the migration patterns and the behavior of some species, iii) increased flooding events, and iv) extreme weather conditions, among others (IPCC, 2014). In addition, human health is being either directly or indirectly affected (especially in the poorest population) by climate change, along with some economic sectors such as agriculture (e.g., due to problematic weather conditions such as droughts and frost) and tourism (tourism destinations change depending on the weather) (Hein et al., 2009; IPCC, 2014). In this framework, climate change becomes relevant and a priority problem within society. In addition, cities play a major role because they are the cause of most of the global emissions due to the different human activities that take place within them (World Bank, 2019).

To reduce a city's GHG emissions, it is first necessary to quantify them and identify the main flows derived from the activities that generate the most emissions. Therefore, in this chapter the carbon footprint (CF) of the city of Cádiz (Southwest of Spain) was analyzed using the two methodologies detailed in Chapter 2: Life Cycle Assessment (LCA) and Environmentally Extended Input-Output Analysis (EEIOA). The objective of this study was to quantify the CF of a city and compare both methodologies, identifying possible discrepancies in the results as well as the advantages and disadvantages of each method. In this sense, the results of this study may be of interest to policy makers to determine which of these tools is the most advisable for the estimation of the CF indicator. As far as we know, this is the first study that evaluates the environmental profile of a Spanish city using the EEIOA methodology. Therefore, the starting point was to provide an answer to the question: *Do both methodologies lead to a similar result?* Firstly, a positive answer is supported by the work of Dias et al. (2018) in which the CF associated to the city of Aveiro (Portugal) was evaluated through LCA and compared with the results of a previous study in which the EEIOA was applied (Dias et al., 2014). In this study, the CF scores resulting from both methodologies reach very similar values despite considering different flows from different databases between them. The quantification of CF in a Spanish region (Galicia) using the EEIOA established that this methodology is a good choice to determine CF associated with production and consumption patterns at a regional level (Roibás et al., 2017). Considering these conclusions, the present chapter aims to demonstrate if both methodologies are also alternative options in the estimation of CF in the case of a Spanish city taking into account the available information and the limitations of the databases at Spanish level.

4.2 MATERIALS AND METHODS

4.2.1 Case study: City of Cadiz

The city of Cadiz with a population of 116,027 inhabitants (IECA, 2018), which was selected as case study (**Figure 4.1**), is the capital of the homonymous province in the Autonomous Community of Andalusia (Southern Spain). However, its population rate has decreased in recent years for many reasons, such as low birth rates and high rental and sale prices, mainly due to its high population density and the lack of residential area to continue growing as Cadiz is located on a peninsula. In economic terms, its inhabitants had an average gross income per capita of 26,891€ per capita in 2015, which corresponds to their average gross income (INE, 2015a). This Spanish city has an economy highly dependent on tourism due to its location (southern coast of Spain) and very favorable weather conditions (Williams et al., 2016). On the one hand, this fact affects the economy of the city, because tourism has a strong seasonality regime during the summer months and, as consequence, the city has a very high unemployment rate, above 33% (IECA, 2021). In addition, tourism also has environmental implications given that tourism is one of the economic sectors most affected by climate change (Hein et al., 2009). For these reasons, the selection of this case study can be considered of potential interest not only for this Spanish city but also for similar cities with the aim of taking measures and developing policies to contrast or minimize its effects and addressing them towards more sustainable cities.

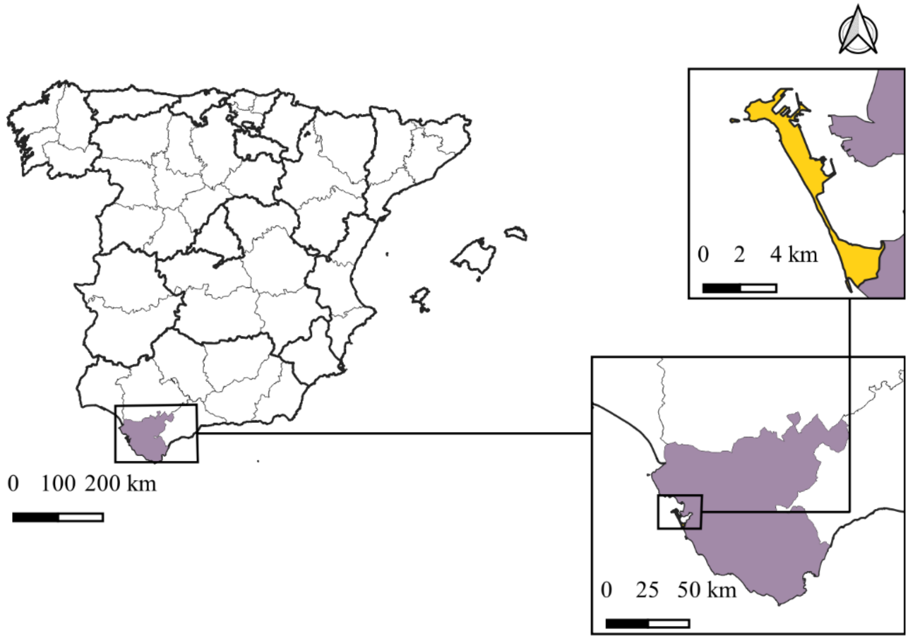


Figure 4.1. Location of the City of Cadiz in the map of Spain

4.2.2 Environmentally Extended Input-Output Analysis methodology

4.2.2.1 Data requirements

As detailed in Chapter 2, the EEIOA methodology calculates the CF of an inhabitant according to the expenses of that inhabitant. In other words, if an inhabitant spends 2,500 € per year on food, then through EEIOA, we can calculate how many emissions it corresponds to in terms of CO_2-eq. To do so, it is necessary to collect data from three main data sources: expenditures of the households per group of the city, the Input-Output table (IO Table), and GHG emission per Branches of Activity.

The IO table has the data corresponding to the monetary transactions between the industrial sectors (64 sectors in the case of Spanish IO Tables). Hence, sectors of the extractive industries are reflected, and it is what gives a life cycle perspective to the methodology. This table is available at national level in the National Institute of Statistics of Spain (INE, 2015b). On the other hand, GHG emissions per Branches of Activity has the emission data in units of tons of CO_2-eq for each of the industrial sectors (64) also available at the national level (INE, 2015c). However, to calculate the carbon footprint using EEIOA, it was necessary to divide the emission values of each sector by the corresponding gross domestic product associated with each sector. In this way, emission data is obtained in units of CO_2-eq·€ $^{-1}$.

Finally, the expenditures of the households per group of the city data are available at regional scale with a four-digit level of disaggregation, corresponding to 116 expenditure groups (IECA, 2015a). In this chapter, it has considered the data on average expenditure per person in the region of Andalusia as a basis for subsequent extrapolation at city level with two specific downscaling factors: downscaling factor 1 (DF_1) and downscaling factor 2 (DF_2), which will be developed in Chapter 2 and they were adapted in the **Equations 4.1** and **4.2**:

$$DF_1 = \frac{Incomes\ per\ household\ in\ Cadiz}{Incomes\ per\ household\ in\ Andalusia} \qquad \text{(\textbf{Equation 4.1})}$$

$$DF_2 = \frac{Expenditures\ per\ person\ in\ Cadiz}{Expenditures\ per\ person\ in\ Andalusia} \qquad \text{(\textbf{Equation 4.2})}$$

Concerning the first downscaling factor (DF_1) there were available data for both, Andalusia and Cadiz (IECA, 2015b). On the contrary, since there was not available information regarding the average level of income per household at city level it has been considered data for the average expenditures per person in the municipalities with more than 100,000 inhabitants in the region of Andalusia (IECA, 2015a), as assumption.

4.2.2.2 Equivalences between expenditures groups and economic sectors of the IO table

In this section, the equivalences between the 116 expenditure groups and the 64 sectors considered in the IO Table were established. Hence, the expenditure groups were related according to the sectors to which they belong, following Regulation (EC) No 1893/2006 (European Commission, 2006). However, as detailed in Chapter 2, some sectors were not directly related to expenses, such as "*Mining and quarrying*". Nevertheless, these sectors were indirectly related to other sectors which do have direct relationships with the expense groups. Thus, the CF corresponding to jewelry expenses, for example, which were considered within the "*Furniture; other manufactured goods*" sector, also indirectly obtained the corresponding contribution from the "*Mining and quarrying*" sector. This was a consequence of the monetary relations that exist between the two sectors contemplated in the IO Table. Therefore, the 116 expenditure groups were grouped into 35 economic sectors as shown in **Table 4.1**.

Table 4.1. Equivalences between expenditures groups per inhabitant and economic sectors of the IO table.

IO table Economic Sectors	Expenditures Groups
Products of agriculture, hunting and related services	Meat
	Fruits
	Vegetables, including potatoes and other tubers
Fish and other fishing products; aquaculture products; support services to fishing	Fish
Food products; beverages; tobacco products	Bread and Cereals
	Dairy Products
	Oils and Fats
	Sugar, confectioneries, honey, chocolate and ice creams
	Other food products
	Coffee, tea and cocoa
	Mineral water, soft drinks and juices
	Spirits and liquors
	Wine
	Beer
	Tobacco
Telecommunications services	Phone, telegraph and fax
Computer programming, consultancy and related services; information services	Information processing material
Paper and paper products	Stationery and drawing materials
Publishing services	Books
	Newspapers
Repair and installation services of machinery and equipment	Repair of all household appliances
Electrical equipment	Big appliances, electrical or not
	Small appliances
Electricity, gas, steam and air conditioning	Electricity
	Gas
	Liquid fuels
	Solid Fuels

Table 4.1 (cont.). Equivalences between expenditures groups per inhabitant and economic sectors of the IO table.

IO table Economic Sectors	Expenditures Groups
Human health services	Medical products
	Medical services
	Dental services
	Non-hospital paramedical services
Motor vehicles, trailers and semi-trailers	Cars
	Repair and maintenance
	Other services related to personal vehicles
	Purchase of personal vehicle spare parts and accessories for repairs performed by household members
Other transport equipment	Bicycles
Furniture; other manufactured goods	Furniture and furnishing articles
	Musical instruments and other durable goods for leisure and culture in covered places
	Equipment for sport, camping and outdoor entertainment
	Jewelry, costume jewelry and watchmaking
Postal and courier services	Postal services
Machinery and equipment n.e.c[7].	Big electric tools and their repairs
	Small tools, various accessories and their repairs
Natural water; water treatment and supply services	Water supply
Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery	Refuse collection
Constructions and construction works	Services for the maintenance and repair of the dwelling

[7] Not contemplated elsewhere

Table 4.1 (cont.). Equivalences between expenditures groups per inhabitant and economic sectors of the IO table.

IO table Economic Sectors	Expenditures Groups
Land transport services and transport services via pipelines	Rail transport (train, metro, urban tram, intercity and long distance)
	Road transport (local and long distance)
	Fuels and lubricants
Air transport services	Passenger transport by air
Retail trade services, except of motor vehicles and motorcycles	Glassware, tableware, cutlery, other household utensils and their repairs
	Non-durable household items
	Materials for the maintenance and current repairs of the home when the repair is carried out by the home itself
Accommodation and food services	Restaurants and cafes
	Canteens and dining rooms
	Accommodation Services
Computer, electronic and optical products	Other equipment for the reception, recording and reproduction of sound and vision
	Photographic and cinematographic equipment and optical instruments
	Supports for recording image, sound and data and subscription to music streaming services
	Telephone and fax equipment
Textiles; wearing apparel; leather and related products	Fabrics
	Garments
	Other articles of clothing and clothing accessories
	Cleaning, repair, tailoring and hire of clothing
	Shoes and other footwear
	Home textiles and their repairs
Insurance, reinsurance and pension funding services, except compulsory social security	Insurance connected with the dwelling
	Insurance connected with health
	Insurance connected with health
	Burial insurance

Table 4.1 (cont.). Equivalences between expenditures groups per inhabitant and economic sectors of the IO table.

IO table Economic Sectors	Expenditures Groups
Other professional, scientific and technical services; veterinary services	Products for pets and other household animals, veterinary and other pets services
Rental and leasing services	Other rentals Other imputed rentals
Public administration and defense services; compulsory social security services	Social protection services
Education services	Early Childhood Education Primary education Secondary education Post-secondary non-tertiary education Tertiary education Other education not defined by level
Creative, arts and entertainment services; library, archive, museum and other cultural services; gambling and betting services	Recreational and sports services Cultural services Gambling
Sporting services and amusement and recreation services	Games, toys and hobbies
Repair services of computers and personal and household goods	Domestic service and other services for housing Repair of audiovisual, photographic and information processing equipment and accessories
Other personal services	Hairdressing and personal aesthetics Personal care devices, articles and products Other personal articles
Real estate services	Actual rental (main dwelling) Actual rental (other dwellings) Rents imputed to the property owned

4.2.2.3 Carbon Footprint calculation

Once all data were compiled from the three main database, the matrices considered in Chapter 2 were built. First, inverse Leontief matrix $(I\text{-}A)^{-1}$ with data from the coefficients available in data source (INE, 2015b) with the 64 sectors considered in rows, and 35 sectors with relation with the expenditures groups in columns. Vector Y contained data from expenditures groups per person downscaled and grouped into the 35 sectors. Finally, vector Z had data of the GHG emissions of the different sectors in units of CO_2-eq·€$^{-1}$.

$$(I-A)^{-1} = \begin{pmatrix} c_{1,1} & \cdots & c_{1,35} \\ \vdots & \ddots & \vdots \\ c_{64,1} & \cdots & c_{64,35} \end{pmatrix}$$ (Inverse Leontief matrix)

$$Y = (y_1 \quad \cdots \quad y_{35})$$ (Expenditures by economic sector vector)

$$Z = \begin{pmatrix} z_1 \\ \vdots \\ z_{64} \end{pmatrix}$$ (GHG emission vector)

The CF was calculated with equation detailed in Chapter 2 (**Equation 2.3**) which was adapted for the study developed in this chapter in **Equation 4.3.**

$$CF = \sum_{j=1}^{35} \sum_{i=1}^{64} c_{ij} \cdot y_j \cdot z_i$$ (**Equation 4.3**)

Where *i* corresponded with each of the 64 economic sectors and *j* with the 35 economic sectors related with the expenditure groups.

4.2.3 Life Cycle Assessment (LCA)

4.2.3.1 Goal and Scope definition

The limits of the system considered in this chapter are the limits of the city of Cádiz. Therefore, all the flows of materials and energy consumed in Cadiz were considered in the LCA.

The functional unit (FU) is the basis for comparing the CF scores using the two proposed methodologies. To establish the FU, it must be taken into account that the function of a city is to maintain the quality of life of its citizens, as well as other geographical areas that depend directly or indirectly on its socio-economic factors, and to support people with different cultures, habits, diets, etc. (Goldstein et al., 2013). In this sense, it was decided to consider one inhabitant and one year as a functional unit in line with other studies, which only consider the residents registered in the cities under study (Goldstein et al., 2013; González-García and Dias, 2019). Thus, the CF evaluated were calculated from the consumption of goods and services by an inhabitant in one year. However, other authors (García-Guaita et al., 2018), consider the equivalent inhabitant, i.e., considering also the non-resident population in the city (students who are not registered in the city, and workers who live in other municipalities and tourists. Nevertheless, the EEIOA databases are per resident (not equivalent). This discrepancy can lead to an overestimation of the carbon footprint calculated through LCA because a part of the residents' CF was associated with the consumption of goods and services by the non-resident population within the city. Thus, and with the aim of comparing both methodologies, a resident in the city should be taken as reference.

4.2.3.2 Life Cycle Inventory (LCI)

In this chapter were considered seven metabolic input and output flows (**Figure 4.2**) which were essential for the development of the cities. In the selection of these flows, those considered by González-García and Dias (2019) have been taken into account: fossil fuels, energy, foods and beverages, building materials, other flows (including paper and cardboard, glass bottles, cork, plastic containers and tap water) as inputs and wastewater and solid wastes as outputs. Bearing in mind that cities were considered as large consumers rather than producers of goods, some flows related to agriculture or industrial activities, such as fertilizers or chemicals, have not been taken into account (Dias et al., 2018; González-García and Dias, 2019). In addition, the production of goods in the city of Cadiz has been also excluded, i.e. it is assumed that all materials and energy flows are imported in order to avoid double counting in line with previous studies (Dias et al., 2018; González-García and Dias, 2019).

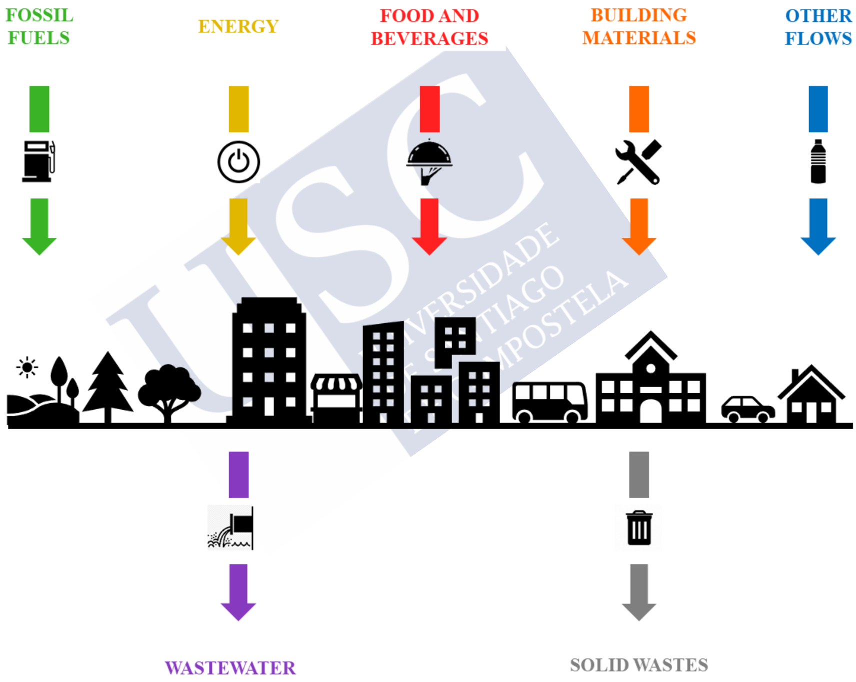


Figure 4.2. Schematic representation of the considered flows in the LCA. Inputs and output flows involve the production processes and the management treatments, respectively.

As for the input flows, the upstream activities involved in their production have been considered, considering the extraction of raw materials, processing, manufacturing and transport up to the city. Background data corresponding to these activities have been taken from Ecoinvent ® database version 3.5 (Moreno Ruiz et al., 2018). Specifically for some food products such as legumes (lentils, chickpeas), sugar, oil, pasta and some meat products (beef, pork and chicken), the background data have been taken from Agri-footprint database (Blonk Agri-footprint BV, 2015). Moreover, background data for wine and beer production have taken from Villanueva-Rey et al. (2014) and Koroneos et al. (2005) respectively.

Concerning building materials, the consumption of concrete, natural stone, cement, aggregates, bricks, asphalt, varnish, tiles, ceramics, steel and wood has been considered. The corresponding consumption data have been collected from different sources, giving priority to local and provincial data over regional or national ones, whenever possible. In cases where the data correspond to a regional or national scale, it has been assumed that a resident of Andalusia or Spain would consume the same amount as a resident of Cadiz. To obtain a good-quality comparison between the CF scores estimated by EEIOA and LCA, the same reference year of 2015 (whenever possible) in both methodologies has been considered. **Table 4.2 to 4.4** details the inventory data and data sources corresponding to each flow considered in the LCA study.

Table 4.2. Inventory Data for the input flows: building materials, fossil fuels, energy and other flows.

Flow	**Scale**		**Source**
Building Materials. Units: kg·inhab^{-1}·year^{-1}			
Concrete	Local	940	(Fueyo Editores, 2015)
Natural Stone	National	104	(IGME, 2018)
Cement	Local	372	(Flacema, 2015)
Aggregates	Regional	275	(FIPA, 2017)
Bricks	National	57.6	(ProfesionalesHoy, 2016)
Asphalt	National	352	(Asefma, 2015)
Varnish	National	10.1	(ASEFAPI, 2019)
Tiles	National	13.6	(HISPALYT, 2015)
Ceramic	National	178	(Manzadeno, 2015)
Steel	National	274	(UNESID, 2015)
Wood	Regional	3.92	(El Periódico de la Energía, 2018)
Fossil Fuels. Units: kg oe[8]·inhab^{-1}·year^{-1}			
Coal	Provincial	0.72	(AAE, 2015)
Fuel oil	Regional	21.0	(AAE, 2015)
Diesel	Provincial	464	(AAE, 2015)
Crude Oil	Provincial	1,216	(AAE, 2015)
Natural Gas	Provincial	418	(AAE, 2015)
Kerosene	Regional	141	(AAE, 2015)
LPG	Regional	40.0	(AAE, 2015)
Petrol	Regional	81.8	(AAE, 2015)
Energy. Units: kg oe·inhab^{-1}·year^{-1}			
Electricity mix	Provincial	331	(AAE, 2015)
Solar energy	Provincial	10.1	(AAE, 2015)
Biomass	Provincial	28.0	(AAE, 2015)
Other flows. Units: kg·inhab^{-1}·year^{-1}			
Paper and cardboard	Regional	2.30	(Aspapel, 2006)
Glass Bottles	National	53.8	(ANFEVI, 2017)
Cork	Provincial	9.20	(EFE Agro, 2015)
Plastic containers	National	122	(CEDEX, 2013)
Tap water	Local	45,990	(Aguas de Cádiz, 2015)

[8] Kilograms oil equivalent.

Table 4.3. Inventory Data for the input flows corresponding to Food and beverages. All data collected are available at regional level. Units: kg·inhab-1·year-1 except Eggs (Units·inhab-1·year-1).

Flow			Source
Pasta and Cereal Products			
	Bread	35.2	(MAPA, 2020)
	Pasta	3.47	(MAPA, 2020)
	Rice	3.52	(MAPA, 2020)
Eggs		123	(MAPA, 2020)
Olives		2.16	(MAPA, 2020)
Dairy products			
	Yogurt	9.68	(MAPA, 2020)
	Milk	14.6	(MAPA, 2020)
	Cheese	7.19	(MAPA, 2020)
Vegetables			
	Potato	29.0	(MAPA, 2020)
	Tomato	14.1	(MAPA, 2020)
	Onion	6.50	(MAPA, 2020)
	Garlic	0.91	(MAPA, 2020)
	Cabbage	1.06	(MAPA, 2020)
	Cucumber	2.11	(MAPA, 2020)
	Green Bean	1.57	(MAPA, 2020)
	Pepper	4.02	(MAPA, 2020)
	Lettuce	3.64	(MAPA, 2020)
	Asparagus	0.61	(MAPA, 2020)
	Spinach	1.04	(MAPA, 2020)
	Aubergine	1.63	(MAPA, 2020)
	Carrot	3.02	(MAPA, 2020)
	Zucchini	2.89	(MAPA, 2020)

Table 4.3 (cont.). Inventory Data for the input flows corresponding to Food and beverages. All data collected are available at regional level. Units: kg·inhab^{-1}·year^{-1}.

Flow			**Source**
Fruits			
	Orange	15.8	(MAPA, 2020)
	Mandarin	4.89	(MAPA, 2020)
	Lemon	2.12	(MAPA, 2020)
	Banana	9.80	(MAPA, 2020)
	Apple	8.87	(MAPA, 2020)
	Pear	4.30	(MAPA, 2020)
	Peach	5.22	(MAPA, 2020)
	Strawberry	2.12	(MAPA, 2020)
	Melon	7.61	(MAPA, 2020)
	Watermelon	9.52	(MAPA, 2020)
	Grapes	1.93	(MAPA, 2020)
	Kiwi	2.30	(MAPA, 2020)
	Avocado	0.81	(MAPA, 2020)
	Pineapple	1.26	(MAPA, 2020)
	Other fresh fruits	5.13	(MAPA, 2020)
Mineral water		84.0	(MAPA, 2020)
Lentil		0.74	(MAPA, 2020)
Chickpea		1.17	(MAPA, 2020)
Bean		0.65	(MAPA, 2020)
Sugar		3.52	(MAPA, 2020)
Oil and other fats		11.7	(MAPA, 2020)
Fish			
	Sole	0.46	(MAPA, 2020)
	Sardine	1.88	(MAPA, 2020)
	Tuna	2.50	(MAPA, 2020)
	Trout	0.23	(MAPA, 2020)
	Hake	2.64	(MAPA, 2020)
	Other fresh fish	9.66	(MAPA, 2020)
	Canned fish	0.71	(MAPA, 2020)

Table 4.3 (cont.). Inventory Data for the input flows corresponding to Food and beverages. All data collected are available at regional level. Units: kg·inhab^{-1}·year^{-1}.

Flow			Source
Meat			
	Beef	3.37	(MAPA, 2020)
	Pork	9.79	(MAPA, 2020)
	Chicken	13.5	(MAPA, 2020)
	Lamb	0.85	(MAPA, 2020)
Coffee and infusion		1.64	(MAPA, 2020)
Juices		11.0	(MAPA, 2020)
Beer		22.4	(MAPA, 2020)
Wine		7.36	(MAPA, 2020)

Table 4.4. Inventory data for the Output flows.

Wastewater. Units: m^3·inhab^{-1}·year^{-1}			
Wastewater	Local	126.4	(ETRA, 2015)
Solid Waste. Units: kg·inhab^{-1}·year^{-1}			
Paper and cardboard recycling	Regional	10.2	(Aspapel, 2006)
Landfill	Regional	489	(Junta de Andalucía, 2016)

4.2.3.3 Life Cycle Impact Assessment (LCIA)

LCA is a methodology that, applied to cities, analyzes the different flows from a life cycle perspective (Goldstein et al., 2013; González-García and Dias, 2019). Hence, LCA quantifies the emissions and discharges throughout the life of a product, from its extraction, processing, transport and consumption up to its treatment as a waste. In this chapter, the CF score has been estimated taking into account a cradle-to-grave perspective and the characterization factors reported by the ReCiPe Midpoint (Hierarchist) method (Huijbregts et al., 2016), which has been also used by other authors (García-Guaita et al., 2018; Goldstein et al., 2013; González-García and Dias, 2019) and allows for comparison of the results.

4.3 RESULTS AND DISCUSSION

4.3.1 Environmentally Extended Input-Output Analysis results

As detailed above, two different downscaling factors have been estimated to be applied in the EEIOA (**Table 4.5**). DF_1 (1.41) was about 37% higher than DF_2 (1.03), indicating that the difference between the income per household between Cadiz and Andalusia was considerably higher than the difference in the expenses per person in both locations. While the income per household in Cadiz were around 40% higher than the income per household in Andalusia in 2015, the expenditures per person in Cadiz were only 3% higher than those in Andalusia. The rationale behind the low variation in the expenses was associated with the fact that the value estimated for expenses in Cadiz corresponds to the average expenditure per person for all Andalusian municipalities with more than 100,000 inhabitants, which accumulate a large part of the population of the entire region. Consequently, it was expected a minor variation regarding the average expenditure per person in Andalusia.

Table 4.5. Downscaling factors and data income and expense data for Andalusia and Cadiz in 2015.

Income per household in Cadiz	**Income per household in Andalusia**	**DF_1**
29,346€	20,851€	1.41
Expenditure per person in Cadiz	**Expenditure per person in Andalusia**	**DF_2**
9,557€	9,294€	1.03

The difference between the downscaling factors directly affects the expenditures by economic sector. **Table 4.6** shows the expenditures per person in Andalusia and Cadiz considering the estimated downscaling factors and disaggregated by each economic sector. The economic sector that contributed most to the annual citizens' expenses in Andalusia and Cadiz (around 23% of the total) was "*Real estate services*", which included the rental and the imputed income.

The second most important sector, with a 12% contribution to total expenditure, was “*Food products; beverages; tobacco products*”. It was followed by "*Accommodation and food services*" (10% of the total). The rest of the sectors reported contributing ratios lower than 10%. The difference between the first two sectors is notable since a person from Cadiz or Andalusia spends almost twice as much on rent as on food. Bearing in mind the averages income per person in Andalusia in 2015 was 7,942 € (INE, 2015d), Andalusians spent around 26% of their incomes on housing. This ratio was close to the alarming 30% from which a rent is considered high enough to harm a citizen's quality of life (Tanguay et al., 2010).

Table 4.6. Expenditure in € by economic sector in Andalusia and Cadiz considering the downscaling factors in 2015.

Economic Sector	Andalusia	Cadiz (DF_1)	Cadiz (DF_2)
Real estate services	2,029	2,856	2,087
Food products; beverages; tobacco products	1,071	1,507	1,101
Accommodation and food services	824	1,159	847
Textiles; wearing apparel; leather and related products	545	767	560
Land transport services and transport services via pipelines	529	745	544
Motor vehicles, trailers and semi-trailers	515	725	530
Products of agriculture, hunting and related services	472	664	485
Electricity, gas, steam and air conditioning	341	480	351
Insurance, reinsurance and pension funding services, except compulsory social security	318	448	327
Human health services	306	431	315
Other personal services	262	369	270
Telecommunications services	256	361	264
Creative, arts and entertainment services; library, archive, museum and other cultural services; gambling and betting services	180	254	186
Fish and other fishing products; aquaculture products; support services to fishing	166	234	171
Retail trade services, except of motor vehicles and motorcycles	151	213	155

Table 4.6 (cont.). Expenditure in € by economic sector in Andalusia and Cadiz considering the downscaling factors in 2015.

Economic Sector	Andalusia	Cadiz (DF_1)	Cadiz (DF_2)
Rental and leasing services	141	198	145
Repair services of computers and personal and household goods	98	138	101
Furniture; other manufactured goods	97	136	100
Education services	95	134	98
Natural water; water treatment and supply services	84	119	87
Computer, electronic and optical products	77	108	79
Electrical equipment	59	84	61
Constructions and construction work	58	82	60
Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery	42	59	43
Sporting services and amusement and recreation services	39	54	40
Other professional, scientific and technical services; veterinary services	31	44	32
Publishing services	31	44	32
Computer programming, consultancy and related services; information services	25	36	26
Air transport services	23	33	24
Public administration and defense services; compulsory social security services	23	32	23
Paper and paper products	18	25	18
Machinery and equipment n.e.c.	17	24	18
Repair and installation services of machinery and equipment	15	21	15
Other transport equipment	6	9	7
Postal and courier services	2	3	2
TOTAL	**8,950**	**12,597**	**9,204**

In terms of emissions by sector, **Table 4.7** details the top ten economic sectors with the highest GHG emissions for every euro produced by the same sector. In this sense, the economic sectors were classified according to their emissions and their size in economic terms. The sector with the highest GHG emission per € was "*Other* *non-metallic mineral products*”, which includes activities such as the manufacture of construction materials such as glass, cement, concrete, ceramic materials, among others. Hence, if this sector generates 1 € in goods, it emits 1.85 kg CO_2-eq into the atmosphere. All of these economic sectors require large amounts of energy such as “*Other non-metallic mineral products*”, "*Electricity, gas, steam and air conditioning*", "*Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery*" (partly due to the wastewater pumping involved in sewerage services), "*Coke and refined petroleum products*", "*Water transport services*" and "*Basic metals*"; or are related to the combustion of fossil fuels such as, “*Fish and other fishing products; aquaculture products; support services to fishing*”, “*Air transport services*”, “*Products of agriculture, hunting and related services*” and “*Land transport services and transport services via pipelines*”).

Table 4.7. The top ten economic sectors in terms of GHG emission per €.

Economic Sector	kg CO_2-eq/€
Other non-metallic mineral products	1.85
Fish and other fishing products; aquaculture products; support services to fishing	1.36
Air transport services	1.33
Electricity, gas, steam and air conditioning	0.92
Products of agriculture, hunting and related services	0.90
Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery	0.76
Land transport services and transport services via pipelines	0.67
Coke and refined petroleum products	0.55
Water transport services	0.51
Basic metals	0.33

Considering the downscaling factors, the expenditures by economic sector, the GHG emissions per € and the inverse Leontief matrix the CF scores have been calculated following the **Equation 3.4** described in Section 4.2.2.3. Thus, the estimated CF scores were 5.25 tCO_2-eq·inhabitant^{-1}·year^{-1} and 3.83 tCO_2-eq·inhabitant^{-1}·year^{-1}

considering DF_1 and DF_2, respectively. However, the contribution of each sector to the CF score did not depend on the downscaling factor since it was applied to the expenses per person and applied equally to all sectors. **Figure 4.3** depicts the different contributions of each sector to the total CF, regardless the downscaling factor considered. Bearing in mind the information detailed in **Figure 4.3**, four sectors concentrated the 61% of the total contributions to the CF scores. These sectors were: "*Food products; beverages; tobacco products*", "*Electricity, gas, steam and air conditioning*", "*Products of agriculture, hunting and related services*" and "*Land transport services and transport services via pipelines*". All of them occupied leading positions in the ranking of expenditures per person detailed in **Table 4.6**. Furthermore, except for "*Food products; beverages; tobacco products*", the remaining three sectors were also among the top ten of the sectors with the highest GHG emission rates per € (**Table 4.7**). Accordingly, these sectors that had an outstanding emission rate were those where the citizens of Cadiz mainly expended their incomes and therefore, were sectors with a significant contribution to the CF score estimated per inhabitant. In the case of "*Food products; beverages; tobacco products*", its important contribution to the CF score was associated with the fact that it was the second sector in which the citizens of Cadiz spent their incomes with a remarkable difference in comparison with the other three sectors. However, although "*Real estate services*" was the sector in which there was more spending per person, it had a contribution of only 3% to the total CF score due to its low GHG emission rate per euro in comparison with the other sectors.

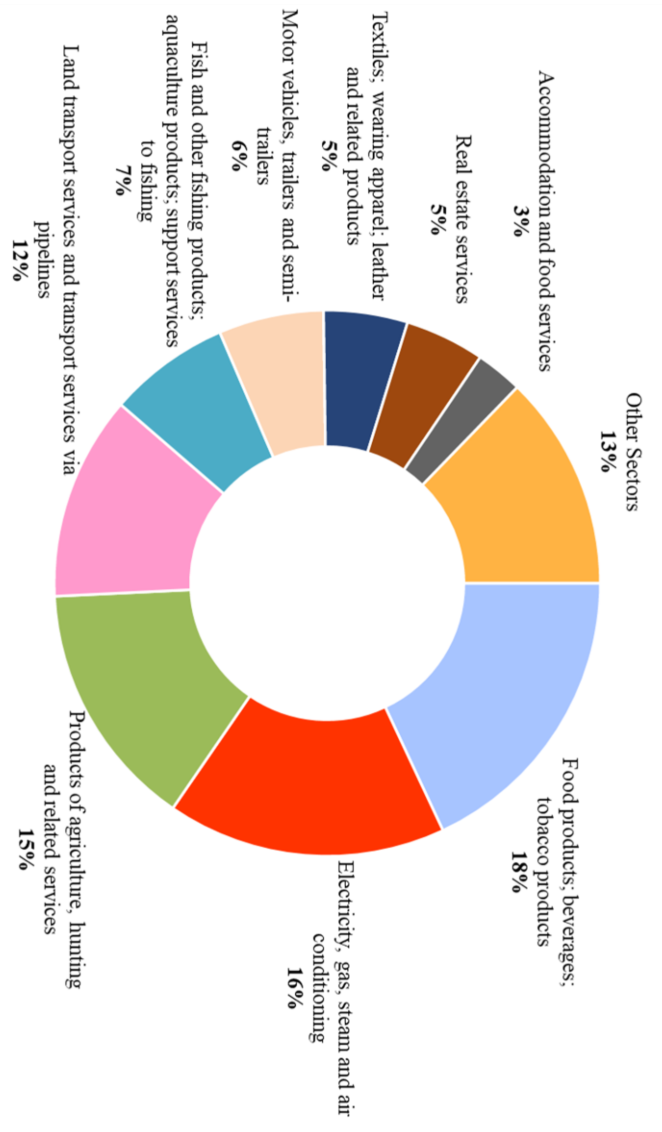


Figure 4. 3. Contributions from the different economic sectors to the CF regardless of the downscaling factor corresponding to Cadiz.

The findings of the EEIOA developed in this chapter coincide with those reported by Dias et al., (2014) for the city of Aveiro (Portugal). In that study, about 72% of the CF score was associated to four economic sectors which were “*Land transport; transport via pipelines*”, “*Food products, beverages and tobacco*”, “*Construction*” and “*Production, collection and distribution of electricity*”. The only sector that differed from our study was "*Construction*" since Dias et al. (2014) considered rental and imputed rents for housing within this sector in contrast to this work. However, the global value of CF score was significantly different from those identified in our study. The CF score obtained for Aveiro was 9.41 tCO_2-eq·inhabitant^{-1}·year^{-1}, considerably higher than our results (5.25 tCO_2-eq·inhabitant^{-1}·year^{-1} and 3.83 tCO_2-eq·inhabitant^{-1}·year^{-1}). The reason behind these differences can be attributed to two issues:

i) the CF obtained for both cities depends directly on the GHG emissions by sector of the corresponding country in terms of kg CO_2-eq per €. Therefore, while for Portugal in 2005 they were 18.85 kg CO_2-eq·€$^{-1}$, for Spain in 2015 they were 11.17 kg CO_2-eq·€$^{-1}$, almost 40% less than in Portugal. One of the most important reasons behind this fact is related with the effect that electricity consumption had on these emission rates. Thus, a growth in the presence of renewable energy sources in the electrical country mix was considered in the case of Spain. Accordingly, the wind power ratio was increased from 14 % in 2006 to 30 % in 2015 in that country (Red Eléctrica de España, 2020), which directly affected the GHG emission, achieving a considerable reduction in the case of Spain in 2015.

ii) differences in methodological issues, especially related to the relationships established between economic sectors and expenditure groups (35 sectors in Cadiz and 21 in Aveiro) and data sources that are different, also cause an associated error when comparing both results. The critical aspect was the equivalences between the expenditures groups and the economic sectors. In the case of Aveiro, 47 expenditure groups were considered, and relations were established with 21 economic sectors. Nevertheless, in the case of Cadiz, 116 expenditure groups were considered, with which relations were established with up to 35 economic sectors. Therefore, the total expenditure per inhabitant of Cadiz was distributed in more economic sectors and, therefore, additional sectors were considered. For example, in the study of Cadiz the economic sector entitled "*Real estate services*" included rental and imputed income. In contrast, rental and imputed rents were considered within the sector "*Construction*" in the study of Aveiro, which had a much higher value in terms of kg CO_2-eq·€$^{-1}$ (0.104 kg CO_2-eq eq·€$^{-1}$ for the case of "Construction" in Aveiro, and 5.16 ·10^{-4} kg CO_2-eq eq·€$^{-1}$ for the case of "Real estate services" in Cadiz).

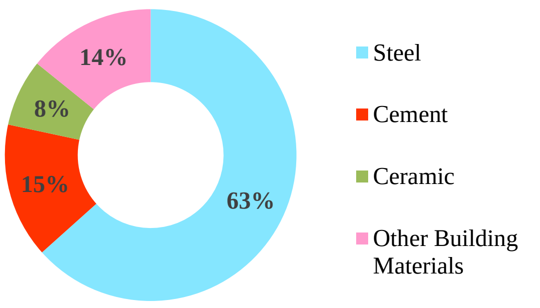
4.3.2 Life Cycle Assessment results

The environmental study has been performed following a cradle-to-city approach and therefore, the inputs of different flows (building materials, fossil fuels, energy, food and beverages, water, packaging materials) to the city have been computed, as well as the generation of specific output flows due to the UM approach with the corresponding treatments (wastewater, landfill and recycling), which took place within the boundaries of the city (see **Table 4.2 to 4.4**). The estimated CF score following an LCA perspective was 5.43 tCO_2-eq·inhabitant^{-1}·year^{-1}. **Table 4.8** summarizes the contributions to CF per input and output flow considered in the analysis. Bearing in mind these results, the main contributing flow responsible for the highest GHG emissions was that of "*Building Materials*". The rationale behind that outstanding effect (37% of the total CF score) was associated with large amounts of energy in the background processes of some construction materials (e.g., steel or cement). This flow, together with "*Energy*" and "*Food and Beverages*" (considering the production of foodstuffs and beverages), concentrated around 72% of the total CF estimated per inhabitant.

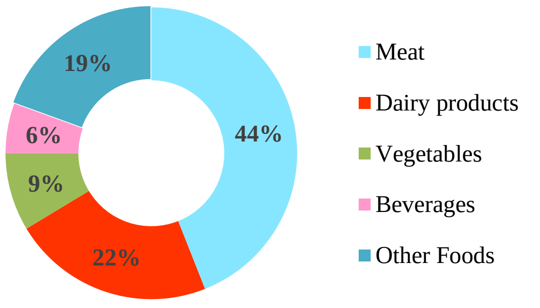
Table 4.8. Carbon Footprint (CF) score per inhabitant and year estimated from an LCA approach. Contributions per analyzed flow are also indicated.

Flows	Contribution %	CF tCO_2-eq·inhabitant^{-1}·year^{-1}
Building Materials	37.4	2.03
Energy	20.9	1.14
Food and Beverages	13.3	0.72
Fossil fuels	11.6	0.63
Other flows	8.7	0.47
Solid Wastes	6.7	0.37
Wastewater	1.4	0.07
TOTAL	100	5.43

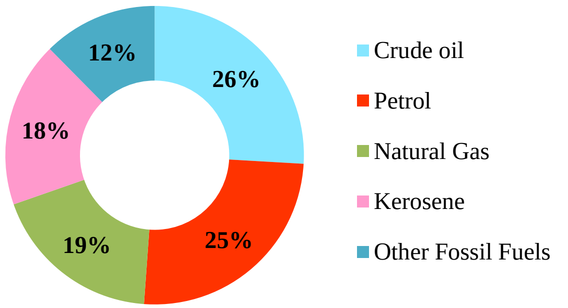
Attention has been given to the assessment per contributing flow to identify the hotspots. With respect to "*Building Materials*", the flows that contributed most to its CF were "*Steel*" (63%) and "*Cement*" (15%). Both construction materials have demanded large energy requirements in their production systems, as well as being the most energy intensive. These results are in line with those identified for the cities of Bilbao and Seville by González-García and Dias (2019) where "*Steel*" and "*Cement*" were also the main responsible products for GHG emission from construction materials. As for "*Food and beverages*" the main contributors were meat products (44%) and "*dairy products*" (22%). Both flows involve livestock activities which produce significant GHG emissions, namely those directly linked to the metabolism of ruminants and those indirectly produced from the use of agricultural machinery in agricultural activities to produce animal feed. The consumption of fossil fuels which were used in transport activities and heat requirements, also made a significant contribution to the CF of Cadiz. Among the fossil fuels, the largest contributions are from the production of diesel required in transport activities, as well as the production of kerosene required for aviation and the production of natural gas required at homes in heating systems. **Figure 4.4** depicts the assessment in detail of contributions from "*Building materials*", "*Food and beverages*" and "*Fossil Fuels*".



(a)



(b)



(c)

Figure 4. 4. Main flows corresponding with (a) "*Building Materials*" (b) "*Food and Beverages*" and (c) "*Fossil Fuels*" and their contributions to CF.

4.3.3 EEIOA vs LCA

Differences between the CF obtained by LCA and EEIOA, which have different methodological procedures, were found. In addition, both methodologies considered different approaches involving different sources and baseline data (LCA for consumption data and EEIOA for economic data). Moreover, the use of different ways to perform the downscaling to identify the expenditures in EEIOA derived also in remarkable differences on the CF score. The use of a downscaling factor based on the income per person (i.e., DF_1), resulted in a minor difference (around 3.4%) in the CF score estimated with both methodologies than that quantified with a downscaling based on expenditures per person (DF_2) (around 42%). This indicates that the DF that most closely matches the results obtained by both methodologies was DF_1. The reason behind this affirmation, bearing in mind that in the LCA the flows considered in the analysis were the most characteristic with the consumption of a city (such as building materials or fossil fuels), DF_1 of the EEIOA was also more specific to the city than the DF_2 which consider that the expenditures of the city of Cadiz were more similar to those of Andalusia.

Nevertheless, with respect to the contributions of the CFs of each methodology, more notable differences can be identified in some of the flows, as shown in **Table 4.9**. To compare the contributions to the CFs of the different methodologies, some relations were established between the main flows considered in LCA and the related economic sectors considered in EEIOA. In addition, for EEIOA the values of the contributions in tCO_2-eq·inhabitant^{-1}·year^{-1} obtained with DF_1 were considered. Thus, for "*Building Materials*" the contribution to CF was 2.03 tCO_2-eq·inhabitant^{-1}·year^{-1} and was related to the economic sectors "*Construction and construction works*" and "*Real estate services*" whose contribution was 0.27 tCO_2-eq·inhabitant^{-1}·year^{-1}, which was seven and a half times less. This large difference was because not all the flows considered within "*Building Materials*" were involved in the corresponding economic sectors (for example, consumption of steel which, in addition to construction, was used to manufacture cars). Regarding the "*Energy*" flow directly related to the economic sector “*Electricity, gas, steam and air conditioning*”, there was not such a difference between each contribution value which was of the same order of magnitude. Nevertheless, the contribution to the CF of “*Food and Beverages*” was three times less than the economic sectors to which it was related “*Products of agriculture, hunting and related services*”, “*Food products; beverages; tobacco products*” and “*Fish and other fishing products; aquaculture products; support services to fishing*”. This difference was since within these sectors, the emissions caused by some flows such as packaging was also implicit, which was not considered within “*Food and Beverages*”. Finally, the sum of the contributions to the CF for the flows “*Solid Wastes*” and “*Wastewater*” was 0.44 tCO_2-eq·inhabitant^{-1}·year^{-1} and these flows were related to the economic sector “*Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery*”, which resulted in a contribution to CF of 0.07 tCO_2-eq·inhabitant^{-1}·year^{-1}. In this case, the difference could be because spending on waste management in Spain is a municipal competence and only part of its spending falls directly on citizens. Therefore, if the economic sector had a lower value in the expenditures in the EEIOA, it also had a lower impact in terms of CF.

Table 4. 9. Contributions from the key flows and the corresponding related economic sectors to the Carbon Footprint score in LCA and EEIOA considering the DF_1.

LCA flow	tCO_2-eq·inhabitant^{-1}·year^{-1}	Economic Sector	tCO_2-eq·inhabitant^{-1}·year^{-1}
Building Materials	2.03	Constructions and construction works Real estate services	0.27
Energy	1.14	Electricity, gas, steam and air conditioning	0.87
Food and Beverages	0.72	Products of agriculture, hunting and related services Food products; beverages; tobacco products Fish and other fishing products; aquaculture products; support services to fishing	2.1
Solid Wastes Wastewater	0.44	Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery	0.07

However, each methodology considers different flows, and establishing relationships between them was not easy. For example, when considering the economic sector "*Land transport; transport via pipelines*", it was intuitive to relate it to transport or, in this case, to the consumption of fossil fuels, however, in "*Land transport; transport via pipelines*", air transport was not considered, nor was natural gas, which was considered in the flow of "*Fossil Fuels*". This reason made it very difficult to compare the results based on the contributions of both methodologies.

There are limitations in the availability of city-specific data in both methodologies. In the LCA inventory, most of the data compiled were at the regional or national level while the data availability at local level represented a minor contribution. In the same way, the databases considered to gather the data for the EEIOA corresponded to the national level (e.g., IO table or the inventory of emissions by sectors of activity) and the regional level (e.g., expenditures per inhabitant). In this sense, it is quite complicated to identify the number of products consumed in the city that are produced in the same city, information that is required when applying LCA. Therefore, and to avoid double counting, it was assumed that all products consumed were imported. Furthermore, unlike other much larger cities such as Madrid or Barcelona, the production of goods in Cadiz is much lower, with the service sector being the focus of its economy (trade, hotel and catering industry) (IECA, 2019).

Concerning EEIOA, the total IO table was considered in the analysis, which includes imports from other countries. However, GHG emissions by sector of activity considered in the EEIOA only corresponded to Spain. A third of the Spanish imports come from four countries: Germany, France, Italy and Portugal (OEC, 2018), which have CF scores in a similar order of magnitude (10.7, 6.9, 7.3 and 7.0 tCO_2-eq·inhabitant^{-1}·year^{-1} respectively) to that estimated in this study (7.5 tCO_2-eq·inhabitant^{-1}·year^{-1}) (Eurostat, 2018). It was therefore assumed that the Spanish CF was in line with those of other importing countries. This assumption implies that GHG emissions from imports were quantified based on the emissions by sector of activity in Spain and not taking into account the emissions corresponding to each country from which these imports are produced.

The most important advantages of EEIOA over LCA are associated with the highest speed of data collection, since data is available in databases, monitored and regulated by governments. In contrast, collecting life cycle inventory data required to conduct an LCA is often tedious because information is scattered among different sources and is often only available at the national (or even regional) level. It is quite complicated to access data at the city level. Furthermore, the procedure for completing an LCA study requires the use of payment databases to identify inventory data of background processes, while the EEIO can be performed free of charge.

Nonetheless, LCA methodology also reports advantages since it is easier to calculate, identify and assess the contributions to the CF from each contributing flow, whereas in the EEIOA, because of the newly established relationships between the expenditure groups and the economic sectors, it is complicated to determine the contributions to the CF score of the expenditure groups. Moreover, the establishment of relationships between the economic sectors and spending groups is a key issue, not an objective one for the time being, which shows that there is still room for improvements in the development of the methodology.

4.4 CONCLUSIONS

Cities that are responsible for the majority of global GHG emissions have a key role to play in the mitigation of climate change. Thus, the quantification of the Carbon Footprint is crucial to define actions and plan strategies to minimize emissions and reduce the associated CF. There are different tools to quantify CF in cities, being LCA and EEIOA the most recognized ones. In this study the CF corresponding to an inhabitant of the city of Cadiz was compared considering the two mentioned methodologies with the purpose of identifying differences, advantages and disadvantages among them.

The results obtained show that EEIOA is a good alternative to LCA, which was more widely used, to analyze the CF of a city, involving some advantages over LCA, such as the speed of data availability and not depending on payment databases (e.g., Ecoinvent or Agri-footprint databases). However, the EEIOA methodology is not yet fully developed. In this regard, it is necessary to create more consensus mainly on two points: i) the use of downscaling factors due to the lack of availability of city-specific data and ii) the establishment of the relationships between expenditure groups and economic sectors in the IO table. In addition, the estimation of emissions derived from imports is another weakness to be considered in the aim of increasing the consistency of the methodology. In this regard, it could be interesting to create a factor that is as close as possible to the reality of the city's expenditure. In contrast, LCA has more advantages than EEIOA when information is required to obtain information on contributions from flows to the CF score. Thus, flows with higher contributions (i.e., that occupy a key role in the CF) are easier to calculate and identify when considering the LCA due to the level of disaggregation of the data.

Nevertheless, EEIOA could be considered as a great tool to quantify and compare the CF of different cities, as well as to identify the key economic sectors. In this regard, the EEIOA can be implemented as an efficient methodology for determining carbon footprint. It also leads to the definition of actions to offset GHG emissions and to foster the change towards a carbon neutral city. Furthermore, it could also be used to identify the main factors affecting the CF in a sample of cities (consumption habits, climate, traffic...). Moreover, it may be of great interest to policy makers, who can decide which methodology can be used depending on the available data or the objective of the study. In addition, both methodologies can be used consecutively: first, EEIOA as a quick first step to assess the profile of the city in terms of its emissions, and then, the LCA to acquire a more in-depth analysis to identify in more detail the flows that contribute most to these emissions.

4.5 REFERENCES

AAE, 2015. energy data of andalusia 2015 (in Spanish). Agencia Andaluza de la Energía. https://www.agenciaandaluzadelaenergia.es/sites/default/files/documentos/datos_energeticos_andalucia_2015.pdf (accessed April 2020)

Aguas de Cádiz, 2015. Current News. https://www.aguasdecadiz.es/actualidad/ (accessed May 2021)

ANFEVI, 2017. Economic, environmental and social contribution of the glass sector in Spain. Glass Spain and the circular economy. Balance 2014/2016 (in Spanish) 44.

ASEFAPI, 2019. Presentation of the association. Spanish association of manufacturers of paint and printing inks (in Spanish). https://doi.org/10.1017/CBO9781107415324.004

Asefma, 2015. Asphalt and paving. Spanish Association of Manufacturers of Asphalt Mixtures (in Spanish) 18.

Aspapel, 2006. Newsletter. http://www.aspapel.es/ (accessed April 2020)

Blonk Agri-footprint BV, 2015. Agri-footprint - Part 2 - Description of Data. Gouda, the Nederlands BSI. (2012). PAS 2050-1: 2012 Assessment of life cycle greenhouse gas emissions from horticultural products. BSI.

CEDEX, 2013. Apparent consumption of plastics in Spain. Public Works Studies and Experimentation Center (in Spanish). Apparent consumption of plastics in Spain

Dias, A., Lemos, D., Gabarrell, X., Arroja, L., 2018. Comparison of tools for quantifying the environmental performance of an urban territory. J. Ind. Ecol. 22, 868–880. https://doi.org/10.1111/jiec.12614

Dias, A.C., Lemos, D., Gabarrell, X., Arroja, L., 2014.

Environmentally extended input-output analysis on a city scale - Application to Aveiro (Portugal). J. Clean. Prod. 75, 118–129. https://doi.org/10.1016/j.jclepro.2014.04.012

EFE Agro, 2015. The cork sector closes its campaign with 90,000 tons (in Spanish). https://www.efeagro.com/ (accessed May 2021)

El Periódico de la Energía, 2018. Andalusia extracts more than 33,000 tons of wood and biomass from its public forests (in Spanish). https://elperiodicodelaenergia.com/ andalucia-extrae-mas-de-33-000-toneladas-de-madera-y-biomasa-de-sus-montes-publicos/ (accessed May 2021)

ETRA, 2015. Wastewater treatment plant data. http://www.grupoetra.com/portfolio-item/edar-cadiz-san-fernando/ (accessed May 2021)

European Commission, 2006. Regulation (EC) No 1893/2006 of the Eurpean Parliament and of the Council of 20 December 2006.

FIPA, 2017. The aggregates sector in 2017. Iberoamerican Federation of Aggregates Producers (in Spanish). http://www.fiparidos.info/ (accessed April 2020)

Flacema, 2015. Sustainability report of the Andalusian cement sector 2015. Andalusian cement and environmental labor foundation (in Spanish).

Fueyo Editores, 2015. Concrete market in 2015 (in Spanish). Artículos Técnicos. Rocas y Miner. http://www.fueyoeditores.com/ (accessed April 2020)

García-Guaita, F., González-García, S., Villanueva-Rey, P., Moreira, M.T., Feijoo, G., 2018. Integrating Urban Metabolism, Material Flow Analysis and Life Cycle Assessment in the environmental evaluation of Santiago de Compostela. Sustain. Cities Soc. 40, 569–580. https://doi.org/10.1016/j.scs.2018.04.027

Goldstein, B., Birkved, M., Quitzau, M.B., Hauschild, M., 2013. Quantification of urban metabolism through coupling with the life cycle assessment framework: Concept development and case study. Environ. Res. Lett. 8. https://doi.org/10.1088/1748-9326/8/3/035024

González-García, S., Dias, A.C., 2019. Integrating lifecycle assessment and urban metabolism at city level: Comparison between Spanish cities. J. Ind. Ecol. 23, 1062–1076. https://doi.org/10.1111/jiec.12844

Hein, L., Metzger, M.J., Moreno, A., 2009. Potential impacts of climate change on tourism; a case study for Spain. Curr. Opin. Environ. Sustain. 1, 170–178. https://doi.org/10.1016/j.cosust.2009.10.011

HISPALYT, 2015. Press file (in Spanish). https://www.hispalyt.es/es/notas-de-prensa (accessed May 2021)

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., van Zelm, R., 2016. ReCiPe2016 : a harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterisation. Int. J. Life Cycle Assess. 1–152. https://doi.org/10.1007/s11367-016-1246-y

IECA, 2021. Andalusian Institute of Statistics and Cartography. Andalusia town by town - Municipal Files (in Spanish). https://www.juntadeandalucia.es/ (accessed May 2021)

IECA, 2018. Andalusian Institute of Statistics and Cartography. Municipal Population Census. Official figures of the municipal population (in Spanish). https://www.juntadeandalucia.es/ (accessed May 2021)

IECA, 2015a. Institute of Statistics and Cartography of Andalusia. Survey of Family Budgets. Base 2006 (in Spanish). http://www.juntadeandalucia.es/ (accessed May 2021)

IECA, 2015b. Institute of Statistics and Cartography of Andalusia. Living Conditions Survey (in Spanish). http://www.juntadeandalucia.es/ (accessed May 2021)

IGME, 2018. 2017 Mining Panorama. National Mining. Geological and Mining Institute of Spain (in Spanish) 2018, 3–45.

INE, 2015a. Urban Audit indicators for cities. National Institute of Statistics (in Spanish). https://www.ine.es/ (accessed May 2021)

INE, 2015b. National annual accounting of Spain: Input-Output tables. National Statistical Institute (in Spanish). https://www.ine.es/dyngs/INEbase/es/ (accessed May 2021)

INE, 2015c. Air emissions accounts by branches of activity (CNAE 2009). National Statistical Institute (in Spanish). https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736176941&menu=ultiDatos&idp=1254735976603 (accessed May 2021)

INE, 2015d. Income per person and consumption unit by Autonomous Community. National Institute of Stadistics (in Spanish) . https://www.ine.es/jaxiT3/Tabla.htm?t=9947 (accessed May 2021

IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Junta de Andalucía, 2016. Andalusia environment report (in Spanish). http://www.juntadeandalucia.es/ medioambiente/ (accessed April 2020)

Koroneos, C., Roumbas, G., Gabari, Z., Papagiannidou, E., Moussiopoulos, N., 2005. Life cycle assessment of beer production in Greece. J. Clean. Prod. 13, 433–439. https://doi.org/10.1016/j.jclepro.2003.09.010

Manzadeno, D.A., 2015. Ceramic Sector Analysis in Spain (in Spanish) 68.

MAPA, 2020. Ministry of Agriculture, Fisheries and Food. Food consumption data (in Spanish). https://www.mapa.gob.es/va/alimentacion/temas/consumo-tendencias/panel-de-consumo-alimentario/series-anuales/ (accessed April 2020)

Moreno Ruiz, E., Valsasina, L., Brunner, F., Symeonidis, A., FitzGerald, D., Treyer, K., Bourgault, G., Wernet, G., 2018. Documentation of changes implemented in ecoinvent database v3.5. Ecoinvent, Zürich, Switzerland. 5, 1–97.

ProfesionalesHoy, 2016. The brick and tile industry presents the balance for 2016 (in Spanish). https://profesionaleshoy.es/arquitectura/ (accessed April 2020)

Red Eléctrica de España, 2020. National statistical series (in Spanish). https://www.ree.es/es/datos/publicaciones/ series-estadisticas-nacionales (accessed April 2020)

Roibás, L., Loiseau, E., Hospido, A., 2017. Determination of the carbon footprint of all Galician production and consumption activities: Lessons learnt and guidelines for policymakers. J. Environ. Manage. 198, 289–299. https://doi.org/10.1016/ j.jenvman.2017.04.071

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C., 2015. The trajectory of the anthropocene: The great acceleration. Anthr. Rev. 2, 81–98. https://doi.org/10.1177/ 2053019614564785

Tanguay, G.A., Rajaonson, J., Lanoie, P., 2010. Measuring the sustainability of cities : An analysis of the use of local indicators. Ecol. Indic. 10, 407–418. https://doi.org/10.1016/ j.ecolind.2009.07.013

UNESID, 2015. Evolution of apparent steel consumption (in Spanish). https://unesid.org/datos-series-historicas-consumo-aparente-de-acero.php (accessed April 2020)

Villanueva-Rey, P., Vázquez-Rowe, I., Moreira, M.T., Feijoo, G.,

2014. Comparative life cycle assessment in the wine sector: Biodynamic vs. conventional viticulture activities in NW Spain. J. Clean. Prod. 65, 330–341. https://doi.org/10.1016/j.jclepro.2013.08.026

Williams, A.T., Randerson, P., Di Giacomo, C., Anfuso, G., Macias, A., Perales, J.A., 2016. Distribution of beach litter along the coastline of Cádiz, Spain. Mar. Pollut. Bull. 107, 77–87. https://doi.org/10.1016/j.marpolbul.2016.04.015

World Bank, 2019. Urban development overview. https://www.worldbank.org/en/topic/urbandevelopment/overview (accessed May 2021)

Chapter 5: **Comparing the carbon footprint of different Spanish cities through Environmentally Extended Input-Output Analysis**

SUMMARY

In this chapter, the Carbon Footprint (CF) of four Spanish cities (Bilbao, Madrid, Santiago de Compostela and Seville) was evaluated through Environmentally Extended Input-Output Analysis (EEIOA) methodology, which were previously analyzed using the Life Cycle Assessment (LCA) methodology. The main objectives of the chapter were to evaluate the CF score of these cities contributing to the development of the methodology and to compare the results with those obtained through LCA in previous studies available in the literature. The results show that Madrid was the city with the highest score (5.98 t CO_2-eq·inhabitant^{-1}·year^{-1}) followed by Santiago de Compostela (5.66 t CO_2-eq·inhabitant^{-1}·year$^{-1)}$, Bilbao (5.26 t CO_2-eq·inhabitant^{-1}·year^{-1}) and Seville (5.22 t CO_2-eq·inhabitant^{-1}·year^{-1}). In addition, the sectors with a greater contribution to CF were those related to food, electricity and fossil fuels consumption. On the other hand, these results differ significantly from those obtained with LCA. However, in both methodologies the main flows that most affect CF coincide. Finally, this chapter allows establishing the EEIOA as a robust and reliable methodology to evaluate the CF of urban systems and contributes to establish measures addressed to mitigate climate change.

5.1 INTRODUCTION

In previous chapters, the importance of analyzing the CF in urban systems was discussed in detail. Accordingly, in Chapter 4 the CF of a city was evaluated by comparing two methodologies: Life Cycle Assessment (LCA) and Environmentally Extended Input-Output Analysis (EEIOA). This chapter is a continuation of Chapter 4 and its purpose is to analyze by means of EEIOA the CF of four Spanish cities with very different characteristics: Bilbao, Madrid, Santiago de Compostela and Seville.

These cities are located in different parts of the Spanish geography. So, they have different climates, cultures and consumption patterns, which can be interesting when analyzing how these variables contribute to CF. These cities have previously been evaluated by LCA in the literature (García-Guaita et al., 2018; González-García and Dias, 2019) as well as in Chapter 3 where the environmental profile of Madrid was evaluated (González-García et al., 2021). Consequently, the main objectives of this chapter were two:

1) To assess the CF of different Spanish cities with the aim of establishing the main differences between them and identifying the main economic sectors with a greater contribution to CF. Accordingly, it is possible to establish how the CF affects some differentiating factors of these selected cities such as climate, diet, culture, etc.

2) To apply the EEIOA methodology described in previous Chapter 2to evaluate different cities in Spain. Accordingly, this chapter aims to contribute to the development of the methodology and to establish its use to give it more robustness and reliability when applied in new case studies.

To achieve these objectives, the chapter was divided into the following sections: Materials and methods where the cities selected as case study were described as well as the main adaptations of the EEIOA methodology were pointed out and, the Results section where the main findings were shown and discussed. Finally, the conclusions obtained from this study were detailed.

5.2 MATERIALS AND METHODS

5.2.1 Case study

The cities selected as case study were Bilbao, Madrid, Santiago de Compostela and Seville. These cities are located in different geographical points within the Spanish territory (

Figure 5.1), with which the climatic and cultural differences are more evident between them. Furthermore, all of them are capitals of the region to which they belong, except in the case of Bilbao, which is the most populated city in the Basque Country, but it is not its capital. Since these cities have been previously analyzed from a LCA approach, therefore, it could be interesting when comparing the results obtained with EEIOA in terms of CF.

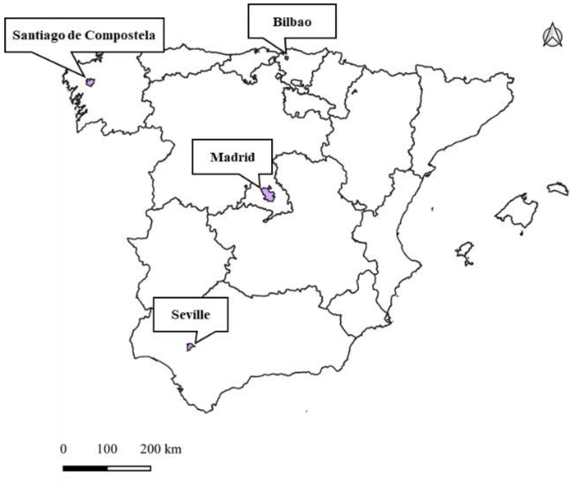


Figure 5.1. Geographical position of the cities considered in this chapter.

5.2.1.1 Bilbao

Bilbao (or Bilbo in Basque, the co-official language in the Basque country) is a city located in the north of Spain near the Cantabrian coast. It belongs to the oceanic climate zone and has an average annual temperature of 13.5 °C (Climate-Data, 2020). Bilbao is the most populated city in the Cantabrian area of Spain with 350,184 inhabitants in 2020 (INE, 2020a). Moreover, it is the core of the metropolitan area around the Nervion river which concentrates a population of approximately one million inhabitants. The population of Bilbao remained stable during the last decade, suffering a slight decrease of 0.8%. In terms of living conditions, the gross income per capita of Bilbao was 15,137 € in 2017 (higher than the Spanish average, which is 11,412 €), in addition the unemployment rate was 12.2 % in 2019, below the unemployment rate mean in Spain (14.1 %) (INE, 2020b). These values show a good economic situation that translates into social well-being. On the other hand, the gross domestic product (GDP) of the city was € 35,282 €·per capita in 2018, in which Services sector was the sector that contributes the most to this value (90%) (Eustat, 2019). Consequently, Bilbao is the most economically relevant city in the Basque country in both manufacturing, construction and tourism (González-García and Dias, 2019).

5.2.1.2 *Madrid*

Madrid (which was also described in Chapter 3) is a city located in the center of the Iberian Peninsula within a cold semi-arid climatic zone with Mediterranean influences with an average annual temperature of 14.5 (Climate-Data, 2020). Madrid is the capital and the most populated city in Spain with 3,334730 inhabitants in 2020, and it has a population growth of 2 % in the last decade, which indicates that the city continues to grow despite its large size (INE, 2020a). The citizens of Madrid have a gross per capita income of 15,930 € per capita, which is higher than the Spanish average, as in the case of Bilbao. It also has a good unemployment rate of 10.5 % which indicates good socio-economic health. In addition, Madrid had a GDP per capita of 43,622 € in 2018 and the sector that contributes the most to this value is also the services sector (as was also mentioned in Chapter 3) with 90% of the total value (IECM, 2021). As Madrid is the capital of Spain, it concentrates many of the state's administrative services, and is an international tourist attraction, welcoming millions of tourists a year.

5.2.1.3 *Santiago de Compostela*

Santiago de Compostela is a city located in the northwest of the Iberian Peninsula, in an oceanic climate zone, like Bilbao with an average annual temperature of 12.7 °C (Climate-Data, 2020). Santiago de Compostela is the capital of the Galicia region and its population is 97,848 inhabitants. In the last decade, the population grew by 3.1 %, which is the largest growth of the cities considered in this study. This fact is reflected in the economic data of the city. Despite the fact that the gross income per capita was not excessively high (13,516 € in 2018), the city has a low unemployment rate (9.8 in 2019) (INE, 2020b). Moreover, the gross domestic product per capita was 37,508 € in 2018, which was higher than that of Bilbao despite the fact that Santiago is a much smaller city. Furthermore, Santiago de Compostela is a city with an internationally recognized tourist attraction, due to its historical heritage and because it is the final destination of the pilgrimage route of the Camino de Santiago.

5.2.1.4 Seville

The city of Seville is located in the south of Spain in a Mediterranean climate zone, in which there is an average annual temperature of 18.8 °C (Climate-Data, 2020). This city is the capital and the most populated city of the Andalusia region with 704,198 inhabitants. Moreover, this large number of inhabitants makes it the fourth most populated city in Spain. Regarding population growth, Seville in the last decade increased its size by almost 2% (INE, 2020a). However, the socio-economic data of the city show worse values with respect to the other cities. The city's unemployment rate in 2018 was 19.1 % higher than the average rate in Spain (14.1 %). In addition, the gross income per capita was 11,346 € in 2017 lower than the average gross income of Spain in the same year (11,412 €) (INE, 2020b) and finally, the GDP per capita is also lower than that of the other cities (19,026 € per capita in 2016) (IECA, 2021). One of the most important sectors of the economy of Seville is the tourist because it is one of the cities with a great historical heritage.

5.2.2 Environmentally Extended Input-Output Analysis methodology

To perform assessment, the methodology described in Chapter 2 was adapted to this case study. Therefore, in this section the different steps necessary to carry out the methodology were detailed. First, the required data and the data sources consulted for this case study were specified. Second, the equivalences were established taking into account the expenditure groups and the economic sectors considered in the databases. And finally, the matrixes and equations used to the calculation of the CF were presented.

5.2.2.1 Data requirements

The data required to perform the EEIOA, starts from three databases as described in Chapter 2: The Input-Output table (IO table), the Greenhouse gases (GHG) emission per Branches of Activity and expenditures of the households per group of the city.

The IO table and GHG emission per Branches of Activity are available only at National level. In this chapter, data corresponding to this database were taken for the year 2016 (INE, 2020c, 2020d). Despite being from different years, the number of sectors and branches of activity of these data sources is the same as in Chapter 4 (64 sectors and 64 branches of activity), only the numerical values of each change.

On the other hand, data for expenditures of the households are available at regional level in the National Statistics Institute for the year 2016 (INE, 2020e). In this data source, data were collected for the 95 expenditure groups available in € per person. However, to obtain data on a local scale, it was necessary to consider a downscaling factor. Therefore, in this chapter the downscaling factor 1 (DF_1) described in Chapter 2 and applied in the case of Cádiz in Chapter 4 was taken into account, which is calculated according to **Equation 5.1**:

$$DF_1 = \frac{Incomes\ per\ household\ in\ City}{Incomes\ per\ household\ in\ Region} \qquad \textbf{(Equation 5.1)}$$

Average household income data are available both locally and regionally at the National Statistical Institute of Spain (INE, 2021, 2020b).

5.2.2.2 Equivalences between expenditures groups and economic sectors of the IO table

Although the number and economic sectors were the same as those used in Chapter 4, the expenditure groups per household were different, so the relationships between the economic sectors and the expenditure groups varied. Therefore, some sectors that were not considered in Chapter 4, in this chapter were considered, when relating groups of expenses with them. This is the case of *“Financial* *services, except insurance and pension funds"* and *"Services of travel agencies, tour operators and other reservation services, and services related thereto"*. Contrary, the *"Machinery and equipment repair and installation services"* sector was not related to any group of expenses in this chapter; therefore, it was not considered. **Table 5.1** shows the equivalences between the economic sectors and the expenditures groups.

Table 5.1. Equivalences between economic sectors and expenditures groups.

IO table Economic Sectors	Expenditures Groups
Products of agriculture, hunting and related services	Meat Fruits Vegetables, including potatoes and other tubers Gardening, plants and flowers
Fish and other fishing products; aquaculture products; support services to fishing	Fish

Table 5.1 (cont.) Equivalences between economic sectors and expenditures groups.

IO table Economic Sectors	Expenditures Groups
Food products; beverages; tobacco products	Bread and Cereals
	Dairy Products
	Oils and Fats
	Sugar, confectioneries, honey, chocolate and ice creams
	Other food products
	Coffee, tea and cocoa
	Mineral water, soft drinks and juices
	Spirits and liquors
	Wine
	Beer
	Tobacco
Telecommunications services	Phone, telegraph and fax
Computer programming, consultancy and related services; information services	Information processing material
Financial services, except insurance and pension funds	Other financial services n.e.c[9].
Paper and paper products	Stationery and drawing materials
Publishing services	Books
	Newspapers
Electrical equipment	Big appliances, electrical or not
	Small appliances
Electricity, gas, steam and air conditioning	Electricity
	Gas
	Liquid fuels
	Solid Fuels

[9] Not contemplated elsewhere

Table 5.1 (cont.) Equivalences between economic sectors and expenditures groups.

IO table Economic Sectors	Expenditures Groups
Human health services	Pharmaceutical products Other medical products Therapeutic apparatus and equipment Medical and hospital services Dental services Non-hospital paramedical services
Motor vehicles, trailers and semi-trailers	Cars Motorcycles and mopeds Repair and maintenance Spare parts and accessories for personal vehicles Other services related to personal vehicles
Other transport equipment	Bicycles
Furniture; other manufactured goods	Furniture and accessories, rugs and other floor coverings Other goods for leisure, sport and culture Jewelry, costume jewelry and watchmaking
Postal and courier services	Postal services
Machinery and equipment n.e.c	Big electric tools and their repairs Small tools, various accessories and their repairs
Natural water; water treatment and supply services	Water supply
Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery	Waste collection Sanitation services
Constructions and construction work	Services for the maintenance and repair of the dwelling
Land transport services and transport services via pipelines	Rail transport (train, metro, urban tram, intercity and long distance) Road transport (local and long distance) Fuels and lubricants

Table 5.1 (cont.) Equivalences between economic sectors and expenditures groups.

IO table Economic Sectors	Expenditures Groups
Air transport services	Passenger transport by air
Retail trade services, except of motor vehicles and motorcycles	Glassware, tableware, cutlery, other household utensils and their repairs Non-durable household items
Accommodation and food services	Restaurants and cafes Canteens and dining rooms Accommodation Services
Computer, electronic and optical products	Other equipment for the reception, recording and reproduction of sound and vision Photographic and cinematographic equipment and optical instruments Supports for recording image, sound and data and subscription to music streaming services
Textiles; wearing apparel; leather and related products	Clothing, cleaning, repair and rental Fabrics and other articles and clothing accessories Shoes and other footwear Home textiles and their repairs
Insurance, reinsurance and pension funding services, except compulsory social security	Insurance connected with the dwelling Insurance connected with health Insurance connected with transport Other insurance
Other professional, scientific and technical services; veterinary services	Products for pets and other household animals, veterinary and other pets services
Rental and leasing services	Other imputed rentals
Services of travel agencies, tour operators and other reservation services, and services related thereto	Tourist packages
Public administration and defense services; compulsory social security services	Social protection services

Table 5.1 (cont.) Equivalences between economic sectors and expenditures groups.

IO table Economic Sectors	Expenditures Groups
Education services	Early Childhood Education Primary education Secondary education Post-secondary non-tertiary education Tertiary education Other education not defined by level
Creative, arts and entertainment services; library, archive, museum and other cultural services; gambling and betting services	Recreational and sports services Cultural services Gambling
Sporting services and amusement and recreation services	Games, toys and hobbies
Repair services of computers and personal and household goods	Domestic service and other services for housing Other services related to housing n.e.c.
Other personal services	Hairdressing and personal aesthetics Electrical appliances for personal care Other personal care appliances, articles and products Other personal articles Other services
Real estate services	Actual rental (main dwelling) Actual rental (other dwellings) Rents imputed to the property owned

5.2.2.3 Carbon Footprint calculation

At this stage, the steps developed in Chapter 2 were followed. First, the inverse Leontief matrix $(I\text{-}A)^{-1}$ was constructed with the 64 sectors available in the rows and the 36 economic sectors established for this case study accordingly with **Section 5.2.2.2**. Secondly, the expenditures by economic sector vector (Y) were defined which contains data for each city in €·inhabitant^{-1} corresponding to 36 economic sectors with equivalences to expenditures groups after applying the corresponding downscaling factor. Hence, each city obtained a different Y vector. Finally, GHG emission vector (Z) was constructed with data of the GHG emissions in tons of CO_2-eq·€$^{-1}$ corresponding to the 64 economic sectors.

$$(I-A)^{-1} = \begin{pmatrix} c_{1,1} & \cdots & c_{1,36} \\ \vdots & \ddots & \vdots \\ c_{64,1} & \cdots & c_{64,36} \end{pmatrix}$$ (Inverse Leontief matrix)

$$Y = (y_1 \quad \cdots \quad y_{36})$$ (Expenditures by economic sector vector)

$$Z = \begin{pmatrix} z_1 \\ \vdots \\ z_{64} \end{pmatrix}$$ (GHG emission vector)

Consequently, bearing in mind the data contained in this matrix and these vectors, the equation described in Chapter 2 (**Equation 2.3**) was adapted to calculate the corresponding carbon footprint score of each city (**Equation 5.2**), where CF_x was the CF for city x.

$$CF_x = \sum_{j=1}^{36} \sum_{i=1}^{64} c_{ij} \cdot y_j \cdot z_i$$ (**Equation 5.2**)

5.3 RESULTS AND DISCUSSION

5.3.1 Expenditures by economic sector

Considering that data on household expenditures are only available at the regional level, the downscaling factor considered in this chapter requires data on average household income for the cities and also the regions to which these cities belong. Bearing in mind **Equation 5.1**, by which the downscaling factor was calculated, it implies that the value is proportional to the difference between the values of the regional and local average income per household.

Consequently, in **Table 5.2** the values of the DF for each city are shown and the corresponding values of the average household incomes at local level and at regional level.

Table 5.2. Downscaling factors for each city and average household incomes at regional and local level.

Region	Regional average household income (€·household^{-1})	City	City average household income (€·household^{-1})	Downscaling factor
Basque Country	34,054	Bilbao	34,999	1.03
Madrid	31,370	Madrid	39,613	1.26
Galicia	25,980	Santiago de Compostela	34,068	1.31
Andalusia	21,966	Seville	29,394	1.34

According to the values of household income, there was a great difference between the regions of the Basque Country and Madrid with respect to Galicia and Andalusia, which have lower values. This indicates that the standard of living in Galicia and Andalusia was lower at the regional level than in the other two regions. However, at the local level, the differences are smaller, and the city of Madrid stands out among them with almost 40,000 € per household. On the other hand, Bilbao was the city that has the least differences with respect to income per household at the regional level, being the DF almost 1. In this sense, when calculating the expenditures considering the DF, expenditures of a citizen of Bilbao per year, were similar to the expenses of any citizen of the Basque Country.

Consequently, **Table 5.3** shows the expenditures corresponding with the 36 economic sectors established in Section **5.2.2.2**, for each city considered in this chapter. The three sectors which concentrates the most annual expenses (between 36 and 41%, depending on the city) were "*Real estate services*", "*Accommodation and food services*" and "*Food products, beverages, tobacco products*". This result coincides with the result obtained in Chapter 4 for the city of Cádiz, in which these three sectors also concentrated most of the annual spending. Hence, the citizens of these cities spend most of their money on housing, restaurants and hotels, and food.

Furthermore, in some sectors, there were differences in terms of spending between cities. One of these sectors was "*Real estate services*" in which Madrid and Bilbao stand out over Santiago de Compostela and Seville. Accordingly, the price of housing in Madrid and Bilbao was higher than in the other two cities. In addition, these values could be related to the ones of household income (see **Table 5.2**), which were also lower for Santiago and Seville, indicating that the price of housing depends on the purchasing power. Moreover, it also highlights the difference between cities in sectors such as "*Education services*" or "*Air transport Services*". In the case of "*Education services*" Madrid stands out with an expense of 346 €·inhabitant^{-1} compared to Bilbao with 228 €·inhabitant^{-1}. With lower values in this sector were Santiago de Compostela (137 €·inhabitant^{-1}) and Seville (129 €·inhabitant^{-1}). This implies that in Madrid and Bilbao there was a greater affinity for private education than in other cities. On the other hand, with regard to the "*Air transport Services*" sector, the value of Madrid stands out over that of other cities, mainly because the city has the largest airport in Spain, and with the largest number of national and international flights.

Table 5.3. Expenditures in €·inhabitant^{-1} for 2016 in the economic sectors for each city.

Economic Sector	Bilbao	Madrid	Santiago de Compostela	Seville
Real estate services	3,342	3,581	2,526	2,383
Accommodation and food services	1,625	1,823	1,170	1,284
Food products; beverages; tobacco products	1,076	1,171	1,292	1,279
Products of agriculture, hunting and related services	900	913	965	852
Land transport services and transport services via pipelines	556	894	699	710
Textiles; wearing apparel; leather and related products	751	834	872	829
Motor vehicles, trailers and semi-trailers	765	813	968	789
Repair services of computers and personal and household goods	506	678	317	254
Insurance, reinsurance and pension funding services, except compulsory social security	487	664	538	453
Rental and leasing services	588	653	537	550
Electricity, gas, steam and air conditioning	485	605	554	444
Other personal services	529	559	491	513
Human health services	473	512	519	462
Postal and courier services	372	449	390	391
Education services	228	346	137	129
Creative, arts and entertainment services; library, archive, museum and other cultural services; gambling and betting services	240	319	221	249
Fish and other fishing products; aquaculture products; support services to fishing	284	255	304	237
Furniture; other manufactured goods	180	185	182	217
Services of travel agencies, tour operators and other reservation services, and services related thereto	184	183	93	121
Retail trade services, except of motor vehicles and motorcycles	132	152	158	177

Table 5.3 (cont.). Expenditures in €·inhabitant^{-1} for 2016 in the economic sectors for each city.

Economic Sector	Bilbao	Madrid	Santiago de Compostela	Seville
Natural water; water treatment and supply services	57	122	64	90
Electrical equipment	111	118	121	117
Publishing services	97	114	73	52
Air transport services	63	107	42	47
Other professional, scientific and technical services; veterinary services	63	101	93	88
Constructions and construction works	100	94	169	115
Sporting services and amusement and recreation services	49	76	56	81
Machinery and equipment n.e.c	26	62	50	35
Computer, electronic and optical products	45	57	29	44
Computer programming, consultancy and related services; information services	35	50	46	41
Telecommunications services	34	44	34	48
Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery	90	44	86	105
Paper and paper products	24	34	26	33
Public administration and defense services; compulsory social security services	42	26	42	22
Other transport equipment	9	7	0	9
Financial services, except insurance and pension funds	3	0	8	6
TOTAL	14,553	16,646	13,867	13,258

Regarding the total values of the annual expenditures of the cities, there is a relationship with respect to the income per household shown in **Table 5.2**. The rationale behind this issue is because Madrid is the city that has the most expenditure per inhabitant, making a significant difference with respect to Bilbao, which is the second city with the highest expenditure per inhabitant, Santiago de Compostela and Seville, the last two with much smaller differences. In this sense, a noticeable difference is observed between the economic level of Madrid and Bilbao with respect to the other cities.

5.3.2 Carbon Footprint

The CF was calculated for each city considering the expenditures per inhabitant (vector Y), the emissions associated with each economic sector (vector Z) and the inverse Leontief matrix, according to **Equation 5.2**.

Figure 5.2 shows the values of the CF obtained in t CO_2-eq·inhabitant^{-1}·year^{-1} for each of the cities. The city that obtained the highest CF value was Madrid. Considering that it is the city with the highest spending per capita and with the highest average income per household, it could be established that these factors directly affect the CF. However, the value obtained in terms of CF for Santiago de Compostela is higher than that of Bilbao, where the per capita expenditure of the Basque city, as well as its income per household, are significantly higher with respect to the Galician city. This was mainly due to the fact that despite the total expenditure per inhabitant in Bilbao was higher than in Santiago, in some key sectors. Sectors such as "*Products of agriculture, hunting and related services*", "*Land transport services and transport services via pipelines*", "*Electricity, gas, steam and air conditioning*" and "*Fish and other fishing products; aquaculture products; support services to fishing*" -which have high values of CO_2 emissions (see **Table 4.7** in Chapter 4), showed expenses per inhabitant in Santiago higher than in Bilbao. Therefore, the CF will be more affected by the higher expenditures in these sectors with higher contributions to GHG emissions.

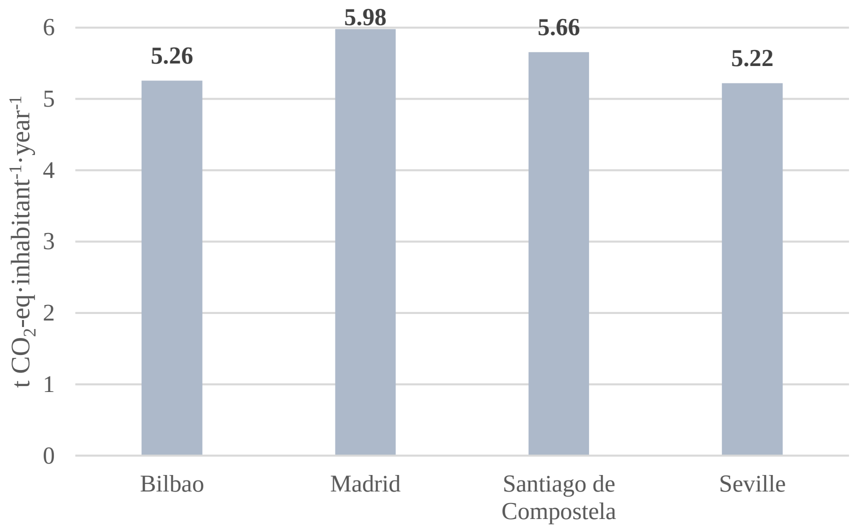


Figure 5.2. CF for each of the cities studied.

In this sense, in the case of Madrid, spending in most sectors was significantly higher than in other cities, including some of the sectors that produce the most GHG emissions such as "*Land transport services and transport services via pipelines*", "*Electricity, gas, steam and air conditioning*" and "*Air transport services*" (see **Table 5.3**). Regarding the sector "*Land transport services and transport services via pipelines*", in the metropolitan area of Madrid there are 2.5 trips·day^{-1}·inhabitant^{-1}, and most of them are made by private transport (de Oña et al., 2021), which was why spending in this sector was so high. Moreover, it must be taken into account that the expenditure data were available at a regional and not a local level, thus, in the methodology these trips from the metropolitan area were considered and not only the transport within the city. Furthermore, in Madrid the variation in temperatures between winter and summer is much greater than in the other cities in the study, with cold winters and hot summers, so the use of heating and air conditioning is greater compared to the other cities; hence, spending in sector "*Electricity, gas, steam and air conditioning*" was also higher. Finally, in the case of "*Air transport services*", as previously mentioned, the expenditures in this sector were high mainly due to the Madrid airport, which offers many more combinations of domestic and international flights than the airports in other cities. For these reasons, Madrid obtained the highest value in CF

Concerning the other cities, Seville was the city with a highest expenditures per inhabitant in "*Land transport services and transport services via pipelines*" and Bilbao the city with the lowest spending. Once again it must be considered that in this sector it affects regional mobility as well as transport within the city. Therefore, despite the fact that Seville and Santiago de Compostela have high expenditures values with respect to this sector, it may be partly due to the abuse of private transportation for mobility in the region.

On the other hand, although Santiago de Compostela and Bilbao have a similar climate, the spending of Santiago de Compostela in sector "*Electricity, gas, steam and air conditioning*" was higher than that of Bilbao, with Seville being the city that spent the least in this sector, this may be due to a higher temperature in winter, which reduces the cost of heating. In addition, Santiago de Compostela was the city that spent the most its inhabitants on sectors related to the food industry. This affected the CF of the city in a negative way, since these sectors were sectors with a high value of GHG emissions. This may be due in part to the high consumption of fruits, vegetables and fish in Galicia compared to the other regions (Esteve-Llorens et al., 2021). Accordingly, climate and diet patterns affect the FC of each of the cities.

5.3.2.1 Economic sectors contributions

Once the total value of the CF was obtained, the sectors that most affected this value of each city were analyzed. Consequently, when reducing emissions, these key sectors must be considered to mitigate CF. **Figure 5.3** shows the contributions of the economic sectors to the CF of each city. The same pattern was repeated in all the cities regarding the order of the economic sectors with the greatest contribution: "*Products of agriculture, hunting and related services*", "*Food products; beverages; tobacco products*", "*Electricity, gas,* *steam and air conditioning*", "*Land transport services and transport services via pipelines*", "*Motor vehicles, trailers and semi-trailers*" and "*Fish and other fishing products; aquaculture products; support services to fishing*". Contributions values vary slightly depending on the city, but with a similar order of magnitude. As might be expected, all these sectors were economic sectors to which citizens allocated a significant part of their annual spending such as "*Products of agriculture, hunting and related services*" and "*Food products; beverages; tobacco products*", as well as sectors with high GHG emission values such as "*Electricity, gas, steam and air conditioning*", "*Land transport services and transport services via pipelines*" and "*Fish and other fishing products; aquaculture products; support services to fishing*".

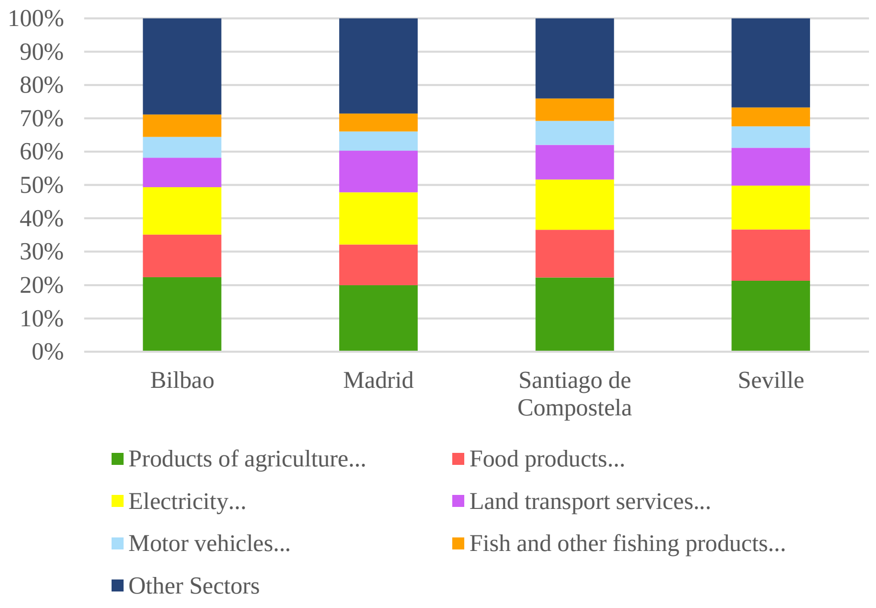


Figure 5.3. Relative contributions of the main economic sectors to the CF of each city.

In the case of "*Products of agriculture, hunting and related services*", it was an economic sector that emits large amounts of GHG emissions, mainly due to livestock (Hyland et al., 2017) and the inhabitants of all cities spend a large part of their annual spending in this sector. For this reason, it was the sector that obtained the most contribution to CF of all cities. To reduce the contribution of the food sectors to CF, it is necessary to make the population aware of CF associated with different foods. By reducing the excess consumption of meat and some products of animal origin, it is possible to mitigate GHG emissions related to these sectors (Esteve-Llorens et al., 2019).

Electricity consumption made a great contribution due to dependence on fossil fuels for the generation of electric power. Currently, coal is the main fossil fuel for electricity generation in Spain (Fundación para el Fomento de la Innovación Industrial, 2016) and is the fossil fuel that most affects climate change (Munawer, 2018). Transport and fishing are also sectors that depend on the combustion of fossil fuels to a great extent (Villanueva-Rey et al., 2018). In this sense, the use of renewable energy for electricity production is key to reducing CF. In addition, the replacement of fossil fuel cars with electric cars, despite being an increasingly implanted measure in society, is still very incipient. Therefore, the use of public transport should be favored over private, so that these contributions to the CF could be reduced.

5.3.3 Comparison with LCA studies

It was previously mentioned that all the cities considered in this chapter were just evaluated using the LCA methodology (García-Guaita et al., 2018; González-García et al., 2021; González-García and Dias, 2019). In this section, the results in terms of CF obtained in this chapter using the EEIOA methodology were compared with those obtained using LCA. In **Figure 5.4**, the CF in t CO_2-eq·inhabitant^{-1}·year^{-1} of the cities selected in this chapter is represented, corresponding to each of these two methodologies. The results show that the CF obtained by LCA was higher in all cities with respect to that obtained in EEIOA, especially in the case of Bilbao, in which the difference was almost double, and in Santiago de Compostela. These differences can be mainly due to three reasons:

i) In LCA some of the flows considered to calculate the CF were industrial flows. For example, within fossil fuels flow, kerosene was considered in these studies as the fuel used in airplanes. Nevertheless, within this flow, commercial flights were not differentiated with respect to passenger flights, so that both were considered. However, in EEIOA only direct flows derived from citizens' expenditures are considered. Therefore, continuing with the example, in sector "*Air transport services*" only passenger flights were considered. This assumption can happen with other flows, such as electricity consumption in restaurants, which use equipment with higher consumption, or fuel consumption in company transport. Consequently, when considering these types of flows, the CF may be affected by increasing its per capita value.

ii) Despite the downscaling factor used in EEIOA, the main source of per capita expenditure data is at the regional level. This means that some of the flows considered can obtain lower values. This is the case, for example, of the "*Repair services of computers and personal and household goods*" sector, which has a much lower cost in Santiago de Compostela and Seville compared to Bilbao or Madrid. This data may be affected by the greater absence of technology among the aging population in rural areas of Galicia and Andalusia. Therefore, even applying a downscaling factor, this data may be lower than expected. Furthermore, in LCA some of the data collected was at a local scale, which allow to avoid this type of estimations in some of the flows.

iii) One of the main flows that contributed to the CF obtained in LCA in the different cities was manufacturing. However, in EEIOA it did not contribute significantly. This also affected the increase in CF obtained by LCA with respect to EEIOA. One of the reasons for this may also be the use of these manufactures for the construction of industrial or business buildings (warehouses, offices, business reforms, etc.) that were not considered in EEIOA.

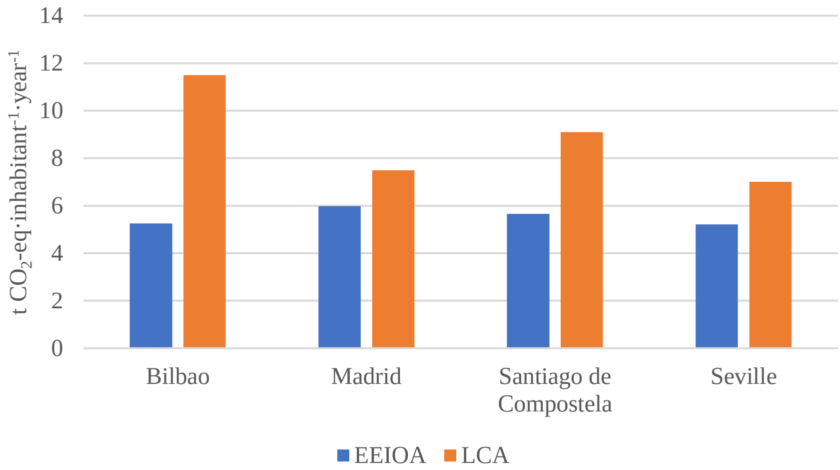


Figure 5.4. Comparison between CF obtained by LCA and EEIOA.

However, food, transport (considering the consumption of fossil fuels) and electricity consumption were both in LCA and EEIOA the flows that contribute the most to the FC of the cities considered in this chapter (García-Guaita et al., 2018; González-García et al., 2021; González-García and Dias, 2019). Hence, although the differences in the global value between both methodologies were significant, the flows that contribute the most to the CF of a city were the same. Therefore, when taking measures to mitigate the effects of climate change, both methodologies can provide information on the key flows that must be acted on.

5.4 CONCLUSIONS

The EEIOA is a methodology that can assess the carbon footprint of a city quickly and through public data sources. In this chapter, the CF of four Spanish cities, located in different parts of the country, was analyzed. This methodology transforms the euros corresponding to the expenses per inhabitant destined to each economic sector in units of CO_2-eq. The results showed that Madrid, which was the city with the highest spending per inhabitant, was also the city with the highest carbon footprint. However, the second city with the highest spending was Bilbao, but in terms of CF, Santiago de Compostela obtained a higher CF than that of Bilbao. Therefore, the fact that the inhabitants spend more does not affect the CF of a city so much, but it depends more depending on which sectors they allocate that spending to. Therefore, there are economic sectors that emit a greater amount of GHG, and therefore have a greater impact on CF. Some of these sectors were "*Products of agriculture, hunting and related services*", "*Land transport services and transport services via pipelines*", "*Electricity, gas, steam and air conditioning*" and "*Fish and other fishing products; aquaculture products; support services to fishing*".

The sectors that contributed the most to the CF values obtained were those related to food, electricity consumption and the consumption of fossil fuels. Consequently, the food patterns, the climate and mobility affected the CF. In the case of Seville, with moderate temperatures in winter and lower heating costs, obtaining the lowest CF value. On the contrary, Madrid, with high temperatures in summer and cold in winter, had a consumption in heating and air conditioning that had an impact on the CF. In addition, the use of aero transport in the citizens of Madrid also contributed to increasing the CF of the city. On the other hand, the higher consumption of foods of animal origin and fish affected the CF of Santiago de Compostela.

Furthermore, the results obtained in this chapter were compared with other studies that evaluated the CF of these cities using LCA. Although the values obtained using both methodologies are very different, the main flows that affect CF to a greater extent are the same. This means that both methodologies can be used to obtain information to reduce the emissions associated with the consumption of the inhabitants of a city. Moreover, EEIOA is a methodology that could be adapted to be able to evaluate the GHG emissions of cities of different countries. Furthermore, as it is a faster methodology than LCA, it can monitor the CF of cities in different years. In this sense, trends could be observed, as well as how the measures taken to fight climate change and help create more sustainable cities.

5.5 REFERENCES

Climate-Data, 2020. Climate of Spain . https://es.climate-data.org/europe/espana-5/ (accessed May 2021)

de Oña, J., Estévez, E., de Oña, R., 2021. Public transport users versus private vehicle users: Differences about quality of service, satisfaction and attitudes toward public transport in Madrid (Spain). Travel Behav. Soc. 23, 76–85. https://doi.org/10.1016/j.tbs.2020.11.003

Esteve-Llorens, X., Darriba, C., Moreira, M.T., Feijoo, G., González-García, S., 2019. Towards an environmentally sustainable and healthy Atlantic dietary pattern: Life cycle carbon footprint and nutritional quality. Sci. Total Environ. 646, 704–715. https://doi.org/10.1016/j.scitotenv.2018.07.264

Esteve-Llorens, X., Van Dooren, C., Álvarez, M., Moreira, M.T., Feijoo, G., González-García, S., 2021. Environmental and nutritional profile of food consumption patterns in the different climatic zones of Spain. J. Clean. Prod. 279. https://doi.org/10.1016/j.jclepro.2020.123580

Eustat, 2019. Statistic Institute of Basque Country (in Spanish) . http://www.eustat.eus/indice.html (accessed May 2021)

Fundación para el Fomento de la Innovación Industrial; Escuela Técnica Superior de Ingenieros Industriales de la Universidad Politécnica de Madrid, 2016. Energy Balance of the Council of Madrid (in Spanish).

García-Guaita, F., González-García, S., Villanueva-Rey, P., Moreira, M.T., Feijoo, G., 2018. Integrating Urban Metabolism, Material Flow Analysis and Life Cycle Assessment in the environmental evaluation of Santiago de Compostela. Sustain. Cities Soc. 40, 569–580. https://doi.org/https://doi.org/10.1016/j.scs.2018.04.027

González-García, S., Caamaño, M.R., Moreira, M.T., Feijoo, G.,

2021. Environmental profile of the municipality of Madrid through the methodologies of Urban Metabolism and Life Cycle Analysis. Sustain. Cities Soc. 64. https://doi.org/10.1016/j.scs.2020.102546

González-García, S., Dias, A.C., 2019. Integrating lifecycle assessment and urban metabolism at city level Comparison between Spanish cities. Ind. Ecol. 1–15. https://doi.org/10.1111/jiec.12844

González-García, S., Dias, A.C., 2019. Integrating lifecycle assessment and urban metabolism at city level: Comparison between Spanish cities. J. Ind. Ecol. 23, 1062–1076. https://doi.org/10.1111/jiec.12844

Hyland, J.J., Henchion, M., Mccarthy, M., Mccarthy, S.N., 2017. The role of meat in strategies to achieve a sustainable diet lower in greenhouse gas emissions : A review. Meat Sci. 132, 189–195. https://doi.org/10.1016/j.meatsci.2017.04.014

IECA, 2021. Institute of Statistics and Cartography of Andalusia. Andalusia Multiterritorial Information System (in Spanish) . https://www.juntadeandalucia.es/institutodeestadisticaycartografia/badea/informe/anual?CodOper=b3_151&idNode=2240 (accessed May 2021)

IECM, 2021. Institute of Statistics of the Community of Madrid. Distribution of GDP by statistical zones and by municipalities according to branches of activity (in Spanish) . http://www.madrid.org/iestadis/fijas/estructu/economicas/contabilidad/epibmb15tab.htm (accessed May 2021)

INE, 2021. Statistics National Institute. Total expenditure, average expenditure and distribution of household expenditure (in Spanish) . https://www.ine.es/jaxiT3/Tabla.htm?t=25145&L=0 (accessed May 2021)

INE, 2020a. Statistics National Institute. Official population figures resulting from the revision of the Municipal Register as of

January 1 (in Spanish) . https://www.ine.es/dynt3/inebase/es/index.htm?padre=517&capsel=525 (accessed May 2021)

INE, 2020b. Statistics National Institute. Urban Audit Indicators for Cities (in Spanish) . https://www.ine.es/jaxiT3/Tabla.htm?t=30140 (accessed May 2021)

INE, 2020c. National annual accounting of Spain: Input-Output tables. National Statistical Institute (in Spanish) . https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736177058&menu=resultados&idp=1254735576581 (accessed May 2021)

INE, 2020d. Air emissions accounts by branches of activity (CNAE 2009). National Statistical Institute (in Spanish). https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736176941&menu=ultiDatos&idp=1254735976603 (accessed May 2021)

INE, 2020e. Total expenditure and average household expenses. National Statistical Institute (in Spanish) . https://www.ine.es/jaxiT3/Tabla.htm?t=10724&L=0 (accessed May 2021)

Munawer, M.E., 2018. Human health and environmental impacts of coal combustion and post-combustion wastes. J. Sustain. Min. https://doi.org/10.1016/j.jsm.2017.12.007

Villanueva-Rey, P., Vázquez-Rowe, I., Arias, A., Moreira, M.T., Feijoo, G., 2018. The importance of using life cycle assessment in policy support to determine the sustainability of fishing fleets: a case study for the small-scale xeito fishery in Galicia, Spain. Int. J. Life Cycle Assess. 23, 1091–1106. https://doi.org/10.1007/s11367-017-1402-z

SUSTAINABILITY INDICES OF URBAN SYSTEMS

Chapter 6: **Assessing the sustainability of urban systems with indicators: Development of the methodology**[10]

SUMMARY

Besides considering the environmental pillar, socio-economic factors must be incorporated when analyzing the sustainability of a city. For this reason, the proposal and development of sustainability indicators with the aim of evaluating urban systems has grown in recent years. In this Chapter, it is developed a method to explore the sustainability of urban systems based on an index consisting of a three-letter label. The methodology to obtain this index consists of several steps: i) selection of a set of representative indicators of the three traditional dimensions of sustainability (social, economic and environmental), ii) normalization of indicators values, iii) attribution of weights to each indicator through the analytical hierarchy process (AHP), iv) obtaining a composite indicator that resulted from the aggregation of the normalized values and v) assignment of a letter (A, B or C) depending on the values obtained for each of the composite indicators. Thus, each urban system studied obtain a letter for each of the dimensions of sustainability deriving into the three-letters label. The criteria for defining a sustainable urban system according to this t label is that it must have at least an A on the label and no C. Therefore, it is necessary to achieve the sustainable category to have a good balance between the three pillars of the sustainability.

[10] Based on the manuscript: González-García, S., Rama, M., Cortés, A., García-Guaita, F., Núñez, A., Louro, L. G., Moreira, M. T., Feijoo, G. (2019). Embedding environmental, economic and social indicators in the evaluation of the sustainability of the municipalities of Galicia (northwest of Spain). *Journal of Cleaner Production*, *234*, 27–42. https://doi.org/10.1016/j.jclepro.2019.06.158

6.1 INTRODUCTION

In the previous Chapters the environmental profile of cities was studied through environmental impacts such as water consumption, carbon footprint and human toxicity among others (Chapters 3, 4 and 5). Therefore, sustainability is studied from the point of view of the interactions a city has with the environment. Thus, attending to the most common definition of a sustainable urban system (Kennedy et al., 2007). Consequently, it is evaluated how much waste and emissions a city generates and how many resources it consumes. Nevertheless, besides the environmental dimension, social and economic ones must be also assessed considering that the function of a city is to improve or maintain the quality of life of its citizens (Goldstein et al., 2013). Thus, urban sustainability must be built on economic, environmental and social pillars (Tanguay et al., 2010).

In recent years, the interest in evaluating urban sustainability indices, as well as the choice of indicators to determine urban sustainability, has been extensively researched in the scientific field (Feleki et al., 2018). Hence, the different pillars can be considered in these indicators and all dimensions of the sustainability can be evaluated. Nevertheless, the development of a sustainability index is complex since it requires stages of normalization and weighting scores (Tanguay et al., 2010). Another added difficulty relates to the fact that each pillar of sustainability comprises completely different aspects, being in some cases not quantitative.

Moreover, there is no consensus on the indicators considered in urban or regional sustainability studies (Macedo et al., 2017) although some attempts have been made in this direction (OCDE, 1993; 1995; Tanguay et al., 2010; Chrysoulakis et al., 2013; Goldstein et al., 2013; Petit-Boix et al., 2017; González-García et al., 2018). Some of the difficulties in developing a consensus on the use of indicators are due to the ambiguity of the definition of sustainability as well as the arbitrariness of the indicators selection method (Tanguay et al., 2010). This problem is aggravated by the fact that the set of indicators is often selected by purely qualitative methods, such as surveys of a group of experts or the general population. Therefore, the application of quantitative or semi-quantitative decision support systems could be useful in selecting an appropriate set of indicators (Chrysoulakis et al., 2013). In addition, the spatial dimension must also be considered for the most part due to the characteristics of the cities of the different regions (tourism, climate...), which may be completely different and, therefore, the set of indicators selected to analyze sustainability may be unsuitable (Feleki et al., 2019). Thus, the most important gap of this research is the description of a methodology to select indicators which is supported by the lack of consensus for the definition of sustainability, the arbitrariness of the selection methods, and the difficulty of applying the same set of indicators in different geographic areas.

In this Chapter, a methodology was developed to evaluate the sustainability of urban systems for different population sizes based on the creation of an index. This index consists of a three-letter label and indicates how sustainable an urban system is in each of the dimensions of sustainability: social, economic, environmental. The methodology developed to create this index consists of different stages: selection of a set of indicators, normalization, weighting, aggregation, assignment of thresholds and definition of the three-letter label. This methodology was developed to be applied in samples of various urban systems (municipalities or cities). Consequently, in Chapters 7 and 8, the methodology developed here is applied to two case studies to demonstrate its applicability.

Hence, this Chapter is structured in two main sections: firstly, the Materials and Methods section that describes the methodology followed according to the following: i) to select the sustainability indicators, ii) to establish the normalization, aggregation and weighting methods and, iii) to obtain a final sustainability index; secondly the Results section where the final set of indicators and the corresponding weights from the analytical hierarchy process (AHP) method are reported.

6.2 MATERIALS AND METHODS

Composite indicators are increasingly used in the field of sustainable development since they are useful instruments for policy-making and for communicating complex issues such as the degree of sustainability compliance (Nardo et al., 2005). The reason behind the use of composite indicators is justified by the fact that they are alternatives that integrate and complement the analysis of several different indicators separately (Tanguay et al., 2010). Nevertheless, it must be borne in mind that, because of their simplicity and sometimes arbitrariness, they can send ambiguous or non-robust messages (Nardo et al., 2005). Besides, the process of constructing composite indicators has some steps that necessarily involve subjective decisions, such as the selection of indicators, the consideration of missing values as well as the choice of normalization, weighting and aggregations methods (Mori and Christodoulou, 2012). Therefore, it is recommended to identify the sources of subjective judgement and to apply a sensitivity assessment to determine the degree of influence of these assumptions (Nardo et al., 2005).

In this Chapter a set of indicators has been defined to study the sustainability of urban systems. Mathematical methods of aggregation and weighting have been considered for data processing. Finally, an index based on a three-letter label has been created from the aggregation of these indicators.

6.2.1 Selection of the indicators set

The selection of appropriate sustainable indicators is a crucial step in the development of a composite indicator to increase its scientific value and credibility. To this end, the procedure and the selection of criteria are carefully defined in order to ensure their transparency and strictness (Tanguay et al., 2010). First, an intensive literature search was carried out to list them, after which the indicators of four specialized agencies were considered, selected for their reliability and the integrity of their data sets: the United Nations (UN, 2015), the European Commission (European Commission, 2015), the Organization for Economic Co-operation and Development (OECD, 2015), The World Bank (Anderson, 2009) and the Bank of Environmental Public Indicators (BPIA, 2017). The United Nations proposes a long list of indicators, embracing from gender equality to peace and justice (UN, 2015).

Initially, the datasets summed up 214 indicators but were completed with 190 more according to those proposed by the Galician Statistics Institute (IGE, 2021) and the Spanish Public Database of Environmental Indicators (MAPAMA, 2017) for data availability reasons. Considering the social, economic and environmental dimensions of sustainable processes (Lozano, 2008; Tanguay et al., 2010), data were collected within each agency, and then all indicators were listed. After removing duplicates, the dataset contained more than 60 indicators, which should be reduced to be manageable. An adapted Leopold Matrix has been developed for this purpose. In the current study, the Leopold Matrix was designed considering social, economic and environmental indicators and criteria for selection. The criteria considered were: i) data availability for the system under study (no indicator is good if there is no information about it) and ii) the frequency of occurrence in the datasets of the bodies consulted. The scale of values for quantifying the criteria is shown in **Table 6.1**.

Table 6.1. Scale for quantifying the criteria of the Leopold Matrix.

Data availability	3	Local scale
	2	Regional or national scale
	1	No data
Frequency[11]	3	Appears on 3 or more sources
	2	Appears on 2 sources
	1	Appears on 1 source

Once the Leopold Matrix was completed, the final relevance of each indicator is determined by multiplying the semi-quantitative

[11] Frequency of occurrence in the datasets of the bodies consulted.

value assigned to each criterion. All indicators whose relevance value was higher than or equal to 6 should be selected. Therefore, there must be at least one criterion with a score of 3.

Then, given that the number of indicators remains high, an additional criterion based on relevance of the indicators in urban systems should be introduced. To this end, a panel of experts made up of 17 people from different specialties such as Chemical and Environmental Engineering (47%), Economic Sciences (32%) and Psychology (21%) was asked to assign independently to each selected indicator the value "1" if it was considered relevant or "0" if it was irrelevant. This panel of experts was made up of partners involved in a multidisciplinary project awarded by the Spanish Ministry of Economy and Competitiveness (CTQ2016-75136-P) as well as related stakeholders such as environmental consultants and associations of municipalities.

6.2.2 Normalization method

As presented above, the data set selected comprises different types of indicators with very multiple units of measurement. When a group of indicators are not comparable with each other, for example, if they have different measurement units, it is necessary to perform a normalization step to express results with the same unit (Phillis et al., 2017). Selecting a suitable standardization method to apply to a specific topic is a difficult choice and should consider the properties of the data and the objectives of the composite indicator (Nardo et al., 2005). In this Chapter, the normalization method selected was re-scaling. As performed in Phillis et al. (2017), all indicators were normalized to obtain a dimensionless result, from 0 to 1; where 0 was the lowest sustainable value and 1 the highest one. To do so, it was important to define the direction of the indicator; a positive indicator means that the highest value (1 in this case) of this indicator means the best sustainable performance, while a negative indicator encompasses worse sustainable performance. Ideally, the indicators should be normalized against benchmarks that, for each indicator, should reflect the target sustainable value as well as the unsustainable value. However, in practice, it is very difficult to define the sustainable and unsustainable edge of each indicator. It should be considered that the methodology developed in this Chapter is intended to be applied to samples composed of various urban systems representative of a region or country. Thus, it must be considered that each of the indicators that were selected obtained values from each of the urban systems that the sample would contain. In this sense, for each indicator there is an urban system with a minimum value, and another urban system with the maximum. Hence, this maximum and minimum values within the range of urban systems were selected for the normalization procedure. Positive indicators were normalized according to **Equation 6.1** and negative indicators according to **Equation 6.2**.

$$I_{qc} = \frac{x_{qc} - min_c(x_q)}{max_c(x_q) - min_c(x_q)} \quad \textbf{(Equation 6.1)}$$

$$I_{qc} = \frac{max_c\left(x_q\right) - x_{qc}}{max_c(x_q) - min_c(x_q)} \quad \textbf{(Equation 6.2)}$$

Where x_{qc} was the value for the urban system c and the indicator q, I_{qc} was the normalized value, and $min_c(x_q)$ and $max_c(x_q)$ were the minimum and the maximum value of x_q across urban systems for the indicator q.

6.2.3 Aggregation and weighting method

In the construction of a composite indicator, it is essential to combine the different indicators in a meaningful way into a few indexes. Aggregation is, together with weighing, the combination of normalized indicators into different indexes. Although different aggregation approaches are available in the literature, one of the most used is to aggregate a set of indicators according to a related topic (Tanguay et al., 2010). Different aggregation methodologies are commonly used, including additive aggregation methods, geometric aggregation methods, and the non-compensatory aggregation method (Gan et al., 2017). In this Chapter was considered the weighted arithmetic mean to calculate the final index obtained for each dimension of sustainability.

In terms of weighting, different weights can be assigned to the indicators to reflect their relative importance; therefore, give them more importance in the calculation of the final composite indicator. Several weighting techniques are available, including equal weighting, principal components analysis, public opinion, budget allocation or analytic hierarchy process (AHP) (Gan et al., 2017). In this Chapter, two approaches were considered: the equal weighting as base case and the AHP methodology, which was considered as a simple and flexible technique that allows comparing several indicators with very different units, even if qualitative and quantitative data are considered. In addition, it implies that the weighing was carried out according to the experience and opinion of the experts in the field. In more detail, the AHP is a structured method that allows prioritizing multiple criteria based on pairwise comparisons of elements (Gompf et al., 2021).

1) The first step in this methodology was to translate a complex problem into a hierarchical structure consisting of an overall goal (i.e., identifying the most relevant indicators regarding the sustainability performance of a city), several criteria that contribute to this goal (i.e., the three dimensions of sustainability), and several attributes (i.e., the set of indicators).

2) The panel of experts detailed in Section 6.2.1 was asked to identify, given the pairs of indicators, which is the most important. Thereafter, they were also asked to provide their relative importance on a scale of 1 to 9 (**Table 6.2**).

3) The third step was to calculate the relative weights of the indicators from the comparison matrix using an eigenvector technique (Gompf et al., 2021).

Table 6.2. AHP measurement scale.

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values

The main disadvantage of this method is that it is an arbitrary process and no weighting structure can rationally justify the attribution of a given weight (Gan et al., 2017). Moreover, the high number of matrices produced may limit the number of indicators selected. Some degree of inconsistency may also occur due to contradictions or careless errors during expert comparisons; however, the method may tolerate these inconsistencies if the consistency ratio is less than 0.1 (Nardo et al., 2005). According to it, the consideration of the equal weighting allowed us to compare the differences on the results.

6.2.4 Label with rating letters for sustainability reporting

At this stage, each urban system had a composite indicator for each dimension of sustainability which score ranging from 0 to 1, and since obtaining a final sustainability score integrating all three dimensions could be controversial, it has been decided to avoid additional weighting procedures. Thus, three different letters (A, B and C) have been proposed to classify the values of composite indicators of the sustainability dimensions. Accordingly, the A rating should correspond to the values with the best performance and the C rating to the worst. Therefore, each urban system should be classified with a sustainability-city-label considering the combination of three letters (A/B/C) one of these letters correspond with one sustainability dimension. For example, if the first letter corresponds to social dimension, the letter of the middle with the economic dimension and the last letter with environmental, an urban system with label AAB had the best values in social and economic dimensions but it had obtained a B in the environmental dimension. The reference scores or thresholds used to establish the segregation between these letters were the quartiles obtained for each group of urban systems which would compose the sample under study. Therefore, to obtain an A rating, the dimension score must be higher than the Q_3 value. In the same way, to obtain a B rating, the dimension score must be between Q_1 and Q_3. Consequently, C rating was acquired with a score lower than the Q_1 value. Finally, the term “sustainable city” should be assigned to each urban system that had at least one A in the combination of letters but not one C. Thus, an urban system with label AAB it would be considered as sustainable, but other urban system with label ACB it would be considered as non-sustainable.

6.3 RESULTS

6.3.1 Indicator set

The selection of the set of indicators was developed following the steps described in Section 6.2.2. The use of the Leopold Matrix considering the criteria based on data availability and frequency of occurrence in the datasets allowed the list of indicators to be reduced from more than 400 to 60. As this number remained unmanageable, relevance was included as an additional criterion by the panel of experts in charge of selecting the set of indicators, which reduced the final list to 29. In addition, considering possible differences between urban systems, four indicators were considered in the economic field: non-financial total incomes (€·inhabitant^{-1}), municipal budget (€·inhabitant^{-1}), surplus/deficit (€·inhabitant^{-1}) and ratio of public/private vehicles (%). The latter considers for the public vehicles the number of buses and for private vehicles, only passenger cars and motorbikes.

In addition, four specific indicators for urban systems with more than 35,000 inhabitants were added to the selection to better understand their behavior even though they had not been considered in the original proposal. These indicators were: i) average rental price per m^{-2} (€), ii) average selling price per m^{-2} (€), iii) number of hotel beds and, iv) number of sustainability plans, participation in projects or sustainability awards received.

Finally, a set of 33 indicators was selected to analyze the small size urban systems (less than 35,000 inhabitants), and a set of 38 indicators was used to analyze the medium and big size urban systems (with the incorporation of these 5 indicators). The final list of indicators proposed for analysis is displayed in **Table 6.3** and **Table 6.4**, including a brief description for each indicator.

Table 6.3. List of indicators selected to assess urban sustainability, common to all urban systems regardless their size.

Criterion	Indicator	Description	Unit
Social	Population graduated in secondary education	Number of inhabitants with secondary education overcome	%
	Number of registered gender violence cases	Number of registered gender violence cases recorded in the municipality along the year	Nº of gender violence cases·1000 inhabitants^{-1}
	Number of women unemployed	Total amount of women with working age without an employment contract	Women unemployed·women at labor age^{-1}
	Population rate at risk of poverty	Percentage of population that earn a salary 50% lower than the average	P<50%·total population^{-1}
	Number of households	Average number of people that live in the households of the municipality	Inhabitants·number of households^{-1}
	Population that participated in the last municipal election	Total number of people that deposit a valid vote in the municipal elections that took place in 2015	Accounted votes·electoral census^{-1}
	Population under 16 years old	Inhabitants under 16 years	P<16·total population^{-1}
	Percentage of population older than 65 years old	Percentage of population over 65 years. A high percentage indicates a high aging population index	%
	Population annual net growth	Growth population rate in the period 2011-2016	%
	Foreign immigrants	Number of inhabitants born abroad, registered in the electoral register	Nº of No-EU immigrants·1000 inhabitants^{-1}

Table 6.3 (cont.). List of indicators selected to assess urban sustainability, common to all urban systems regardless their size.

Criterion	Indicator	Description	Unit
Social	Population density	Number of inhabitants / Total municipality surface	Inhabitants/km^2
	Number of leisure facilities	Number of entertainment establishments in the municipality	Nº of leisure facilities·1000 inhabitants^{-1}
	Distance to continued attention points and hospitals	Distance, in km, between the city hall and the closer hospital/surgery	km
	Total expense in social services	Total expense in social services and employment policies	€·inhabitant^{-1}
Economic	GDP per inhabitant	GDP of the municipality / Number of total inhabitants	€·inhabitant^{-1}
	City unemployment rate	Number of unemployed population / Total active population	%
	Average household income	Gross income of the municipality / Total number of households	€·household^{-1}
	Number of permanent contracts signed	Total amount of permanent contracts signed throughout the year	Number contracts·1000 inhabitants^{-1}
	Number of business	Total number of companies with registered office in the municipality	Number companies·1000 inhabitants^{-1}
	Municipal budget	Adjusted budget	€
	Non-financial total incomes	Chapters I-VII of the municipal budget	€·inhabitant^{-1}
	Surplus/Deficit	Difference between net budgetary rights liquidated and recognized obligation	€·inhabitant^{-1}
	Indebtedness	Financial debt of the municipality	€·inhabitant^{-1}
	Investment	Chapter VI of the municipal budget. It measures the investment effort	€·inhabitant^{-1}

Table 6.3 (cont.). List of indicators selected to assess urban sustainability, common to all urban systems regardless their size.

Criterion	Indicator	Description	Unit
Environmental	Ratio of public/private vehicles	Division between the number of busses and the number of passenger cars and motorbikes	%
	Ozone	Average ozone concentration in the air	$\mu g \cdot m^{-3}$
	NO_2	Average NO_2 concentration in the air	$\mu g \cdot m^{-3}$
	PM10	Average PM_{10} concentration in the air	$\mu g \cdot m^{-3}$
	Total domestic water consumption	Volume of water consumed in the households (m^3) per year	$m^3 \cdot household^{-1}$
	Total electrical use	Amount of electricity (MWh) consumed per inhabitant per year	MWh/inhabitant
	Surface of green area	Total surface (in km^2) corresponding to the green area of the municipality/total surface	%
	Surface of pedestrian zone	Total surface (in km^2) corresponding to the pedestrian zone in the municipality/total surface	%
	MSW collected	Amount (in tons) of Municipal Solid Waste (MSW) collected in the municipality	$kg \cdot inhabitant^{-1}$

Table 6.4. List of potential indicators selected to assess urban sustainability, exclusive for medium size and big urban systems.

Criterion	Indicator	Description	Unit
Economic	Rental price	Average price rental price per m^2	€·m^{-2}
	Sale price	Average sale rental price per m^2	€·m^{-2}
	Hotel beds	Number of total hotel places available in the municipality/1000 inhabitants	Number of places·1000 inhabitants^{-1}
Environmental	Environmental activity	Number of sustainability plans, participation in projects and awards received in the municipality according to its environmental awareness	Number of issues
	Non-Compliance Wastewater Treatment	Compliance or not with the guidelines established by the European Commission in terms of wastewater treatment	Dimensionless

6.3.2 Measured weighting after AHP application

The AHP method establishes a pairwise comparison that determines how long one parameter is more important than another (Gompf et al., 2021). This model of analysis was used to formulate and analyze unstructured problems in different fields of science (Veisi et al., 2016). In addition, there are several studies that use the AHP method with the aim of assigning weights to different indicators (Fu et al., 2021; Gompf et al., 2021; Lu et al., 2021).

The panel of experts from different specialties (Chemical and Environmental Engineering, Economic Sciences and Psychology) was asked to evaluate according to their experience, the relative weights of the different indicators within each sustainability dimension. Thus, an eigenvector was built being the scores displayed in **Table 6.5**.

Consequently, each pillar of the sustainability obtained an independent vector, therefore, the sum of the weights of each pillar adds up to 1. In the case of social dimension, the indicator with the highest relative weight was "Number of registered gender violence cases" with a value of 14.7%. In economic dimension the indicator "City unemployment rate" obtained the highest relative weight with a 12.4% in the case of medium and big size urban systems vector, and a 16.4% in the case of small size urban systems. Thus, different values were obtained for the different sets of indicators considered according to the size of the urban systems studied. This was because the AHP methodology was applied to each set of indicators independently, for which different vectors with the corresponding relative weights were obtained. Accordingly, in the case of environmental dimension, the indicator for the medium and big size urban systems with the highest relative weight was "Non-Compliance Wastewater Treatment" with a 15.4%. However, considering the relative weights of the indicators for small size urban systems the indicator with highest relative weight was "Surface of pedestrian zone" with a 18.2%.

Table 6.5. Priority vector according to the experts.

Pillar	Indicator	Priority vector
Social	Population graduated in secondary education	0.034
	Number of registered gender violence cases	0.147
	Number of women unemployed	0.097
	Population rate at risk of poverty	0.119
	Number of households	0.035
	Population that participated in the last municipal election	0.027
	Population under 16 years old	0.052
	Percentage of population older than 65 years old	0.054
	Population annual net growth	0.050
	Foreign immigrants	0.053
	Population density	0.040
	Number of leisure facilities	0.038
	Distance to continued attention points and hospitals	0.123
	Total expense in social services	0.129

Table 6.5 (cont.). Priority vector according to the experts.

Pillar	Indicator	Priority vector: Medium and big size	Priority vector: Small size
Economic	GDP per inhabitant	0.062	0.056
	City unemployment rate	0.124	0.164
	Average household income	0.108	0.118
	Number of permanent contracts signed	0.077	0.094
	Number of business	0.061	0.079
	Municipal budget	0.076	0.083
	Non-financial total incomes	0.062	0.059
	Surplus/Deficit	0.091	0.079
	Indebtedness	0.092	0.111
	Investment	0.064	0.158
	Rental price	0.064	
	Sale price	0.079	
	Hotel places	0.042	
Environmental	Ratio of public/private vehicles	0.077	0.070
	Ozone	0.064	0.110
	NO_2	0.095	0.101
	PM10	0.088	0.117
	Total domestic water consumption	0.093	0.118
	Total electrical use	0.093	0.134
	Surface of green area	0.108	0.092
	Surface of pedestrian zone	0.076	0.165
	MSW collected	0.127	0.093
	Environmental activity	0.045	
	Non-Compliance Wastewater Treatment	0.135	

6.3.3 Final methodology developed

In this Chapter, a methodology was developed to evaluate and determine the sustainability of urban systems based on an index. **Table 6.6** summarizes the different steps identified and the methods selected to develop this index. The stages through which this index was developed first consist of a selection of a set of indicators, with indicators that belong to the three traditional dimensions of sustainability: social, economic and environmental (Feleki et al., 2018). After the compilation of the data of these indicators, the values are normalized by means of a rescaling, with which the final values will be within a scale of 0 to 1. These indicators were then added by means of the weighted arithmetic mean considering the respective weight of each indicator obtained from the AHP method to finally obtain a composite indicator for each of the dimensions of sustainability. Therefore, the final score for each dimension of the sustainability was a letter A, B or C (A correspond with the best score and C to lowest) depending on the values reached in the composite indicators. It must be considered that this methodology was developed to be applied to a group of urban systems. Thus, the thresholds established to determine from which values a composite indicator is considered to be A, B or C, depend on the values of other urban systems. In this sense, this methodology was based on a comparative analysis where the values are high or low with respect to other urban systems of the same sample (Rozhenkova et al., 2019). Hence, it is important when selecting the sample of urban systems to which this methodology is going to be applied, to identify a significant number of urban systems that are representative of a certain area (region or country), and consider reference cities or municipalities, with sustainability accreditations, so that the method is much more robust and has much more reliability.

Table 6.6. Synthesis of the methodology developed

Step	**Sustainability dimension**			**Description**
	Social	**Economic**	**Environmental**	
Selection of the indicators set	14 social indicators	13 for Medium and big size urban systems 10 for small size urban systems	10 for medium and big size urban systems 8 for small size urban systems	Selection of a set of indicators from international and national databases. Number of the final selected indicators for each dimension
Normalization	Re-scaling	Re-scaling	Re-scaling	All the values of the selected indicators are scaled on a scale from 0 to 1
Weighting	AHP	AHP	AHP	A relative weight is attributed to each indicator through the AHP
Aggregation	weighted arithmetic mean	weighted arithmetic mean	weighted arithmetic mean	Indicators scaled values are aggregated tacking into account the corresponding relative weights
Composites indicators	Social composite indicator	Economic composite indicator	Environmental composite indicator	After aggregation, each dimension obtained a composite indicator with a value between 0 and 1
Three-letter label	A, B or C	A, B or C	A, B or C	The values of the composite indicators are assigned a letter depending on the quartiles, considering the values of the composite indicators of other urban systems under study

6.4 CONCLUSIONS

Research on the assessment of sustainable urban systems is maturing. However, there is still no consensus on the definition and quantification of the sustainability of a given population, incorporating concepts such as quality of life, equity, social inclusion and environmental issues. This Chapter deals with the development of a methodology to evaluate the sustainability of urban systems, based on the analysis of indicators related to social, economic and environmental dimensions. Moreover, in this chapter, an easy-to-interpret index was designed, based on a three-letter label. In this way, to define a sustainable urban system, it is necessary not only to stand out in, for example, environmental results, but there must be a balance between the three main pillars of sustainability (social, economic and environmental), making the method be more robust.

This methodology to evaluate the sustainability of urban systems can be applied to groups of municipalities or cities in a given area. Therefore, and with the aim of demonstrating its robustness and discussing its potential, it is applied in Chapter 7 to a sample of Galician municipalities and in Chapter 8 to a sample of representative Spanish cities.

6.5 REFERENCES

Anderson, C., 2009. City sustainability indicators World Bank. https://www.eu-ems.com/event_images/ Downloads/The World Bank.pdf (accessed January 2018)

Chrysoulakis, N., Lopes, M., San José, R., Grimmond, C.S.B., Jones, M.B., Magliulo, V., Klostermann, J.E.M., Synnefa, A., Mitraka, Z., Castro, E.A., González, A., Vogt, R., Vesala, T., Spano, D., Pigeon, G., Freer-Smith, P., Staszewski, T., Hodges, N., Mills, G., Cartalis, C., 2013. Sustainable urban metabolism as a link between bio-physical sciences and urban planning: The BRIDGE project. Landsc. Urban Plan. 112, 100–117. https://doi.org/10.1016/j.landurbplan.2012.12.005

European Commission, 2015. Indicators for Sustainable Cities, European Commission. https://doi.org/10.2779/61700

Feleki, E., Vlachokostas, C., Moussiopoulos, N., 2018. Characterisation of sustainability in urban areas: An analysis of assessment tools with emphasis on European cities. Sustain. Cities Soc. 43, 563–577. https://doi.org/10.1016/j.scs.2018.08.025

Fu, X.M., Liu, G.J., Liu, Y., Xue, Z.K., Chen, Z., Jiang, S.S., Chen, H.X., Yu, H.M., Wang, C.Y., 2021. Evaluation of the implementation of marine functional zoning in China based on the PSR-AHP model. Ocean Coast. Manag. 203, 105496. https://doi.org/10.1016/j.ocecoaman.2020.105496

Gan, X., Fernandez, I.C., Guo, J., Wilson, M., Zhao, Y., Zhou, B., Wu, J., 2017. When to use what: Methods for weighting and aggregating sustainability indicators. Ecol. Indic. https://doi.org/10.1016/j.ecolind.2017.05.068

Goldstein, B., Birkved, M., Quitzau, M.B., Hauschild, M., 2013. Quantification of urban metabolism through coupling with the life cycle assessment framework: Concept development and case study. Environ. Res. Lett. 8. https://doi.org/10.1088/1748-9326/8/3/035024

Gompf, K., Traverso, M., Hetterich, J., 2021. Using analytical hierarchy process (AHP) to introduce weights to social life cycle assessment of mobility services. Sustain. 13, 1–10. https://doi.org/10.3390/su13031258

Hardi, P., Zdan, T., 1997. Assessing Sustainable Development: Principles in Practice, Assessing Sustainable Development: Principles in Practice. https://doi.org/10.1002/msj.20251

IGE, 2021. Galician Institute of Statistics (in Galician). Home page. https://www.ige.eu/web/ (accessed May 2021)

Kennedy, C., Cuddihy, J., Engel-yan, J., 2007. The Changing Metabolism of Cities 11.

Lozano, R., 2008. Envisioning sustainability three-dimensionally. J. Clean. Prod. 16, 1838–1846. https://doi.org/10.1016/j.jclepro.2008.02.008

Lu, S., Wu, F., Wang, Z., Cui, Y., Chen, C., Wei, Y., 2021. Evaluation system and application of plants in healing landscape for the elderly. Urban For. Urban Green. 58, 126969. https://doi.org/10.1016/j.ufug.2020.126969

Macedo, J., Rodrigues, F., Tavares, F., 2017. Urban sustainability mobility assessment: indicators proposal. Procedia Eng. 134, 731–740.

MAPAMA, 2017. Ministry of Agriculture, Fisheries and the Environment. Spanish Public Database of Environmental IndicatorsMinistry for Ecological Transition (in Spanish) http://www.mapama.gob.es/es/calidad-yevaluacion-%0Aambiental/ (accessed December 2018)

Mori, K., Christodoulou, A., 2012. Review of sustainability indices and indicators: Towards a new City Sustainability Index (CSI). Environ. Impact Assess. Rev. 32, 94–106. https://doi.org/10.1016/j.eiar.2011.06.001

Nardo, M., Saisana, M., Tarantola, A., Stefano, S., 2005. Tools for Composite Indicators Building 1–134.

OCDE, 1993. OECD core set of indicators for environmental performance reviews: A synthesis report by the group on the state of the environment, Environmental Monographs.

OECD, 2015. OECD Better Life Index. How’s Life? 2015 Meas. Well-being.

Phillis, Y.A., Kouikoglou, V.S., Verdugo, C., 2017. Urban sustainability assessment and ranking of cities. Comput. Environ. Urban Syst. 64, 254–265. https://doi.org/10.1016/j.compenvurbsys.2017.03.002

Rozhenkova, V., Allmang, S., Ly, S., Franken, D., Heymann, J., Sdg, U., 2019. The role of comparative city policy data in assessing progress toward the urban SDG targets. Cities 95, 102357. https://doi.org/10.1016/j.cities.2019.05.026

Tanguay, G.A., Rajaonson, J., Lanoie, P., 2010. Measuring the sustainability of cities : An analysis of the use of local indicators. Ecol. Indic. 10, 407–418. https://doi.org/10.1016/j.ecolind.2009.07.013

UN Global Goals, 2015. The Global Goals. Glob. Goals 1–10. https://sdgs.un.org/goals (accessed May 2021)

Veisi, H., Liaghati, H., Alipour, A., 2016. Developing an ethics-based approach to indicators of sustainable agriculture using analytic hierarchy process (AHP). Ecol. Indic. 60, 644–654. https://doi.org/10.1016/j.ecolind.2015.08.012

Chapter 7: **Application of a methodology to evaluate the sustainability of municipalities in Galicia with different population sizes** [12]

SUMMARY

Despite the fact that the use of indicators for the evaluation of the sustainability of urban systems has grown in recent years, there are not many studies that analyze small municipalities. Therefore, in this chapter the methodology developed in Chapter 6 was applied to a case study composed of 64 municipalities in the Galicia region (northwestern Spain) classified according to their population size in medium size, small size and village. In order to select these municipalities, a screening method was developed based on certain criteria that allow obtaining a representative sample of the entire region. In addition, two different weighting methods: equal weight and measured weight with analytical hierarchy process (AHP). The results showed that the northern municipalities scored more sustainable than those in the south. On the other hand, regardless of the weighting method, 57% of the medium size municipalities were rated sustainable compared to 45% of those of the categories of Village and Small Size categories. Therefore, this could indicate that the size of the municipality was relevant for measuring sustainability. In addition, there were no significant differences between the results obtained with the different weighting methods. Bearing in mind the main findings, the applied developed in this chapter can be considered robust to be applied in the assessment of municipalities or cities.

[12] Based on published study: González-García, S., Rama, M., Cortés, A., García-Guaita, F., Núñez, A., Louro, L.G., Moreira, M.T., Feijoo, G. (2019). Embedding environmental, economic and social indicators in the evaluation of the sustainability of the municipalities of Galicia (northwest of Spain). *Journal of Cleaner Production*, *234*, 27–42. https://doi.org/10.1016/j.jclepro.2019.06.158

7.1 INTRODUCTION

Sustainable cities are related to the creation of spaces for social, business and technological development. Research on sustainable cities is maturing and new challenges are emerging associated with small municipalities or villages, whose assessment is still incipient (Feleki et al., 2018; Ubels et al., 2019). A small municipality or village is an ecosystem of limited size driven by specific mechanisms and dynamics that are the product and result of interactions at multiple levels (Visvizi and Lytras, 2018). This small municipalities and villages, also named as rural areas, account for 28.2% of the European population (Eurostat, 2019). Nowadays, population is moving towards large urban systems (Ibrahim et al., 2018) and villages are depopulating at a worrying rate (Wang et al., 2019). The depopulation of rural areas involves several social, economic and demographic problems related to the lack of specific services, such as secondary schools, courts or health and leisure centers, which affect the availability of services, well-being and quality of life, supported by the fact that the costs of providing services are also much higher when the population is distributed in many small settlements rather than concentrated in larger ones (Ubels et al., 2019). For this reason, the European Commission established a Bled Declaration for a smarter future for rural areas in the European Union and launched the EU Action for Smart Villages (European Commission, 2018). The main objective is to develop rural areas where people want to live, work and benefit from local services, tourism, etc. Rural communities need jobs, basic services and connectivity, as well as proactive entrepreneurship (Zou et al., 2019).

Spain is experiencing, along with other southern European countries such as Greece, Portugal and Italy, significant population losses in rural areas (ENRD, 2018; World Bank, 2019). Although depopulation rate is higher inside the country, attention has been paid to Galicia (Northwest Spain) since this Spanish region leads the rural population decline since 2008 (small municipalities lose 25 rural inhabitants per day), driven mainly by the economic crisis[13] and the lack of jobs.

The Galician region is divided into 313 municipalities with different social, economic and environmental characteristics. These municipalities can make essential contributions to solve many of the major social challenges, such as climate change or the sustainable supply of food, biomass and energy (Esteve-Llorens et al., 2019). In the same way that their tourism and culture can motivate employment and investment in these areas (Otero-Giráldez et al., 2012).

In this chapter, the methodology developed in Chapter 6 was applied in a case study of 64 Galician municipalities. These municipalities were selected using a screening method, taking into account criteria to obtain a representative sample of the entire region. Thus, this chapter had two main objectives: first, to demonstrate the robustness and reliability and secondly, to evaluate the sustainability of a representative number of municipalities of different population sizes.

Accordingly, this chapter was structured in two sections: a first section focused on selecting the municipalities that constitute the sample or case study, and a second section based on the application of the developed methodology to the sample with the corresponding discussion of the results.

7.2 MATERIALS AND METHODS

7.2.1 Selection of the sample

The municipalities which composed the sample considered in this chapter were located in Spain, a country with multiple commercial and leisure attractions (climate, culture, gastronomy and landscape) that make it an important destination for many Europeans. Accordingly, sustainability problems related to socioeconomic and

[13] https://www.farodevigo.es/galicia/2016/01/04/galicia-lidera-caida-poblacion-rural/1379739.html (accessed February 2021)

environmental flows should be addressed. The selected case study includes a sample of Galician municipalities taken as representative of the 313 that make up the Galician region. Galician municipalities share culture, climate and legislation, but with major differences in their metabolism. In terms of diversity, some municipalities rely heavily on industry (Vigo, As Pontes de García Rodriguez), while others base their economy on the primary sector (Burela, Lalín) or tourism (Santiago de Compostela, Sanxenxo); some are experiencing a demographic boom (Oleiros, O Pereiro de Aguiar), while others are suffering ageing population (Covelo, A Cañiza); most are environmentally proactive (Pontevedra), but there are exceptions (Ourense) according to information available from public data sources. The fact that municipalities in the same region present such different aspects makes them attractive for comparing their sustainability and identifying the spots to improve. In order to complete the task of collecting data, the Galician Federation of Municipalities and Provinces (FEGAMP[14]) has provided information and data sources, essential to complete a sustainability assessment.

7.2.1.1 Step 1

Once the scope of the initial selection has been established, the first task was to develop a quantitative and reproducible methodology based on the available data to carry out a first selection of cities among 313 Galician municipalities. To do so, the first step was to gather demographic data (population, singular entities of population, age range, city surface and population density) from each municipality. As a first action, all municipalities with more than 35,000 inhabitants were chosen on the basis that they are relevant economic and cultural centers for the region. These municipalities are the main cities of Galicia: A Coruña, Ferrol, Lugo, Pontevedra, Ourense, Santiago de Compostela and Vigo, and additionally, the medium size municipalities of Narón and Vilagarcía de Arousa. From now, the terms "city" and "municipality" were considered

[14] http://www.fegamp.gal/

synonymous in this chapter. **Table 7.1** displays a detailed description with characteristic information of these municipalities.

Table 7.1. Main characteristics of the Galician municipalities with more than 35,000 inhabitants.

Municipality	Population (Inhabitant)	Pop. density (Inhabitants·km^{-2})	Population growth (%)
Vigo	295,364	2,638	-0.59
Coruña (A)	245,711	6,378	-0.14
Ourense	105,233	1,223	-3.17
Lugo	98,276	295	2.76
Santiago de Compostela	97,260	437	2.57
Pontevedra	83,029	683	1.28
Ferrol	66,065	818	-10.3
Narón	39,080	576	2.08
Vilagarcía de Arousa	37,456	840	-1.24

Table 7.1 (cont.). Main characteristics of the Galician municipalities with more than 35,000 inhabitants.

Municipality	Household avg. income (€·inhabitant^{-1})	GDP (€·inhabitant^{-1})
Vigo	16,388	27,416
Coruña (A)	18,445	30,781
Ourense	17,126	22,364
Lugo	16,570	23,412
Santiago de Compostela	18,332	37,508
Pontevedra	16,400	25,920
Ferrol	14,852	23,641
Narón	13,813	18,868
Vilagarcía de Arousa	13,203	18,221

Table 7.1 (cont.). Main characteristics of the Galician municipalities with more than 35,000 inhabitants.

Municipality	Weather	Other
Vigo	Coastal Atlantic	Industrialized coastal city
Coruña (A)	Coastal Atlantic	Main administrative city
Ourense	Inland Atlantic	Third highest aging index in Galicia
Lugo	Inland Atlantic	Very low population density
Santiago de Compostela	Coastal Atlantic	Capital of Galicia, with high tourism rate
Pontevedra	Coastal Atlantic	Environmentally proactive
Ferrol	Coastal Atlantic	Sharp decline in recent years
Narón	Coastal Atlantic	Periphery of Ferrol
Vilagarcía de Arousa	Coastal Atlantic	Industrialized coastal city

7.2.1.2 Step 2

An indicator based on the Population Density (PD)/Singular Entities of Population (SEP) ratio was defined and calculated for each city, considering PD as the number of registered inhabitants of the municipal area in km^2. Both parameters are the most representative of the demographic situation of cities and will allow municipalities to be grouped into as many categories as desired within each province. Each municipality within each province of the region was ordered taking into account the corresponding PD/SEP ratio. In this sense, four rankings of municipalities corresponding to the provinces of A Coruña, Lugo, Pontevedra and Ourense were obtained. In each of these provinces, all municipalities were classified into four groups according to their PD/SEP ratio. Group 1 was formed with the municipalities with the highest values of the PD/SEP ratio (i.e., municipalities with a high population density and a low singular population density such as the municipality of Burela in the province of Lugo). Therefore, group 4 was formed with the municipalities with the lowest values of the PD/SEP ratio (i.e., municipalities with scattered populations such as the municipality of Castro Caldelas in the province of Ourense). Finally, the rankings of the provinces divided into four groups were distributed under a Gaussian distribution according to the following criteria:

i) Municipalities were ranked from highest to lowest.

ii) No more than 70% of municipalities must be included in the central groups (groups 2 and 3) and the distribution must be adequate to obtain the minimum standard deviation. The system was solved by iterative calculation in Excel using the *Solver* tool.

iii) Once the system was solved, the ranges of indicators for each group were simply determined by counting the number of cities belonging to each group from the highest value of the PD/SEP ratio to the lowest.

7.2.1.3 Step 3

Now, the cities were grouped into 4 different groups within each of the 4 provinces under study (A Coruña, Lugo, Ourense and Pontevedra), making a total of 16 groups containing 304 municipalities (excluding the 9 cities previously chosen). This number must be significantly reduced in order to be able to manage the data, avoiding losing the representativeness of the data relating to the demographic situation of the provinces. With this objective, each of the 4 groups contained in each province was studied individually. First, the PD/SEP indicator for each city was drawn together with the average PD/SEP ratio for the whole group on a spider web diagram. Second, a certain deviation from the mean (±30% in this study) was established and represented in the spider web diagram. Finally, all municipalities whose proportion remains within the established range were pre-selected, considering a certain degree of deviation from the average. This process was repeated for each group, so that the number of potentially eligible cities was considerably reduced. Thus, **Figures 7.1 to 7.4** show the spider graphs of the groups of each province with the municipalities classified according to their PD / SEP ratio, the mean value of each group and the range from which the municipalities were pre-selected.

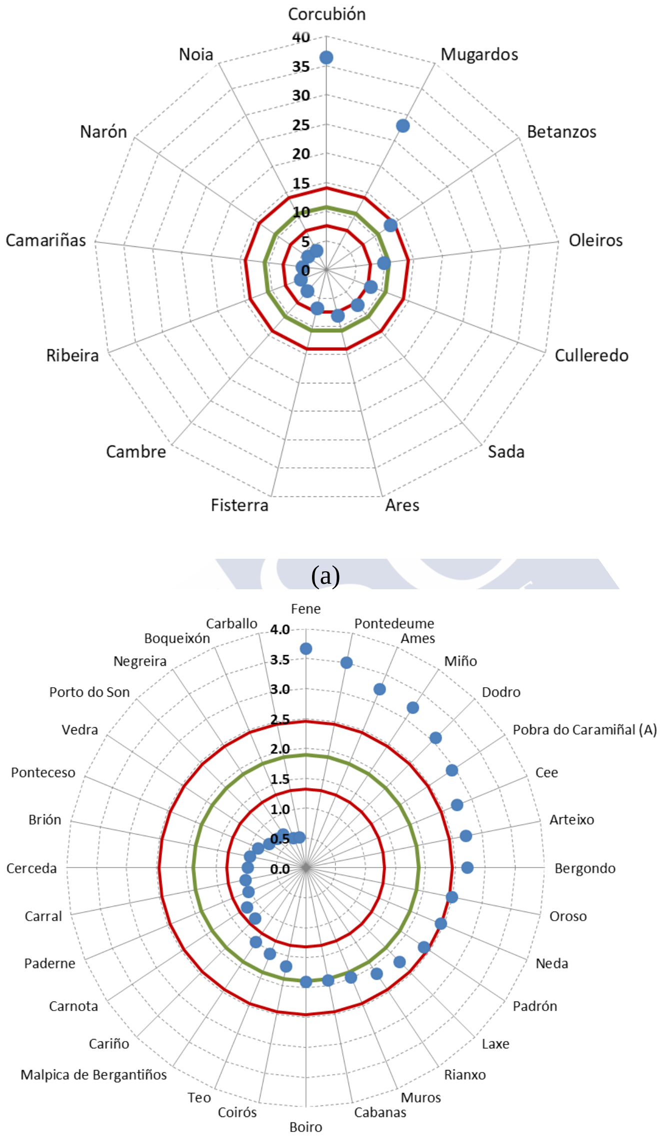
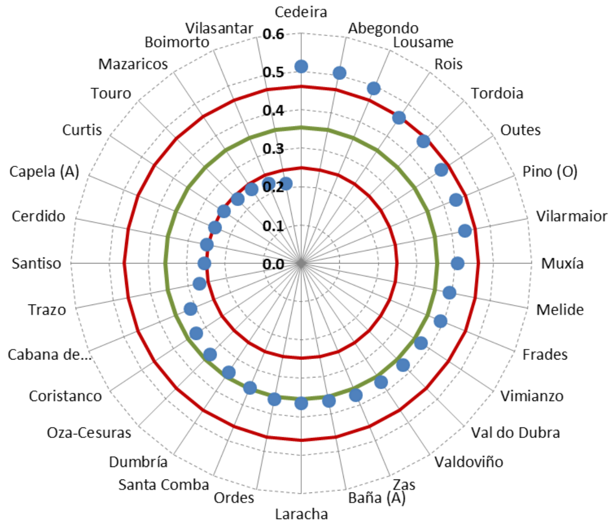
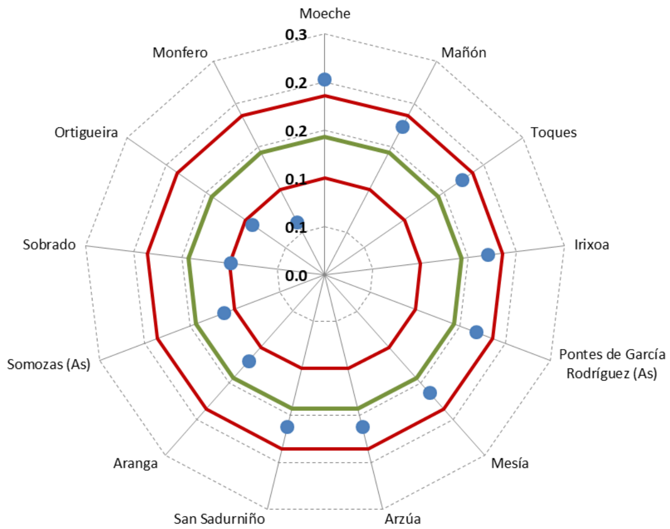


Figure 7.1. Spider web diagrams for the preselection of the municipalities in the province of A Coruña. (a) Group 1, (b) Group 2.

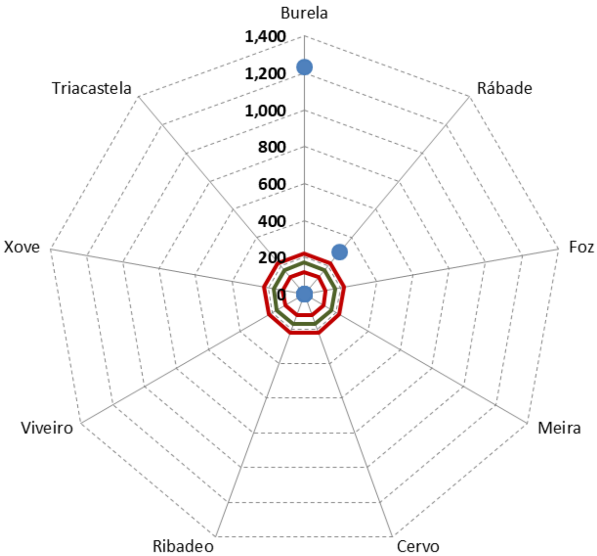


(c)

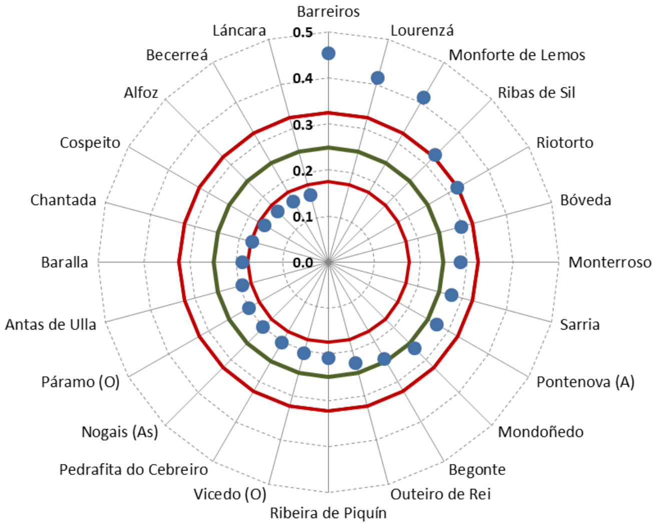


(d)

Figure 7.1 (cont.). Spider web diagrams for the preselection of the municipalities in the province of A Coruña. (c) Group 3, (d) Group 4.

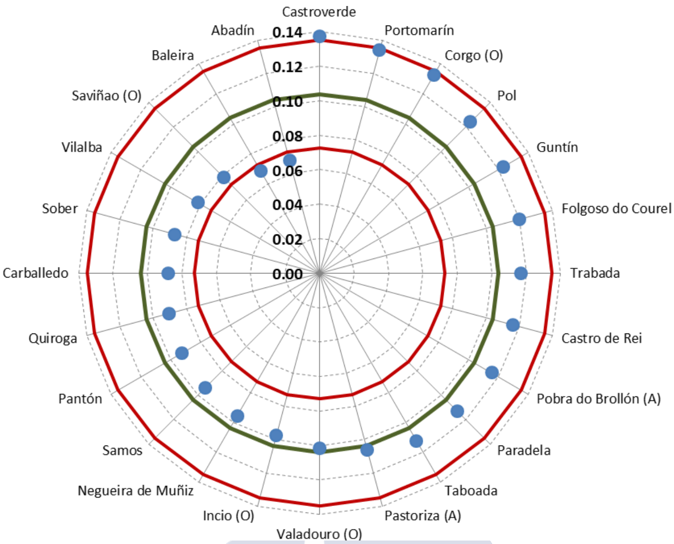


(a)

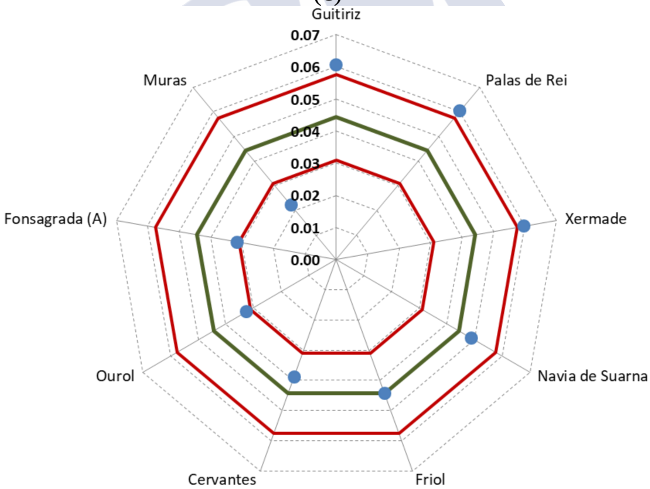


(b)

Figure 7.2. Spider web diagrams for the preselection of the municipalities in the province of Lugo. (a) Group 1, (b) Group 2.

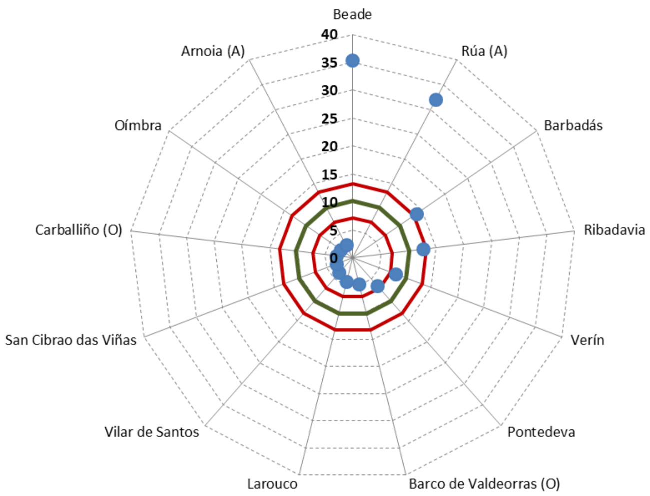


(c)

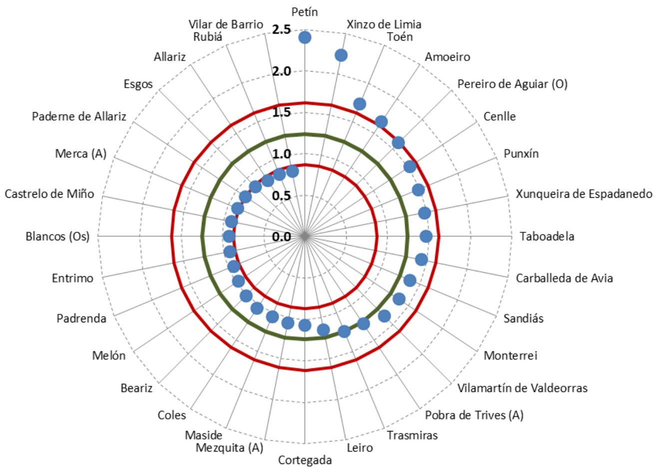


(d)

Figure 7.2 (cont.). Spider web diagrams for the preselection of the municipalities in the province of Lugo. (c) Group 3, (d) Group 4.

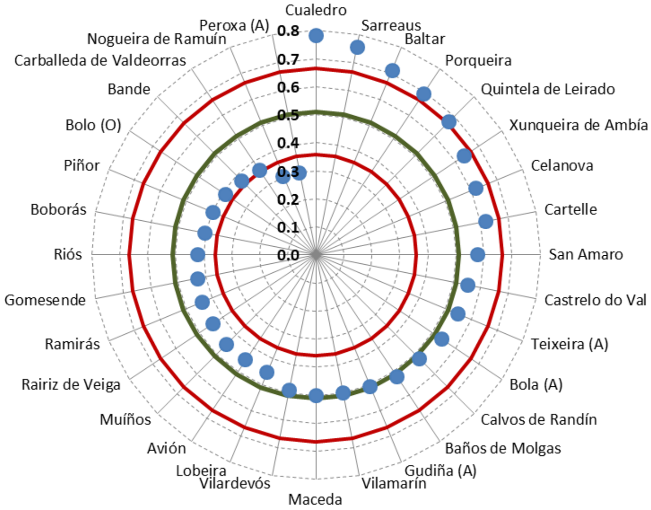


(a)

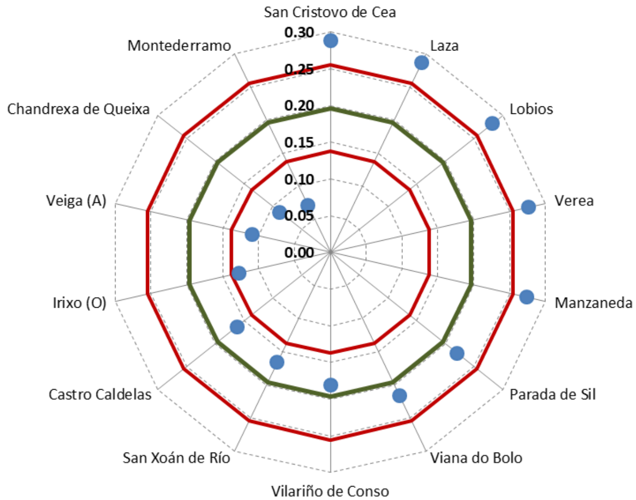


(b)

Figure 7.3. Spider web diagrams for the preselection of the municipalities in the province of Ourense. (a) Group 1, (b) Group 2.

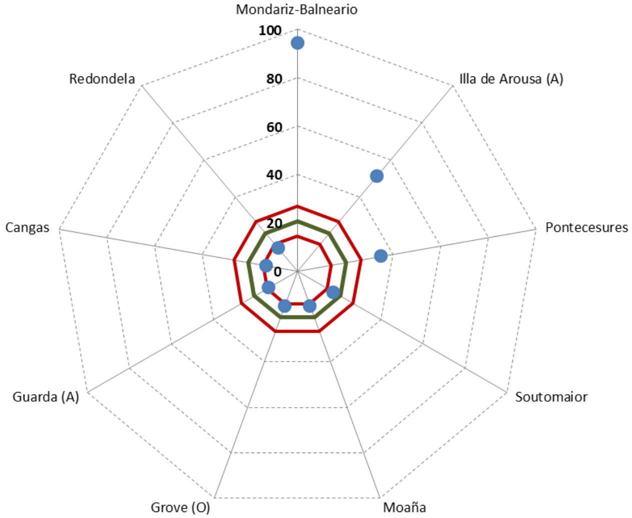


(c)

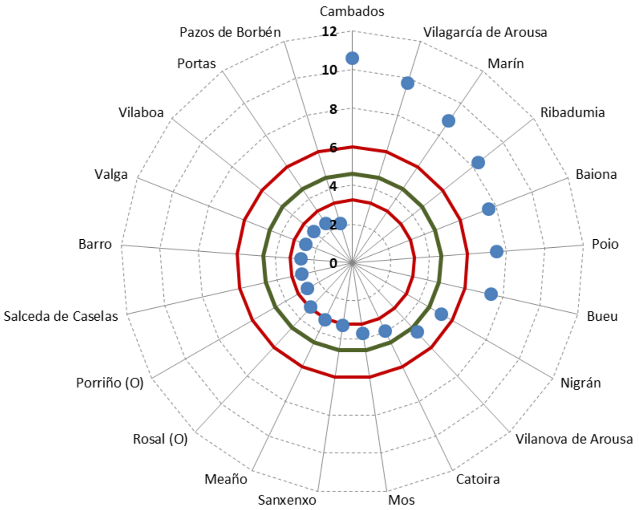


(d)

Figure 7.3 (cont.). Spider web diagrams for the preselection of the municipalities in the province of Ourense. (c) Group 3, (d) Group 4.

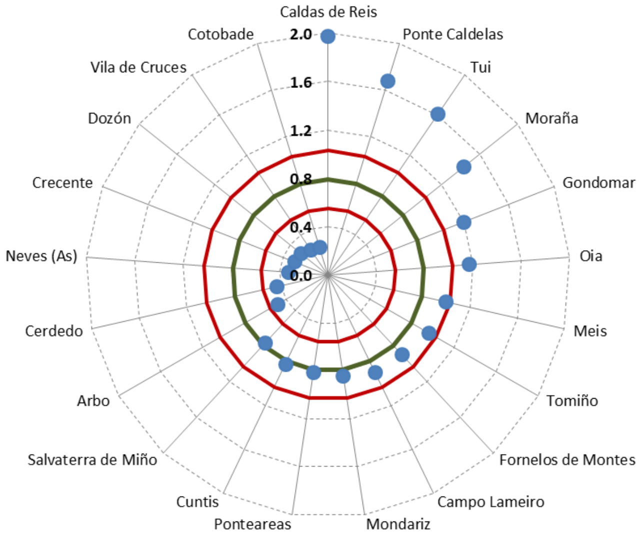


(a)

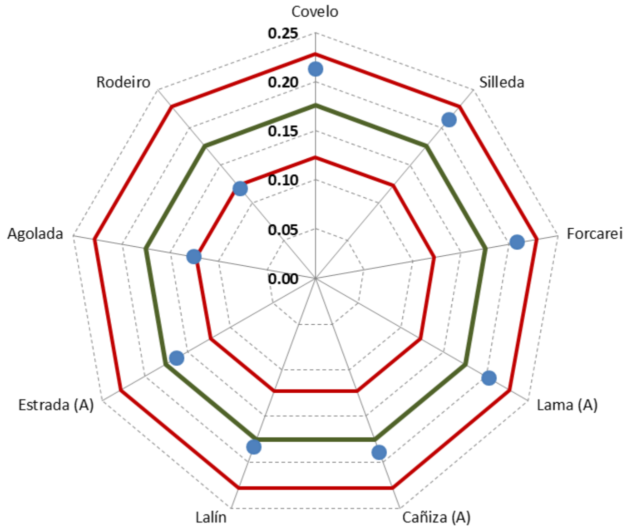


(b)

Figure 7.4. Spider web diagrams for the preselection of the municipalities in the province of Pontevedra. (a) Group 1, (b) Group 2.



(c)



(d)

Figure 7.4 (cont.). Spider web diagrams for the preselection of the municipalities in the province of Pontevedra. (c) Group 3, (d) Group 4.

Furthermore, it should be borne in mind that in the case of the municipalities corresponding to group 1 of Lugo province, none of them were within the established deviation (see **Figure 7.2a**). This was due to the high PD/SEP ratios for Burela and Rábade, exceptional cases in Galicia and the result of a past political issue.

These municipalities have experienced economic growth due to a specific economic situation. This was the case of Burela, which experienced an economic growth of the fishing sector in which European economic aid was key to the positioning of its fishing port (MAPA, 2013). In the case of Rábade, the economic growth was because the arrival of the railway between Madrid and A Coruña allowed the creation of large merchandise warehouses. For this reason, they have a small municipal area and a unique entity of population. Consequently, the municipality with the DP/ESP ratio closest to the limit was selected for analysis.

7.2.1.4 Step 4

As a result of the above steps, the number of potentially eligible cities was reduced from 304 to 170 (43, 41, 55 and 22 municipalities in A Coruña, Lugo, Ourense and Pontevedra respectively), including cities with more than 35,000 inhabitants. However, despite being a considerably smaller number, it remained unmanageable. Then, to obtain a similar number of municipalities per province, the Leopold matrix procedure was applied according to three criteria (see **Table 7.2**):

i) The availability of data being considered the most important. This table also shows the scale of values for quantifying each criterion. This tool allows to obtain quantitative results considering both the importance and magnitude of the indicator and being qualitatively assigned a value according to a scale. Quantitative results were obtained by multiplying the rows and the columns of the matrix. The criteria considered for the analysis were: Transparency and data availability for the municipality under study. An assessment was made of whether databases were available to compile the information needed for analysis.

ii) Administrative and demographic representativeness: The relevance of the municipality with respect to the region was evaluated, that was, if there was court, firehouse, local police, national police, outpatient clinic, etc. or public services which were not present in all municipalities.

iii) Environmental commitment: The environmental awareness of the municipality was marked taking into account whether it was proactive in environmental measures.

Table 7.2. Scale of quantification of the Leopold Matrix criteria for the selection of municipalities.

Criterion	Mark	Description
Transparency and data availability	3	Data available from public sources
	2	Required internal sources or assumptions
	1	No data/High uncertainty
Administrative and demographic representativeness	3	Court/county or capital full services availability
	2	Essential services
	1	Lack of demographic representativeness
Environmental commitment	3	Frequent environmental activity
	2	Occasional environmental activity
	1	No proactive environmental activity

Once the Leopold Matrix was completed, the final score for each municipality was determined by multiplying the value assigned to each criterion. Subsequently, to obtain a similar number of municipalities per province, a threshold level of 8 points was established as the first requirement to be selected. All municipalities sharing the highest ratings were selected and a minimum of 1 city was established for groups 1 and 4 while a minimum of 3 municipalities was established for groups 2 and 3. However, large differences in the samples of selected municipalities per province were not desired since a similar order of magnitude was required between provinces, as well as a geographical distribution balance. Consequently, it was necessary to consider some municipalities such as Pontes de García Rodríguez, where the leading company in the electricity sector in Spain is located) or Quiroga, which is an important municipality in wine tourism.

7.2.1.5 Step 5

Finally, the selected municipalities were classified into three categories according to their population: i) village - if it has less than 5,000 inhabitants; ii) small city - if it has a population between 5,000 and 50,000 inhabitants; and iii) medium city - if it has more than 50,000 inhabitants. The objective of this final classification was to avoid comparisons of sustainability results between cities and towns because of their inherent characteristics. **Table 7.3** displays the classification by category of inhabitants and **Figure 7.5.** Distribution of the selected municipalities per province. shows its corresponding geographical distribution throughout the Galician community. Therefore, data were collected from 64 municipalities, distributed as follows: 20 municipalities in A Coruña, 12 municipalities in Lugo, 17 municipalities in Ourense and 15 municipalities in Pontevedra.

Table 7.3. Classification of municipalities according to their population.

Category	Municipalities
Medium Size	Vigo, Coruña (A), Ourense, Lugo, Santiago de Compostela, Pontevedra, Ferrol.
Small Size	Betanzos, Oleiros, Sada, Narón, Rianxo, Muros, Melide, Ordes, Santa Comba, Pontes de García Rodríguez (As), Arzúa, Sarria, Castro de Rei, Vilalba, Ribadavia, Verín, Pereiro de Aguiar (O), Celanova, Moaña, Grove (O), Vilagarcía de Arousa, Vilanova de Arousa, Sanxenxo, Tomiño, Ponteareas, Salvaterra de Miño, Silleda, Cañiza (A), Lalín, Estrada (A)
Village	Aranga, Cabanas, Cerdido, Laxe, Muxía, Cabanas, Zas, Monterroso, Mondoñedo, Vicedo (O), Pedrafita do Cebreiro, Pobra do Brollón (A), Quiroga, Fonsagrada (A), Rábade, Carballeda de Avia, Monterrei, Pobra de Trives (A), Cortegada, Coles, Castrelo de Miño, Castrelo do Val, Baños de Molgas, Lobeira, Rairiz de Veiga, Ramirás, Vilariño de Conso, Covelo

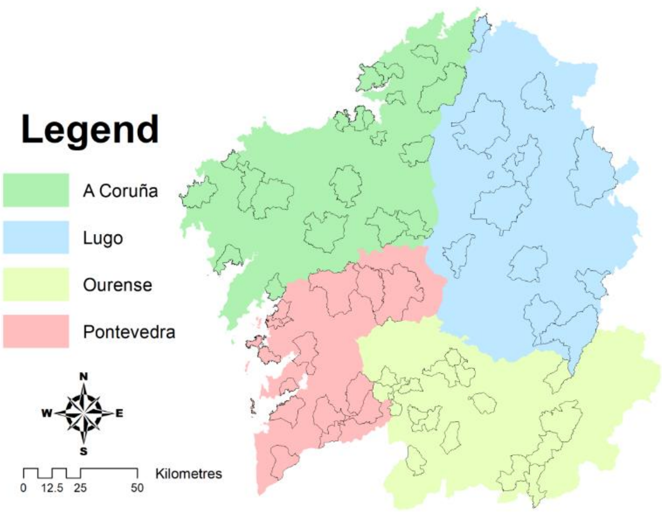


Figure 7.5. Distribution of the selected municipalities per province.

7.2.2 Methodology for the sustainability assessment

The methodology used for the evaluation of the sustainability of the selected municipalities was based on the methodology previously developed in Chapter 6. Therefore, the main purpose was to obtain a three-letter label that indicates the degree of sustainability of each selected municipality. To do so, the set of indicators chosen in Chapter 6 was adapted to this case of study and information necessary for the sustainability analysis was collected. Different official datasets were consulted, such as the Galician Statistics Institute (IGE, 2021), Google Earth (Google, 2019) the Spanish Statistics Institute (INE, 2021), Meteogalicia[15], Directorate General of Traffic of Spain [16], Ministry of Development[17] and Ministry of Interior[18] as well as specific information provided by FEGAMP.

[15] http://www.meteogalicia.gal/web/index.action
[16] http://www.dgt.es/es/
[17] https://www.fomento.es
[18] http://www.interior.gob.es

However, in the case of the indicator of MSW collected, data were available only at regional level. For this reason, the indicator was not considered in the present study. Consequently, it was used a set of 37 indicators for medium size municipalities, and a set of 32 indicators for small size municipalities and villages. The indicators set considered in this chapter is shown in **Table 7.4** where it is indicated in which group of municipalities each indicator was used.

Table 7.4. Set of indicators selected to, and group of municipalities according to size where each indicator was used.

Criterion	Indicator	Unit	Municipalities
Social	Population graduated in secondary education	PSE·total population^{-1}	All municipalities
	Number of registered gender violence cases	Nº of gender violence cases·1000 inhabitants^{-1}	All municipalities
	Number of women unemployed	Women unemployed·women at labor age^{-1}	All municipalities
	Population rate at risk of poverty	P<50%·total population^{-1}	All municipalities
	Number of households	Inhabitants·number of households^{-1}	All municipalities
	Population that participated in the last municipal election	Accounted votes·electoral census^{-1}	All municipalities
	Population under 16 years old	P<16·total population^{-1}	All municipalities

Table 7.4 (cont.). Set of indicators selected to, and group of municipalities according to size where each indicator was used.

Criterion	Indicator	Unit	Municipalities
Social	Percentage of population older than 65 years old	%	All municipalities
	Population annual net growth	%	All municipalities
	Foreign immigrants	Nº of No-EU immigrants·1000 inhabitants^{-1}	All municipalities
	Population density	Inhabitants/km^2	All municipalities
	Number of leisure facilities	Nº of leisure facilities·1000 inhabitants^{-1}	All municipalities
	Distance to continued attention points and hospitals	km	All municipalities
	Total expense in social services	€·inhabitant^{-1}	All municipalities
Economic	GDP per inhabitant	€·inhabitant^{-1}	All municipalities
	City unemployment rate	%	All municipalities
	Average household income	€·household^{-1}	All municipalities
	Number of permanent contracts signed	Number contracts·1000 inhabitants^{-1}	All municipalities
	Number of business	Number companies·1000 inhabitants^{-1}	All municipalities
	Municipal budget	€	All municipalities
	Non-financial total incomes	€·inhabitant^{-1}	All municipalities
	Surplus/Deficit	€·inhabitant^{-1}	All municipalities
	Indebtedness	€·inhabitant^{-1}	All municipalities
	Investment	€·inhabitant^{-1}	All municipalities
	Rental price	€·m^{-2}	Medium size
	Sale price	€·m^{-2}	Medium size
	Hotel beds	Number of places·1000 inhabitants^{-1}	Medium size

Table 7.4 (cont.). Set of indicators selected to, and group of municipalities according to size where each indicator was used.

Criterion	Indicator	Unit	Municipalities
Environmental	Ratio of public/private vehicles	%	All municipalities
	Ozone	$\mu g{\cdot}m^{-3}$	All municipalities
	NO_2	$\mu g{\cdot}m^{-3}$	All municipalities
	PM10	$\mu g{\cdot}m^{-3}$	All municipalities
	Total domestic water consumption	$m^3{\cdot}household^{-1}$	All municipalities
	Total electrical use	MWh/inhabitant	All municipalities
	Surface of green area	%	All municipalities
	Surface of pedestrian zone	%	All municipalities
	Environmental activity	Number of issues	Medium Size
	Non-Compliance Wastewater Treatment	Dimensionless	Medium Size

Once the indicator data were collected for the corresponding municipalities, the values were normalized using the re-scaling method as previously described in Chapter 6. In this way, all indicators will have a value on a scale, from 0 to 1, with 0 being the most unfavorable value in terms of sustainability.

After normalizing step and in order to create a global index, the values of each dimension of sustainability were independently aggregated using the weighted arithmetic mean. To calculate the corresponding weight of each indicator, two procedures were considered in this chapter to compare the results obtained with each. The first weighting procedure used was equal weighting, i.e., the same weight was considered for all indicators. The other one was based on the weights obtained by the analytical hierarchy process (AHP) method detailed in Chapter 6. However, as previously noted, in the environmental pillar, one of the indicators was not considered in this chapter, so the weights within the environmental dimension were recalculated to follow the same hierarchical order and the sum of all weights was 1. **Table 7.5** shows the weights considered through the AHP method.

Table 7.5. Priority vector used in this Chapter.

Pillar	Indicator	Priority vector
Social	Population graduated in secondary education	0.034
	Number of registered gender violence cases	0.147
	Number of women unemployed	0.097
	Population rate at risk of poverty	0.119
	Number of households	0.035
	Population that participated in the last municipal election	0.027
	Population under 16 years old	0.052
	Percentage of population older than 65 years old	0.054
	Population annual net growth	0.050
	Foreign immigrants	0.053
	Population density	0.040
	Number of leisure facilities	0.038
	Distance to continued attention points and hospitals	0.123
	Total expense in social services	0.129

Table 7.5 (cont.). Priority vector used in this Chapter.

Pillar	Indicator	Priority vector	
		Medium size	Small size/Village
Economic	GDP per inhabitant	0.062	0.056
	City unemployment rate	0.124	0.164
	Average household income	0.108	0.118
	Number of permanent contracts signed	0.077	0.094
	Number of business	0.061	0.079
	Municipal budget	0.076	0.083
	Non-financial total incomes	0.062	0.059
	Surplus/Deficit	0.091	0.079
	Indebtedness	0.092	0.111
	Investment	0.064	0.158
	Rental price	0.064	
	Sale price	0.079	
	Hotel places	0.042	
Environmental	Ratio of public/private vehicles	0.088	0.077
	Ozone	0.073	0.122
	NO_2	0.108	0.111
	PM10	0.100	0.129
	Total domestic water consumption	0.107	0.130
	Total electrical use	0.107	0.148
	Surface of green area	0.124	0.101
	Surface of pedestrian zone	0.087	0.182
	Environmental activity	0.051	
	Non-Compliance Wastewater Treatment	0.154	

Finally, a composite indicator was obtained for each of the pillars of sustainability with values between 0 and 1 for each of the municipalities. These values were transformed into a letter A, B or C (A being the most sustainable situation) following the methodology described in Chapter 6. Finally, for each group of municipalities, the first (Q_1) and third quartiles (Q_1 and Q_3, respectively) were calculated to the values of the composite indicators of each of the pillars of sustainability. Accordingly, a municipality with a value of a composite indicator higher than the calculated Q_3, was assigned with a value of A. The municipalities that obtained values between Q_1 and Q_3 were assigned a B, and finally the municipalities with values lower than Q_1 were assigned a C. In accordance with the criteria set out in

Chapter 6, a sustainable municipality was defined as a municipality that obtained at least an A and no C on its three-letter label.

7.3 RESULTS

As previously described, two different weighting procedures were considered in this chapter: equal weight and measured weight trough AHP method. So, different results were obtained depending on the weighting procedure considered.

7.3.1 Equal weighting

Tables 7.6 to 7.8 display the scores per sustainability dimension for each municipality considered for analysis in the category of village, small and medium size cities, respectively, considering equal weighting. The calculated values of the first quartile and the third quartile for each dimension of sustainability are also shown in these tables. The difference between the values of the quartiles (Q_1-Q_3) indicates the dispersion between the values of the composite indicators of the municipalities of each group in all dimensions of sustainability. That is, the more different the quartiles, the greater the difference between the values of the composite indicators. Considering this, the medium size group is the group that obtains the values of the quartiles with the most difference in the three dimensions of sustainability. This means that in terms of sustainability, it is the group in which the municipalities are most different from each other. On the contrary, the small size group obtains the values of the quartiles with the smallest differences, which implies greater equality between municipalities in terms of sustainability.

Table 7.6. Social, Economic and Environmental scores for municipalities included in the category "village".

Municipality	Social	Economic	Environmental
Aranga	0.401	0.494	0.570
Cabanas	0.570	0.418	0.433
Cerdido	0.414	0.421	0.581
Laxe	0.456	0.165	0.639
Muxía	0.504	0.419	0.739
Zas	0.466	0.411	0.539
Fonsagrada (A)	0.404	0.392	0.606
Mondoñedo	0.509	0.349	0.698
Monterroso	0.497	0.357	0.579
Pedrafita do Cebreiro	0.455	0.413	0.595
Pobra do Brollón (A)	0.346	0.264	0.590
Quiroga	0.410	0.300	0.552
Rábade	0.545	0.390	0.566
Vicedo (O)	0.545	0.390	0.566
Baños de Molgas	0.385	0.300	0.383
Carballeda de Avia	0.451	0.171	0.564
Castrelo de Miño	0.422	0.235	0.391
Castrelo do Val	0.385	0.261	0.413
Coles	0.584	0.470	0.343
Cortegada	0.415	0.258	0.562
Lobeira	0.288	0.304	0.369
Monterrei	0.349	0.198	0.491
Pobra de Trives (A)	0.519	0.278	0.594
Rairiz de Veiga	0.384	0.173	0.405
Ramirás	0.382	0.285	0.412
Vilariño de Conso	0.511	0.656	0.589
Covelo	0.311	0.286	0.606
Third Quartile value	0.499	0.405	0.582
First Quartile value	0.377	0.255	0.404

Table 7.7. Social, Economic and Environmental scores for municipalities included in the category "small size".

Municipality	Social	Economic	Environmental
Arzúa	0.478	0.462	0.576
Betanzos	0.566	0.338	0.327
Melide	0.483	0.339	0.612
Muros	0.362	0.346	0.697
Narón	0.581	0.309	0.421
Oleiros	0.662	0.458	0.392
Ordes	0.485	0.397	0.377
Pontes de García Rodríguez (As)	0.506	0.596	0.460
Rianxo	0.439	0.319	0.497
Sada	0.624	0.291	0.323
Santa Comba	0.453	0.402	0.398
Castro de Rei	0.371	0.421	0.554
Sarria	0.478	0.391	0.515
Vilalba	0.517	0.375	0.520
Celanova	0.351	0.279	0.435
Pereiro de Aguiar (O)	0.483	0.406	0.454
Ribadavia	0.454	0.369	0.595
Verín	0.456	0.332	0.523
Cañiza (A)	0.262	0.280	0.587
Estrada (A)	0.486	0.319	0.547
Grove (O)	0.478	0.451	0.413
Lalín	0.449	0.404	0.415
Moaña	0.550	0.267	0.406
Ponteareas	0.530	0.215	0.422
Salvaterra de Miño	0.442	0.268	0.511
Sanxenxo	0.483	0.408	0.421
Silleda	0.496	0.446	0.520
Tomiño	0.519	0.238	0.517
Vilagarcía de Arousa	0.588	0.295	0.409
Vilanova de Arousa	0.492	0.408	0.392
Third Quartile value	0.511	0.400	0.520
First Quartile value	0.443	0.288	0.404

Table 7.8. Social, Economic and Environmental scores for municipalities included in the category "medium size".

Municipality	Social	Economic	Environmental
A Coruña	0.691	0.548	0.372
Ferrol	0.355	0.038	0.508
Lugo	0.637	0.407	0.657
Ourense	0.428	0.476	0.581
Pontevedra	0.654	0.421	0.630
Santiago de Compostela	0.686	0.659	0.447
Vigo	0.509	0.399	0.209
Third Quartil value	0.672	0.537	0.617
First Quartile value	0.420	0.391	0.364

After estimating the sustainability scores, the next procedure was to assign the rating method scales for the cities from AAA to CCC taking into account the previously estimated values (letters order and dimension: social-economic-environmental). Therefore, the municipality with the AAA sustainability label should be considered sustainable in all its dimensions. On the contrary, a CCC label should be far from sustainable patterns. According to the established criteria, a municipality which presented a combination of classification letters including at least one C or no A was labelled as unsustainable. **Table 7.9** displays the municipalities with the corresponding rating levels. Of the initial list of 64 cities, 30 were identified as sustainable, corresponding to 12 villages, 14 small size cities and 4 medium size cities. Of the entire sample, only 2 municipalities acquired the best combination of letters (AAA). Surprisingly, none of the medium size cities were able to reach the triple A rating. Two cities (A Coruña and Santiago) were classified as AAB and Pontevedra and Lugo as BBA.

Table 7.9. Sustainability rating levels for the Galician municipalities under study. Gray boxes identify the ones tagged as sustainable.

A Coruña					
Village	**Label**	**Small Size**	**Label**	**Medium Size**	**Label**
Aranga	BAB	Arzúa	BAA	Coruña (A)	AAB
Cabanas	AAB	Betanzos	ABC	Ferrol	CCB
Cerdido	BAB	Melide	BBA	Santiago de Compostela	AAB
Laxe	BCA	Muros	CBA		
Muxía	AAA	Narón	ABB		
Zas	BAB	Oleiros	AAC		
		Ordes	BBC		
		Pontes de García Rodríguez (As)	BAB		
		Rianxo	CBB		
		Sada	ABC		
		Santa Comba	BAC		
Lugo					
Village	**Label**	**Small Size**	**Label**	**Medium Size**	**Label**
Fonsagrada (A)	BBA	Castro de Rei	CAA	Lugo	BBA
Mondoñedo	ABA	Sarria	BBB		
Monterroso	BBB	Vilalba	ABA		
Pedrafita do Cebreiro	BAA				
Pobra do Brollón (A)	CBA				
Quiroga	BBB				
Rábade	ABB				
Vicedo (O)	ABB				

Table 7.9 (cont.). Sustainability rating levels for the Galician municipalities under study. Gray boxes identify the ones tagged as sustainable.

Ourense					
Village	**Label**	**Small Size**	**Label**	**Medium Size**	**Label**
Baños de Molgas	BBC	Celanova	CCB	Ourense	BBB
Carballeda de Avia	BCB	Pereiro de Aguiar (O)	BAB		
Castrelo de Miño	BCC	Ribadavia	BBA		
Castrelo do Val	BBB	Verín	BBA		
Coles	AAC				
Cortegada	BBB				
Lobeira	CBC				
Monterrei	CCB				
Pobra de Trives (A)	ABA				
Rairiz de Veiga	BCB				
Ramirás	BBB				
Vilariño de Conso	AAA				

Table 7.9 (cont.). Sustainability rating levels for the Galician municipalities under study. Gray boxes identify the ones tagged as sustainable.

Pontevedra					
Village	**Label**	**Small Size**	**Label**	**Medium Size**	**Label**
Covelo	CBA	Cañiza (A)	CCA	Pontevedra	BBA
		Estrada (A)	BBA	Vigo	BBC
		Grove (O)	BAB		
		Lalín	BAB		
		Moaña	ACB		
		Ponteareas	ACB		
		Salvaterra de Miño	CCB		
		Sanxenxo	BAB		
		Silleda	BAA		
		Tomiño	ACB		
		Vilagarcía de Arousa	ABB		
		Vilanova de Arousa	BAC		

According to the results from the rating system, 57% in the "medium size" municipalities and 45% of sustainable municipalities included in the categories "village" and "small size" attained an A rating in the environmental dimension.

In addition, considering the values given in **Table 7.6 to 7.8**, the distance between the value of each municipality and the value of the quartiles was indicative of how close or far a municipality of the A rating was. For example, As Pontes de García Rodríguez had a rating of B in the social dimension, but its value was 0.506 with respect to the value of 0.511 of the third quartile, being very close to the rating A in this dimension.

7.3.2 Measured weighting after AHP application

In accordance with the scores obtained per sustainability dimension and after the estimation of the corresponding quartiles (see

Table 7.6 to 7.8) and the priority vector obtained applying AHP (see **Table 7.5**), **Table 7.10** summarizes the municipalities with the corresponding rating levels. Slight differences have been identified regarding the ranking achieved with equal weighting. Of the initial list of 64 cities, 25 were identified as sustainable corresponding to 13 villages, 8 small size cities and 4 medium size cities. Only one additional village (Monterroso) was identified as sustainable as difference to the previous weighting approach. Nevertheless, six municipalities in the "small size" category lost the condition of sustainable with the measured weighting approach (Ribadavia, Verín, O Grove, Lalín, Sanxenxo and Vilagarcía de Arousa). Regardless the weighting approach considered Muxía and Vilariño de Conso acquired the triple A rating but one additional municipality in the category of "Village" (Pedrafita do Cebreiro) and two municipalities in the category of "Small size" (Arzúa and Melide) achieved this score with the measured weighting approach. However, again, none of the medium size cities were able to achieve this mark and minor differences in letter combinations were identified in these municipalities regardless of the weighting approach. Thus, the most important differences were identified in the "small size" category, where it was observed some outstanding differences in the rating of some municipalities.

Table 7.10. Sustainability rating levels for the Galician municipalities under study. Gray boxes identify the ones tagged as sustainable.

A Coruña					
Village	**Label**	**Small Size**	**Label**	**Medium Size**	**Label**
Aranga	BAA	Arzúa	AAA	Coruña (A)	AAB
Cabanas	AAB	Betanzos	ABC	Ferrol	CCB
Cerdido	BAA	Melide	AAA	Santiago de Compostela	AAB
Laxe	BCA	Muros	CBA		
Muxía	AAA	Narón	ABB		
Zas	BAB	Oleiros	AAC		
		Ordes	BBB		
		Pontes de García Rodríguez (As)	BAB		
		Rianxo	BBB		
		Sada	ABC		
		Santa Comba	AAC		

Table 7.10 (cont.). Sustainability rating levels for the Galician municipalities under study. Gray boxes identify the ones tagged as sustainable.

Lugo					
Village	**Label**	**Small Size**	**Label**	**Medium Size**	**Label**
Fonsagrada (A)	BBA	Castro de Rei	CAA	Lugo	BBA
Mondoñedo	ABA	Sarria	BBB		
Monterroso	BBA	Vilalba	ABA		
Pedrafita do Cebreiro	BBA				
Pobra do Brollón (A)	CBA				
Quiroga	BBB				
Rábade	ABB				
Vicedo (O)	ABB				
Ourense					
Village	**Label**	**Small Size**	**Label**	**Medium Size**	**Label**
Baños de Molgas	CBC	Celanova	CCB	Ourense	BBB
Carballeda de Avia	BCB	Pereiro de Aguiar (O)	BAB		
Castrelo de Miño	BCC	Ribadavia	BCA		
Castrelo do Val	BBC	Verín	BBB		
Coles	BAC				
Cortegada	CBB				
Lobeira	CBC				
Monterrei	CCB				
Pobra de Trives (A)	ABA				
Rairiz de Veiga	BCB				
Ramirás	BBB				
Vilariño de Conso	AAA				

Table 7.10 (cont.). Sustainability rating levels for the Galician municipalities under study. Gray boxes identify the ones tagged as sustainable.

Pontevedra					
Village	**Label**	**Small Size**	**Label**	**Medium Size**	**Label**
Covelo	CBA	Cañiza (A)	CBA	Pontevedra	BBA
		Estrada (A)	BBA	Vigo	CBC
		Grove (O)	BBB		
		Lalín	BAC		
		Moaña	BCB		
		Ponteareas	BCB		
		Salvaterra de Miño	CCB		
		Sanxenxo	BBB		
		Silleda	ABB		
		Tomiño	BCB		
		Vilagarcía de Arousa	BBB		
		Vilanova de Arousa	BCC		

Finally, the results were analyzed per province. **Table 7.11** shows the number of sustainable municipalities identified per province with both weighting methods. In the case of the northern provinces (A Coruña and Lugo) the number of sustainable municipalities was higher than in the southern provinces (Ourense and Pontevedra). There rationale behind this result is mainly associated with economic factors. This can be explained by the fact that municipalities in the south, despite having a larger number of inhabitants, have a municipal budget similar to that of municipalities in the north. In addition, the weighting procedure significantly affects the results in the two southern provinces, with 12 municipalities identified as sustainable by equal weighting and only 6 when measured weighting was applied. Therefore, attention should be paid on the selected weighting method to identify and report the sustainability results since discrepancies on the results could be identified. Accordingly, more research should be required in the definition of the most favorable weighting method.

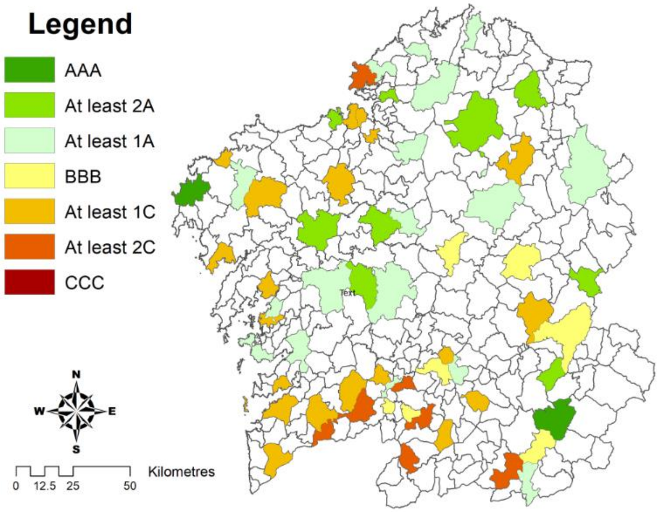
Table 7.11. Number of sustainable municipalities per province.

	Sustainable Municipalities	
	Equal Weighting	Measured Weighting
A Coruña	11	10
Lugo	7	8
Ourense	5	3
Pontevedra	7	3

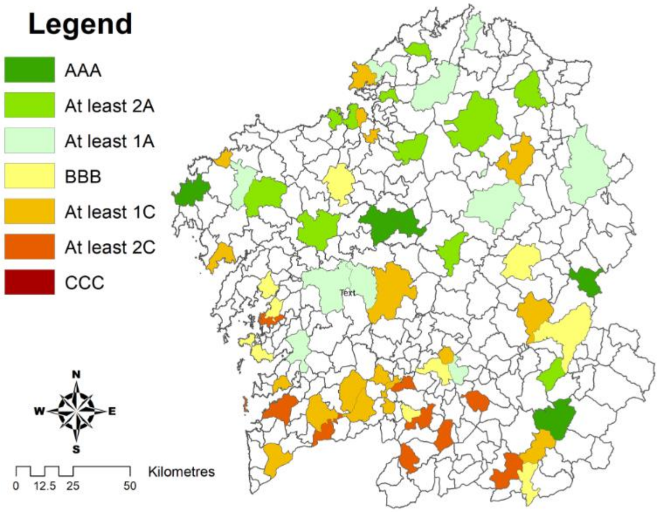
7.3.3 Sustainability ranking of municipalities

Figure 7.6 represents graphically the distribution of sustainable and unsustainable municipalities considering a color code and considering the two approaches of weighting indicators. The location of a municipality on different rating scales depended to a large extent on its intrinsic characteristics, as well as on the criteria chosen for the rating (i.e., the three-letter rating must have at least an A rating and no C rating to achieve the sustainable denomination). According to the results, the proposed method for assessing the sustainability of municipalities appears to be sufficiently robust. Regardless the weighting for the indicators, no major differences in the results have been detected in municipalities of the categories "village" and "medium size" as displayed in **Figure 7.6**. On the contrary, the weighting approach affects the labelling of sustainable in small size municipalities. This issue was related with these municipalities that have only one letter A in the three-letter combination derived from equal weighting approach. The rationale behind these results was because these municipalities achieve a low normalized value in indicators with a high measured weight (i.e., number of registered gender violence cases per 1,000 inhabitants, city unemployment rate, investment, average household income and ozone concentration in air). This combination makes them susceptible to lose the condition of sustainable. On the other hand, municipalities of southern Galicia occupy a worse position in terms of sustainability than those of the north due to the low values in the municipal budget per inhabitant.

Accordingly, and although some assumptions might be necessary mostly related to the municipalities that should be part of the sample and with specific indicators representative of the region, the methodology could be useful for policy makers and governments in acquiring strategies to revitalize municipalities under a sustainable approach. For example, a better distribution of the municipal budget in the south of the region. The methodology considers a series of indicators concerned with the sustainability of cities or municipalities, which provide information on local conditions, allowing comparisons within the sample. Although there have been no problems with the collection of information from the different indicators, as public data sets (in some cases, local and regional data) were used, limitations caused by the accessibility of the data in other regions may appear.



(a)



(b)

Figure 7.6. Distribution and graphical classification of Galician municipalities according to their sustainability score. a) Equal-weighting, b) Measured weighting according to AHP.

7.4 CONCLUSIONS

Most studies related to the proposal of sustainability indicators only consider highly populated urban areas, but this perspective needs to be adapted to more variable ranges of cities, towns and villages. Only in this way it is possible to reflect the real situation of the area under study and become aware of the needs of each of the municipalities. A sustainable municipality must guarantee equal access to municipal services, encourage the participation of its citizens in social activities, create local value chains and establish sustainable procurement principles, based on its strengths and resources, as well as the development of new opportunities. However, they should demand good governance, rural development policies and citizen participation, fighting against the centralization of public services and exploiting trade unions with other small towns and cities.

In this chapter, the methodology developed in Chapter 6 was applied to a sample of municipalities of different population sizes. Consequently, 64 representative municipalities of the Galicia region were selected using specific criteria. The sustainability scores show important differences between the Galician municipalities of the north and the south, where the low values of the municipal budget per inhabitant adversely affect the sustainability. Moreover, although different weighting approaches were proposed (equal weighting and measured weighting based on experts' opinion), no outstanding differences in the letters combination were identified regardless the approach in municipalities under the categories "village" and "medium size".

The evaluation of sustainability in municipalities in Galicia, in addition to putting into practice a novel methodology, could be considered interesting for Policy Makers when creating measures in line with improving the sustainability of municipalities. Although it was applied to a case study focused on the Galician region, the methodology has potential to be applied in other cases of study. On the other hand, this methodology could be applied considering time as a variable, with the objective of identifying trends in the municipalities.

7.5 REFERENCES

ENRD, 2018. European Network for Rural Development. Smart Villages: Revitalising Rural Services'. Eu Rural Rev. 26, 1–51.

Esteve-Llorens, X., Moreira, M.T., Feijoo, G., González-García, S., 2019. Linking environmental sustainability and nutritional quality of the Atlantic diet recommendations and real consumption habits in Galicia (NW Spain). Sci. Total Environ. 683, 71–79. https://doi.org/10.1016/j.scitotenv.2019.05.200

European Commission, 2018. Smart villages Bled declaration - for a Smarter Future of the Rural Areas in EU 1–2.

Eurostat, 2019. Distribution of population by degree of urbanisation, dwelling type and income group. https://ec.europa.eu/eurostat/web/products-datasets (accessed May 2021)

Feleki, E., Vlachokostas, C., Moussiopoulos, N., 2018. Characterisation of sustainability in urban areas: An analysis of assessment tools with emphasis on European cities. Sustain. Cities Soc. 43, 563–577. https://doi.org/10.1016/j.scs.2018.08.025

Google, 2019. Google Earth Pro (7.3.2.5776).

Ibrahim, M., El-Zaart, A., Adams, C., 2018. Smart sustainable cities roadmap: Readiness for transformation towards urban sustainability. Sustain. Cities Soc. 37, 530–540. https://doi.org/10.1016/j.scs.2017.10.008

IGE, 2021. Galician Institute of Statistics (in Galician). Home page. https://www.ige.eu/ (accessed May 2021)

INE, 2021. Statistics National Institute (in Spanish). Home page.

https://www.ine.es/ (accessed May 2021)

MAPA, 2013. Ministry of Agriculture, Fisheries and Food. Analysis of the potential of IFOP and FEP aid: fishing port of Burela (in Spanish). https://www.mapa.gob.es/es/pesca/ temas/fondos-europeos/Burela_tcm30-73746.pdf (accessed May 2019)

Otero-Giráldez, M.S., Álvarez-Díaz, M., González-Gómez, M., 2012. Estimating the long-run effects of socioeconomic and meteorological factors on the domestic tourism demand for Galicia (Spain). Tour. Manag. 33, 1301–1308. https://doi.org/10.1016/j.tourman.2012.04.005

Ubels, H., Bock, B., Haartsen, T., 2019. An evolutionary perspective on experimental local governance arrangements with local governments and residents in Dutch rural areas of depopulation. Environ. Plan. C Polit. Sp. 37, 1277–1295. https://doi.org/10.1177/2399654418820070

Visvizi, A., Lytras, M.D., 2018. It's not a fad: Smart cities and smart villages research in European and global contexts. Sustain. 10, 1–10. https://doi.org/10.3390/su10082727

Wang, C., Zhang, Y., Yang, Y., Yang, Q., Hong, J., 2019. What is driving the abandonment of villages in the mountains of Southeast China? L. Degrad. Dev. 30, 1183–1192. https://doi.org/10.1002/ldr.3303

World Bank, 2019. Urban development overview. https://www.worldbank.org/en/topic/urbandevelopment/overview (accessed May 2021)

Zou, H., Feng, L., Xi, H., Ben, Y., 2019. Comprehensive Management for Better Rural Infrastructure and Service Delivery: Lessons from the Implementation of China's Six Point Rural Action Plan in Guizhou Province. New Urban Agenda Asia-Pacific 279–300.

Chapter 8: **Evaluation of the sustainability of Spanish cities**[19]

SUMMARY

After developing a methodology to evaluate the sustainability of urban systems by means of a set of sustainability indicators, and after its application in 64 municipalities in the Galician region, in this chapter the methodology is applied to Spanish cities. Thus, the main objective is to consolidate the methodology developed, so that it can be used in different urban systems regardless of population size and location. So, bearing in mind the three pillars of sustainability (social, economic and environmental), this chapter aims to evaluate the level of sustainability of 31 representative Spanish cities through multiple sustainability indicators, which have been aggregated into a composite sustainability indicator reported by a three-letter code. Within the geographical and socio-demographic framework of Spain, the results show considerable differences between the cities in the south and the north of the country. Accordingly, most of the cities with the best sustainability scores are located in the north of the country. Examples of this category are Pamplona and L'Hospitalet de Llobregat. Cities such as Murcia, Gijon, Badajoz and Huelva obtained the worst results in all the sustainability pillars. For this group of cities, actions for the improvement of sustainability have been identified.

[19] Based on published study: Rama, M., González-García, S., Andrade, E., Moreira, M.T., Feijoo, G. (2020). Assessing the sustainability dimension at local scale: Case study of Spanish cities. Ecological Indicators, 117, 106687. https://doi.org/10.1016/j.ecolind.2020.106687

8.1 INTRODUCTION

In Chapter 6 a methodology to assess the sustainability of urban systems was developed using an index based on a three-letters label. In this way, a simple method was proposed to define and identify a sustainable urban system. This methodology was applied to a case study of 64 municipalities in Galicia (a region in north-western Spain) in Chapter 7. These municipalities were divided into three groups according to population size. However, only nine of them had more than 35,000 inhabitants. Thus, Chapter 7 concludes that this methodology can be considered robust being validated in small municipalities. Nevertheless, to validate the methodology with urban systems of larger population size it is necessary to apply it to a case study with a larger number of cities. Moreover, the case study was focused only on a certain region. Therefore, the set of indicators may not be adequate if this methodology is applied in other regions with different climates, diets, cultures, etc.

Bearing in mind these issues, in the present chapter it was evaluated the sustainability of sample including the 31 most representative Spanish cities. Hence, this chapter complemented the two previous chapters in such a way that:

1) It applied the methodology developed in Chapter 6 to Spanish cities with a population size between 80,000 and 800,000 inhabitants with the aim of validating the methodology for cities with more than 35,000 inhabitants.

2) The study area was expanded from a region to a country. Consequently, it was determined if the methodology allows evaluating cities in other regions with significant differences in climate, diet, consumption of citizens, etc. In addition, the sample of cities was very varied in terms of the predominant economic sectors, which in some are tourism, in others industry and agriculture. Therefore, relationships were established between the sustainability of each city with various factors, economic, climatic, etc.

The main objective of this chapter was to expand and consolidate the methodology developed in Chapter 6, i.e., guaranteeing its robustness and its application to different case studies regardless of the location and population size. For this, the chapter is mainly divided into a section of Materials and methods, where the city selection procedure was detailed as well as the adaptation of the methodology developed in Chapter 6. On the other hand, the results section shows the main findings of this chapter.

8.2 MATERIALS AND METHODS

8.2.1 Definition of the case study

In this chapter, a list of 31 Spanish cities has been proposed for analysis. Among the cities considered there are the ones with more than 250,000 ± 5,000 inhabitants that are Valencia, Seville, Zaragoza, Malaga, Murcia, Palma de Mallorca, Las Palmas de Gran Canaria, Bilbao, Alicante, Cordoba, Valladolid, Vigo, Gijon, L'Hospitalet de Llobregat, Vitoria-Gasteiz and A Coruña.

These cities are representative of 11 of the 17 autonomous communities that constitute Spain. Therefore, the most populated cities of the rest of autonomous communities were selected to consider representative cities in all regions. These cities are Pamplona, Albacete, Santander, Logroño and Badajoz. It should be noted that Madrid and Barcelona: the two most populated and important Spanish cities in cultural, economic and political terms (Rico et al., 2019), have not been taken into account due to the large differences in terms of number of inhabitants with respect to the rest of Spanish cities (the inhabitants of Barcelona are twice those of the third most populated Spanish city, i.e. Valencia, and Madrid is the third most populated city in the European Union).

However, some relevant cities at Spanish administrative level such as Oviedo, Santa Cruz de Tenerife, Santiago de Compostela and Toledo, have not been selected in the previously mentioned procedure. Therefore, they have been also included in the analysis. Moreover, some cities with small size were also selected to consider samples with different sizes of cities in all regions. These cities are Burgos, Huelva and Ourense. Finally, other criteria of selection were taken into account to complete the sample such as considering cities with an important historical heritage such as Tarragona and Lugo; as well as Pontevedra, a sustainable city at international level (Barral, 2015a). **Figure 8.1** shows the geographic distribution of he selected cities on the map of Spain.

The selected cities present good geographical dispersion and are considered representative of all Spanish regions. Finally, these cities are classified into three groups according to their population: large (inhabitants > 350,000 ± 5,000), medium (200,000 ± 5,000 < inhabitants < 350,000 ± 5,000) and small (inhabitants < 200,000 ±5,000). This classification avoids comparisons between cities with large differences in the number of inhabitants. **Table 8.1** details the cities evaluated and some outstanding characteristics such as population size in 2019 and average net incomes in 2017 (INE, 2020).

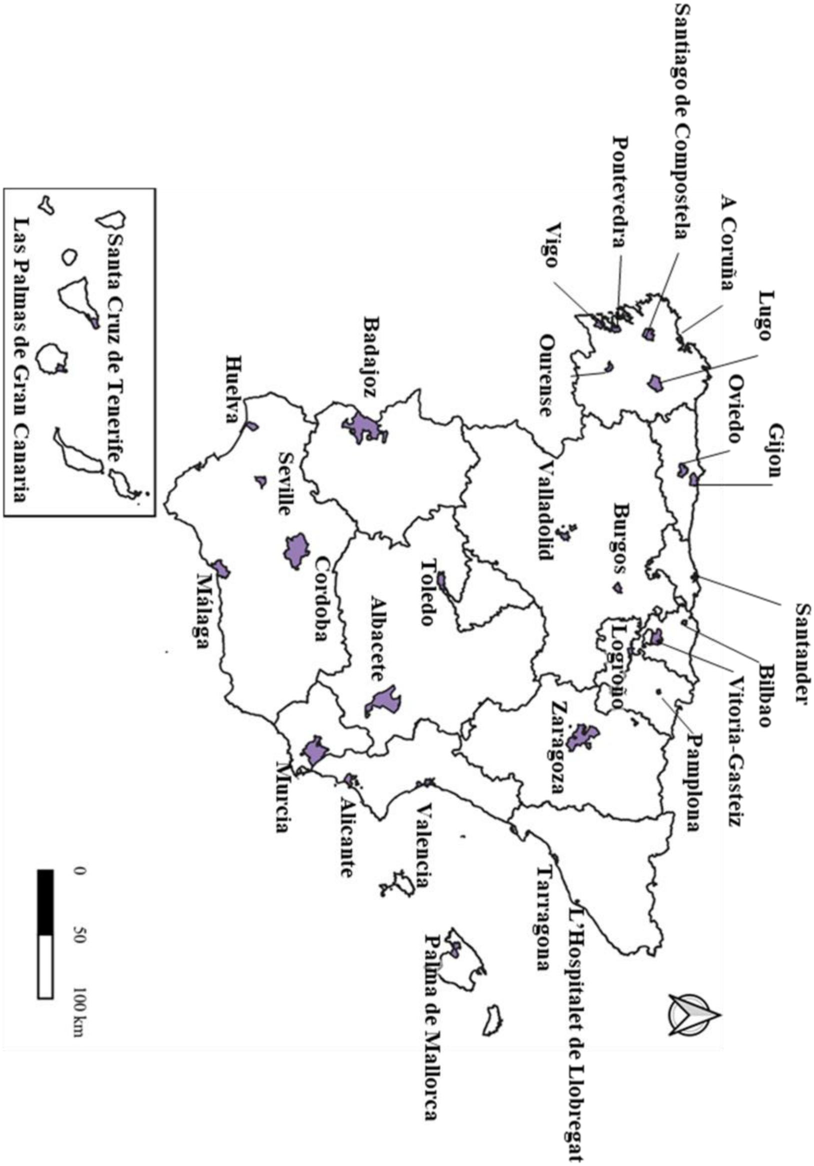


Figure 8.1. Location on the map of the Spanish cities considered in the study.

Table 8.1. Cities considered for assessment and main characteristics.

	Population size (number of inhabitants)	Average net incomes (€·inhabitants^{-1})
Large Size		
Valencia	794,288	12,453
Seville	688,592	11,346
Zaragoza	674,997	13,211
Malaga	574,654	10,119
Murcia	453,258	10,703
Palma de Mallorca	416,065	12,513
Las Palmas de Gran Canaria	379,925	11,364
Bilbao	346,843	15,137
Medium Size		
Alicante	334,887	10,802
Cordoba	325,701	10,629
Valladolid	298,412	13,230
Vigo	295,364	12,083
Gijon	271,780	12,882
L'Hospitalet de Llobregat	264,923	10,917
Vitoria - Gasteiz	251,774	14,367
A Coruña	245,711	13,516
Oviedo	219,686	13,704
Santa Cruz de Tenerife	207,312	11,337
Pamplona	201,653	13,215

Table 8.1 (cont.). Cities considered for assessment and main characteristics.

	Population size (number of inhabitants)	Average net incomes (€·inhabitants^{-1})
	Small Size	
Burgos	175,821	13,347
Albacete	173,329	11,223
Santander	172,539	13,272
Logroño	151,136	12,854
Badajoz	150,702	10,728
Huelva	143,663	10,165
Tarragona	134,515	12,967
Ourense	105,233	11,892
Lugo	98,025	11,884
Santiago de Compostela	97,260	13,516
Toledo	84,873	13,365
Pontevedra	83,029	11,831

8.2.1.1 Inventory data

Once the set of indicators and cities to be studied had been established, a compilation of data for each indicator was conducted for each city. For this purpose, the consultation of data was carried out considering local sources: websites of the municipalities; regional sources: websites of the different regional statistics institutes, website of regional governments and institutions (e.g. air quality data are available from meteorological agencies); national sources: Statistics National Institute (INE, 2019), national government (Accountability, 2016; Government of Spain, 2016) and national institutions (Directorate General of Traffic, 2016; Electoral Commission, 2015; Public Service of State Employment, 2017), as well as data collected from Spanish ministerial offices and services (Ministry of Development, 2018; Ministry of Health Social Services and Equality, 2017). In addition, data were obtained from on-line observatories such as Datosmacro (Expansion, 2019), Idealista (Idealista, 2016), Spanish companies guide (Universia, 2019) and the Ais group (Ais Group, 2016). Mention has also been made of data from cities that do not comply with the regulations on wastewater treatment, information compiled through a newspaper article published in El País (Planelles, 2018).

Regarding information corresponding to leisure facilities, it was estimated by means of a Google search in the different Spanish cities considering different leisure options: leisure centers, theatres and concert halls, cinemas, art galleries, museums, sport centers, gyms, golf clubs, swimming pools, ice skating rinks, spas, thematic parks, children parks and bowling alleys. In addition, when geographical data were not available in the mentioned sources, "Google Earth Pro (7.3.2.5776)" (2019) was used to calculate data regarding the surface of cities (km^2), green areas (km^2) and pedestrian areas (km^2), according to the limited traffic areas of each city. Some data corresponding to studied cities, such as GDP and the population density, are shown in **Table 8.2**.

Table 8.2. Cities considered for assessment and main characteristics.

	Population density ($inhabitants \cdot km^{-2}$)	GDP ($€ \cdot inhabitant^{-1}$)	(Source) Year
	Large Size		
Valencia	5,852	22,153	(1) 2014
Seville	4,876	18,461	(2) 2015
Zaragoza	683	17,153	(3) 2011
Malaga	1,439	17,021	(3) 2015
Murcia	503	19,227	(2) 2016
Palma de Mallorca	1,949	27,994	(3) 2015
Las Palmas de Gran Canaria	3,756	19,248	(2) 2015
Bilbao	8,438	30,890	(3) 2012

Table 8.2 (cont.). Cities considered for assessment and main characteristics.

	Population density (inhabitants·km^{-2})	GDP (€·inhabitant^{-1})	(Source) Year
	Medium Size		
Alicante	1,640	18,191	(2) 2015
Cordoba	260	16,724	(3) 2015
Valladolid	1,514	22,492	(2) 2014
Vigo	2,685	24,416	(3) 2014
Gijon	1,499	31,773	(3) 2014
L'Hospitalet de Llobregat	20,466	23,200	(1) 2016
Vitoria - Gasteiz	876	32,252	(3) 2012
A Coruña	6,458	24,987	(3) 2014
Oviedo	590	38,656	(3) 2014
Santa Cruz de Tenerife	1,353	19,217	(2) 2015
Pamplona	7,803	29,100	(3) 2015
	Small Size		
Burgos	1,640	27,205	(2) 2016
Albacete	141	19,067	(2) 2015
Santander	4,947	15,826	(3) 2014
Logroño	1,906	26,044	(2) 2015
Badajoz	105	15,748	(2) 2015
Huelva	953	18,125	(2) 2017
Tarragona	2,272	41,900	(3) 2017
Ourense	1,220	19,720	(3) 2014
Lugo	294	21,800	(3) 2014
Santiago de Compostela	440	32,637	(3) 2014
Toledo	361	17,169	(2) 2015
Pontevedra	684	21,253	(3) 2014

(1) City council website; (2) National Statistics Institute (INE, 2021); (3) Regional Statistic Institute.

8.2.2 Description of the methodology

8.2.2.1 Indicators set

In the case study described in this chapter, the population size of all cities selected was more than 35,000 inhabitants. Therefore, in this case the set of 38 indicators was used. However, in this study and given that it focuses on city level, a further selection has been performed, removing from the list the pre-selected indicators no relevant for the case study. This was the case of the indicator "distance to continued attention points and hospitals", which could be representative at municipality level, but not at city level. Nevertheless, and to maintain the number of indicators in the set, an additional one within the health sector has been introduced. This is the case of the "Number of hospital beds". Consequently, **Table 8.3** shows the final indicators to be considered in the sustainability assessment.

Table 8.3. Set of indicators selected for analysis.

Pillar	Indicator	Unit
Social	Population graduated in secondary education	%
	Number of registered gender violence cases	No of demands·1000 inhabitants^{-1}
	Women unemployed	Women unemployed·Women at working age^{-1}
	Population rate at risk of poverty	%
	People per household	Inhabitants·Number of Households^{-1}
	Population that participated in the last municipal election	Account votes·electoral census
	Population under 16 years old	%
	Population older than 65 years old	%
	Population annual net growth	%
	Ratio of immigrants	%
	Population Density	Inhabitants·km^{-2}
	Number of leisure facilities	No. leisure facilities·1000 inhabitants^{-1}
	Number of hospital bed	No. Hospitals Beds·1000 inhabitants^{-1}
	Total expense in social services	Expense in social services·inhabitant^{-1}

Table 8.3 (cont.). Set of indicators selected for analysis.

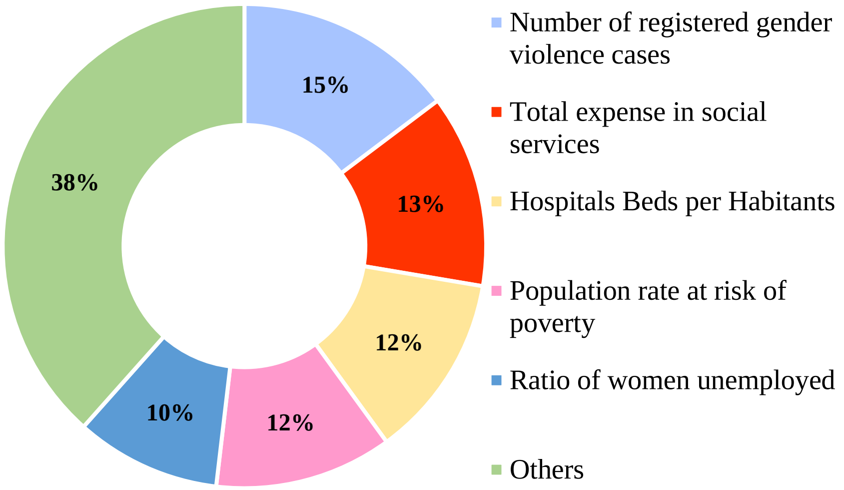
Pillar	Indicator	Unit
Economic	GDP per capita	€·inhabitant^{-1}
	City unemployment rate	%
	Average household income	€·household^{-1}
	Number of permanent contracts signed per 1000 inhabitants	No. contracts·1000 inhabitants^{-1}
	Number of businesses per 1000 inhabitants	No. business·1000 inhabitants^{-1}
	Municipal budget per inhabitant	€
	Non-financial total incomes	€·inhabitant^{-1}
	Surplus/Deficit	€·inhabitant^{-1}
	Indebtedness	€·inhabitant^{-1}
	Investment	€·inhabitant^{-1}
	Average rental price per m^2	€·m^{-2}
	Average sale price per m^2	€·m^{-2}
	Number of hotel places	No hotel places·1000 inhabitants^{-1}
Environmental	Ratio of public/private vehicles	%
	Ozone	μg·m^{-3}
	NO_2	μg·m^{-3}
	PM10	μg·m^{-3}
	Total domestic water consumption per dwelling	m^3 ·households^{-1}
	Total electrical use per capita	MWh·inhabitant^{-1}
	Surface of green area	%
	Surface of pedestrian zone	%
	MSW collected	kg·inhabitant^{-1}
	Non-Compliance Wastewater Treatment	Dimensionless
	Sustainability plan, participation in projects and awards	No. plans

8.2.2.2 Normalization, weighting and aggregation

Data collected from indicators may be in different units of measurement, making it difficult to compare and operate with the different values – e.g., the units corresponding of the indicator "number of hospital beds" are completely different, for example, with the indicator "population density". Thus, prior normalization of data is necessary before aggregating indicators.

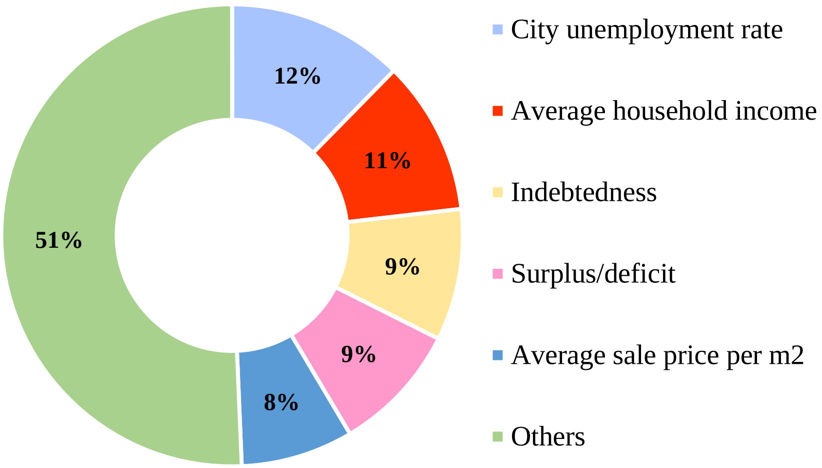
The normalization method selected in this chapter was Re-Scaling. Thus, as described in Chapter 6, and in Chapter 7, this method consists of obtaining values between 0 and 1 for each indicator, considering 1 as the best value for the indicator. It must be taken into account that in negative indicators, such as the "City unemployment rate", in which the lowest values are the closest to a sustainable situation, through the normalization method these values were transformed so that obtaining a 1 was the most favourable value (Nardo et al., 2008).

The next step to obtain an index, is to define the weight of the indicators. Therefore, weighting attributes a different weight for each indicator. However, it is common the use of a method attributing the same weight, and therefore, considering all indicators with equal relevance. Nevertheless, there are different methodologies such the analytical hierarchy process (AHP). Both methods (equal weight and AHP) were used in Chapter 7, so that no significant differences were obtained between them. However, it was concluded that the most restrictive method in terms of sustainability was AHP. For this reason, in this chapter the weights established for each indicator were assigned through the AHP methodology developed in Chapter 6. Moreover, in the case of indicator "Number of hospital beds", considering that it is also an indicator within the health category, the same weight that was established for the replaced indicator "distance to continued attention points and hospitals" was preserved. The assignment of the weights relative to each indicator was carried out considering the three pillars of sustainability separately. Therefore, for each indicator of each pillar of sustainability, a relative weight was obtained. Thus, the sum of all the relative weights of the indicators of each pillar of sustainability must be 1. **Figure 8.2** details the distribution of the weights assigned to each indicator resulting from the AHP methodology.

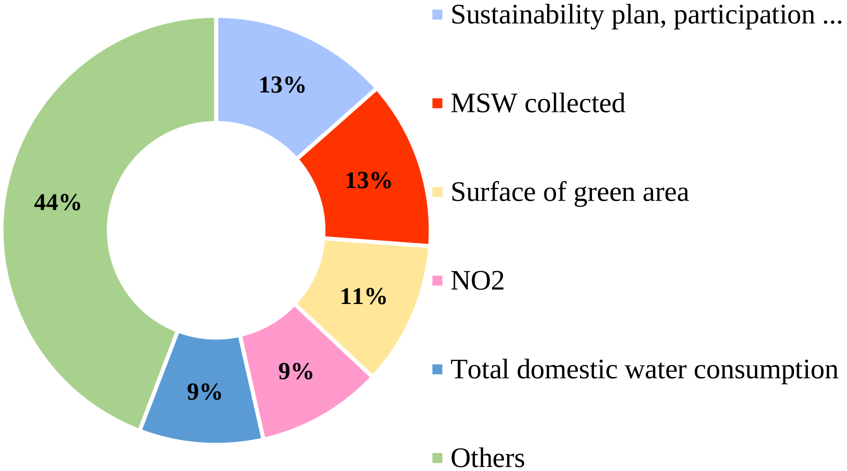


(a)

Figure 8.2. Percentage distribution of the weights of the (a) social indicators, highlighting the five indicators with greater weight attributed by the AHP method.



(b)



(c)

Figure 8.2 (cont.). Percentage distribution of the weights of the (b) economic indicators and (c) environmental indicators highlighting the five indicators with greater weight attributed by the AHP method.

On the other hand, aggregation determines the conceptual framework used in order to combine indicators of the three pillars either separately or together (Tanguay et al., 2010). In this chapter, following the methodology developed in Chapter 6, the indicators for each pillar of sustainability were added using the arithmetic mean weighted separately. Therefore, a composite indicator with a value of 0 to 1 was finally reached for each of the pillars of sustainability. Consequently, each city three composite indicators were obtained, one for the social pillar, other for the economic and another for the environmental with values between 0 and 1, being the more favorable situation in terms of a sustainability occurs when these values were closer to 1.

Nevertheless, *based on what value in each of these pillars is a city considered sustainable?* In this chapter, a sustainable city was defined according to the three-letters code also developed in Chapter 6. Hence, to establish thresholds within these composite indicators, they were divided for the quartiles into a Gaussian distribution. Cities whose value of the composite indicator, regardless of the sustainability pillar, was higher than that of the third quartile (Q_3), obtained an A rating. Cities with values between the first and third quartiles (Q_1 and Q_3 respectively) obtained a B rating. Finally, cities whose values were worse than Q_1 obtained a C rating. In this sense, the best values of composite indicators were designed with the letter A and the worst with C. For example, if the value of Q_3 was 0.65, and a city obtained a value of the social composite indicator of 0.68, this city has a mark of A in the social dimension. Therefore, a city had a code with 3 letters for each dimension of sustainability, and these letters can be A, B or C, depending on the value of the city in the corresponding composite indicator.

Since this chapter aims to define a sustainable city through this three-letter code, it was established that a city with at least one A and no C in the code should be considered as sustainable city. Therefore, according with this criterion, the sustainability of a city depends on three independent values corresponding with the three pillars of sustainability. Consequently, this is in line with the concept of *strong* *sustainability* which considers that a poor result derived from low values in the environmental indicators cannot be compensated with satisfactory values in the economic or social ones (Cabello et al., 2019). In addition, within the sample analysed, there were cities that have been awarded the international recognition of sustainable city. These cities were Vitoria-Gasteiz and Pontevedra (Barral, 2015b; Rioja-Andueza, 2019). Therefore, they have been considered as reference points in the analysis.

8.3 RESULTS AND DISCUSSION

8.3.1 Ranking of cities

After compiling the inventory data for each indicator, the mathematical methodology detailed in Section 8.2.2 has been applied to obtain a composite indicator for each city and sustainability dimension. This composite indicator was the result of aggregating the corresponding values and the attributed weights. As a result, cities were rated between 0 and 1. The values of the first and third quartiles between cities in the same size category were then calculated. **Table 8.4** displays the values for the composite indicators of cities classified by size. The distance between quartiles indicates the difference between cities within the same size category. For example, in the medium size category the difference between the quartiles for the economic factor is 0.069, while in the small size category it is 0.258. This implies that, in economic terms, medium-sized cities were more similar to each other than smaller cities.

Table 8.4. Values for the composite indicators associated to each city for the three sustainability dimensions and corresponding quartiles.

Large size			
City	**Social**	**Economic**	**Environmental**
Valencia	0.386	0.425	0.746
Seville	0.414	0.365	0.643
Zaragoza	0.514	0.383	0.629
Malaga	0.303	0.333	0.494
Murcia	0.375	0.307	0.415
Palma de Mallorca	0.565	0.545	0.455
Las Palmas de Gran Canaria	0.451	0.415	0.698
Bilbao	0.526	0.637	0.554
First quartile value	0.378	0.341	0.465
Third quartile value	0.523	0.515	0.684
Medium Size			
City	**Social**	**Economic**	**Environmental**
Alicante	0.313	0.435	0.601
Cordoba	0.405	0.326	0.586
Valladolid	0.491	0.460	0.624
Vigo	0.482	0.399	0.483
Gijon	0.347	0.335	0.446
L'Hospitalet de Llobregat	0.569	0.607	0.682
Vitoria-Gasteiz	0.662	0.448	0.502
A Coruña	0.557	0.449	0.505
Oviedo	0.517	0.432	0.552
Santa Cruz de Tenerife	0.450	0.468	0.416
Pamplona	0.688	0.516	0.774
First quartile value	0.405	0.399	0.483
Third quartile value	0.569	0.468	0.624

Table 8.4 (cont.). Values for the composite indicators associated to each city for the three sustainability dimensions and corresponding quartiles

Small Size			
City	**Social**	**Economic**	**Environmental**
Burgos	0.516	0.553	0.577
Albacete	0.617	0.272	0.364
Santander	0.434	0.639	0.399
Logroño	0.749	0.518	0.459
Badajoz	0.311	0.242	0.388
Huelva	0.301	0.230	0.349
Tarragona	0.616	0.493	0.522
Ourense	0.493	0.475	0.468
Lugo	0.612	0.394	0.601
Santiago de Compostela	0.653	0.563	0.437
Toledo	0.743	0.566	0.500
Pontevedra	0.573	0.424	0.643
First quartile value	0.449	0.303	0.390
Third quartile value	0.644	0.561	0.564

Finally, the assignment to each city of a three-letter code was conducted considering the values indicated in **Table 8.4**. Thus, cities with a score higher than the third quartile have been rated as A in the corresponding dimension of sustainability. Cities with values between the first and the third quartiles have been rated as B, and consequently, cities with values below the first quartile have been classified as C. For example, Toledo, classified within the Small Size category, obtained a score of 0.743 in the social composite indicator, a value clearly higher than that corresponding to the third quartile (0.644). Thus, Toledo was ranked as A in the social dimension. Following this approach Toledo obtained a three-letter code AAB (social-economic-environmental). Having in mind the criterion described in Section 8.2.2.2 to define a city as sustainable (sustainable cities are those that in the three-letter code obtain at least one A and no C), Toledo can be considered as a sustainable city.

Accordingly, all cities have obtained a three-letter code between AAA and CCC resulting in 27 possible combinations, of which only 7 should define a city as sustainable. **Table 8.5** details the different three-letter codes of the selected Spanish cities. The first letter corresponds to the social aspect, the second to the economic variable and the third to the environmental one. According to the results, 13 of the 31 studied cities have been identified as sustainable, most of them being small-sized cities. However, the best scores have been obtained in the cities corresponding to the medium-sized category, with two cities ranked with a triple A code (AAA). This was why the C rank was concentrated in fewer cities in the small towns: Alicante had two C and Huelva and Badajoz had three C each. Therefore, the number of sustainable cities was higher. In addition, there was much more dispersion in the values of the composite indicators of the small cities, which indicates that the differences between them were much greater. In the case of medium-sized cities, the dispersion was much less than in the case of small cities, except in the cases where it was rated AAA: Pamplona and L'Hospitalet de Llobregat, which were outlined in all the composite indicators. Thus, there was a greater number of cities between quartiles 1 and 3, and therefore fewer sustainable cities.

Table 8.5. Cities studied with their corresponding three-letter code.

Big Size		Medium Size		Small Size	
Valencia	BBA	Alicante	CBB	Burgos	BBA
Seville	BBB	Cordoba	BCB	Albacete	BCC
Zaragoza	BBB	Valladolid	BBA	Santander	CAB
Malaga	CCB	Vigo	BBB	Logroño	ABB
Murcia	CCC	Gijon	CCC	Badajoz	CCC
Palma de Mallorca	AAC	L'Hospitalet de Llobregat	AAA	Huelva	CCC
Las Palmas de Gran Canaria	BBA	Vitoria-Gasteiz	ABB	Tarragona	BBB
Bilbao	AAB	A Coruña	BBB	Ourense	BBB
		Oviedo	BBB	Lugo	BBA
		Santa Cruz de Tenerife	BAC	Santiago de Compostela	AAB
		Pamplona	AAA	Toledo	AAB
				Pontevedra	BBA

On the other hand, there were four cities that have been classified as CCC: Murcia, Gijon, Badajoz and Huelva. Moreover, all the cities under study with the letter A in the environmental score achieve the sustainability category as detailed in **Table 8.5**. The rationale behind this finding could be cities with an important environmental commitment, are usually those whose citizens have a certain welfare state, otherwise, the municipality and citizens would give priority to economic and social development. On the contrary, there were some cities with an A in the letter code corresponding to social or economic aspects which do not achieve the category of sustainable city. These were the cases of Palma de Mallorca, Santa Cruz de Tenerife or Santander, whose letter codes were AAC, BAC and CAB respectively. The first two are cities with high tourist influence, which brings great economic benefits, but which demands a large consumption of electricity and water and generates large amount of waste. On the other hand, the reason why Santander has not been classified as sustainable was due to depopulation. Furthermore, in the case of Palma de Mallorca although its code has two A, according to established criteria, does not reach the category of sustainable. In this sense, a balance between social, economic and environmental indicators is required to be sustainable.

In the case of the four cities ranked as CCC, it is important to note how close they were to the threshold established by the first quartile. It is thus possible to identify the indicators on which they have the lowest scores to propose actions to improve the global performance. The main differences between the first quartile value and the composite indicator obtained correspond to the social composite indicator for the cities of Badajoz and Huelva. The rationale behind these results is due to the notable differences in the values achieved in the social indicators. However, the social composite indicator in the case of Murcia is similar to that of the first quartile. The same happened for the environmental composite indicator in the case of Badajoz. These differences or similarities indicate how close one city was to acquiring a B score on some of the sustainability dimensions. **Figure 8.3** presents the values of the first quartile and the values of the composite indicators for the cities that have rated CCC.

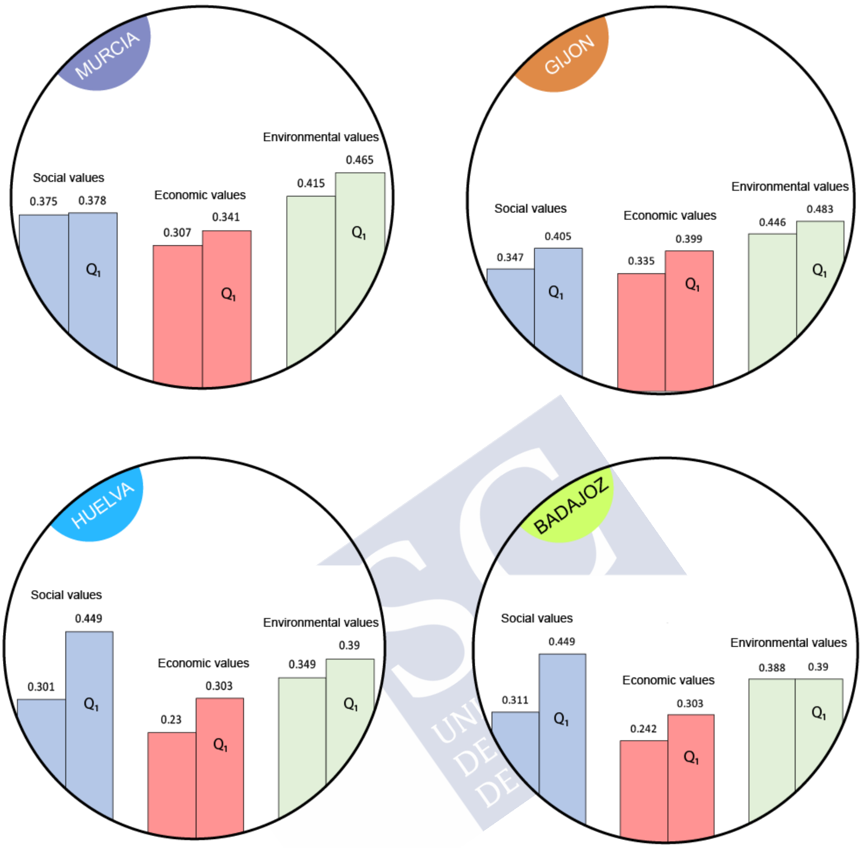


Figure 8.3. Composite indicators and first quartile values of the cities rated as CCC.

Bearing in mind that each composite indicator depends on multiple indicators, it should be necessary to identify these indicators with the lowest scores to propose for improvement. **Table 8.6** shows the cities ranked as CCC as well as the indicators that obtained a value of 0 after the normalization step.

Table 8.6. Cities with rating CCC and the indicators whose relative values after normalization were 0.

City	Social Indicators	Economic Indicators	Environmental Indicators
Murcia	People per dwelling	Average household income	Ratio of public/private vehicles
	Population Density	Non-financial total incomes	Surface of green area
	Number of leisure facilities per 1,000 inhabitants	Average rental price per m^2	Sustainability plan, participation in projects and awards
	Total expense in social services	Average sale price per m^2	
		Number of hotel places	
Gijon	Ratio of population under 16 years old	Number of permanent contracts signed per 1000 inhabitants	Surface of green area
	Hospitals Beds per inhabitants		MSW collected
			Non-Compliance Wastewater Treatment

Table 8.6 (cont.). Cities with rating CCC and the indicators whose relative values after normalization were 0.

Badajoz	Ratio of immigrants	GDP per inhabitant	Ratio of public/private vehicles
	Population Density.	Non-financial total incomes	
	Number of leisure facilities per 1,000 inhabitants	Surplus/deficit	Total domestic water consumption
	Total expense in social services	Investment	
Huelva	Number of registered gender violence cases per 1,000 inhabitants	City unemployment rate	Ozone
	Ratio of women unemployed	Number of permanent contracts signed per 1000 inhabitants	PM10
	Population rate at risk of poverty	Indebtedness	

In the case of Murcia, the social indicators “people per dwelling” and “population density” were related to the size of the city and whether or not it was a compact population. However, Murcia had the smallest green area despite its surface was relatively large. Consequently, the city should consider the incorporation of both elements in future urban planning strategies to achieve a sustainable category. In economic terms, it highlights indicators related to the price of housing. These indicators were stimulant indicators, that is high rental and sale housing prices indicate the high purchasing power in the city. This reality was explained by the low values of the “average household incomes” and “non-financial total incomes” that refer to tax collection.

Gijon was one of the few cities that do not comply with wastewater discharge limits. Moreover, it was the medium-sized city with the highest production of waste and must also improve the extension of green areas in terms of environmental indicators. Consequently, the city should take these aspects into account in its improvement strategy and pay attention to the design of better urban planning having in mind both wastewater and solid waste management.

On the other hand, although Gijon has been ranked as C in the economic pillar, it has only obtained the lowest value in one economic indicator. The reason for this result was due to the small difference between the quartiles in the case of economic indicators in medium-sized cities, which means that cities with few differences in some values of the indicators have a remarkably different result in the letter ranking. Moreover, bearing in mind the social pillar, Gijon was the medium-sized city with the lowest number of hospital beds as well as with the lowest population ratio under 16 years of age.

Badajoz and Huelva, as shown in **Figure 8.3**, have the greatest challenges within social indicators. In the case of Badajoz with the lowest "ratio of immigrants" within the category of small cities, it could imply a low number of inhabitants of working age, which may also explain, together with the low number of companies, the low GDP per inhabitant and the low level of attraction as a working pole. Moreover, the low expenditure on social services was easily related to municipal budget indicators, which were also shown in **Table 8.6**.

Regarding Huelva, it was the small city with the highest number of registered cases of gender-based violence and the highest ratio of unemployed women. It therefore requires the promotion of gender equality projects by city policy makers.

In addition, some of these indicators have a high weight attributed by the AHP methodology. This was the case of the number of registered cases of gender violence or the total expenditure on social services in the case of social indicators, the urban unemployment rate as an economic indicator or the MSW collected within the environmental indicators. This makes it more difficult for cities with low relative values in these indicators to achieve sustainable city status.

According to geographical distribution, most sustainable cities were in the north, especially the geographical area in which Bilbao, Vitoria-Gasteiz, Pamplona, Logroño and Burgos were located. On the one hand, Bilbao and Vitoria-Gasteiz belong to the Basque country and this region has an independent fiscal management; thus, the expenditure on social services was the highest of all cities. Logroño also stand out for its expenditure on social services and ranks as the first for the small-sized city group. In the case of Burgos, it was the city with not only the lowest unemployment rate of the small cities, but also it has a large surface of green zones. Pamplona, on the other hand, has the smallest population at risk of poverty in medium-sized cities, a low number of unemployed people and many sustainability plans. Therefore, Pamplona together with L'Hospitalet de Llobregat were a good example of balance between the three dimensions of sustainability. In addition, cases such Toledo and L'Hospitalet de Llobregat could be positively affected due to the proximity of both cities to Madrid and Barcelona respectively.

Contrary, the worst sustainability results were obtained mainly in the south. This was due to the high rate of unemployment registered in the regions of Andalusia, Murcia and Extremadura, as well as the high ratio of population at risk of poverty. Moreover, in Andalusia the low number of permanent contracts signed indicated a low quality of jobs. This was in part because tourism is a key economic factor in the south of Spain, which is characterized by being a seasonal sector with precarious jobs (Martí et al., 2017). The geographical distribution of cities can be seen in **Figure 8.4**.

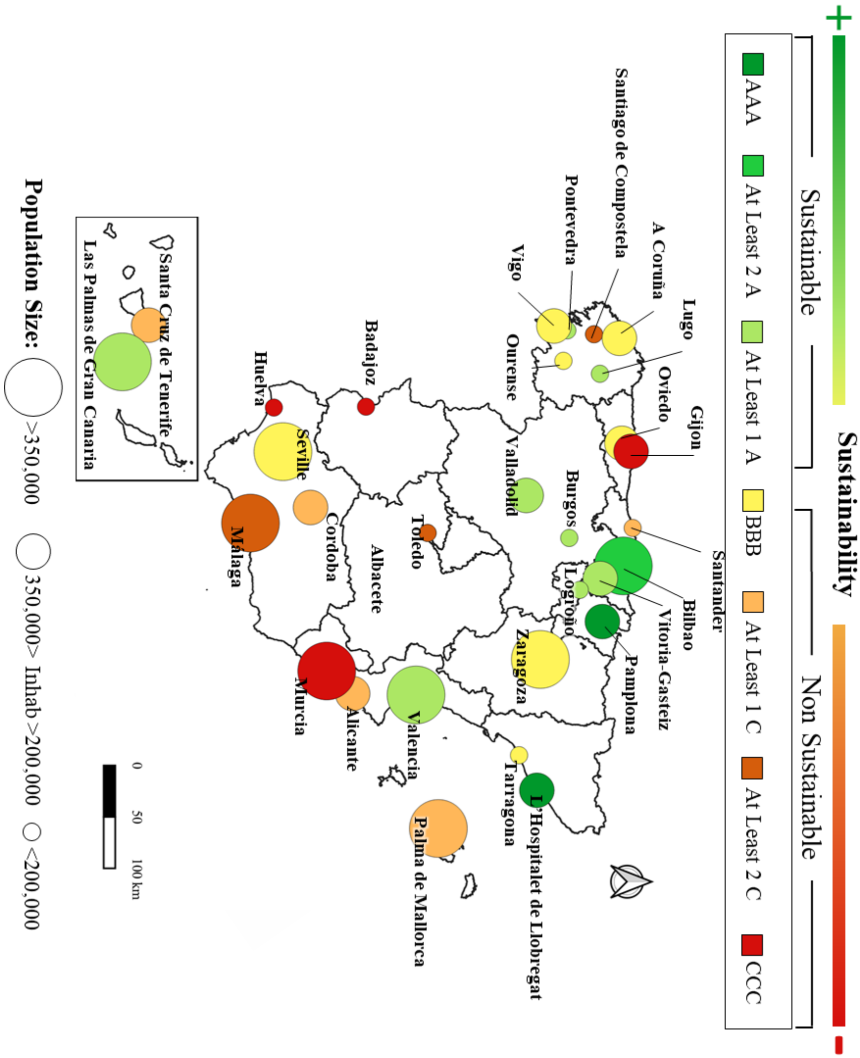


Figure 8.4. Representation of results in color categories where the lowest values in terms of sustainability that achieved a CCC score were represented in dark red and the best values, with a AAA score, were represented in dark green.

This inequality in terms of sustainability between the north and south of the country was associated with historical reasons. Regional differences in education in the preindustrial era between the north and the south of Spain are linked to higher illiteracy rates in the south of the country. Accordingly, there was greater industrial development in the northern regions (Beltrán-Tapia and Martinez-Galarraga, 2018). Thus, in regions such as Andalusia (south of Spain), most of the gross value added comes from the agricultural sector. On the contrary, in other regions such as the Basque country (north of Spain), the main economic power is the industry, which generates much more wealth and, consequently, increases indicators such as GDP and income per capita (Beltrán-Tapia and Martinez-Galarraga, 2018; Tirado et al., 2016). More recently, although Andalusia has made significant socio-economic progress since Spain joined the European Union, it remains one of the least developed regions in Europe (Cabello et al., 2019.). In addition, its coastal areas have suffered more from the consequences of the economic crisis on tourism (a key sector in its economy) than other areas that affect other sectors indirectly (Cabello et al., 2019).

The criterion for defining sustainability proposed is a non-compensatory one, therefore good results in the environmental pillar do not compensate for poor results in the economic and social one. This consideration may affect some cities, such as Malaga, whose city council had a solid environmental program with experience of more than 20 years (City council of Malaga, 2017), but because it has a high rate of unemployment and poverty, it does not qualify as sustainable in this study. In addition, cities with a low ranking are taking measures and actions to achieve a more sustainable city status. This is the case of Murcia, where the University of Murcia launched a dissemination project in collaboration with the city council and other institutions with the aim of raising awareness and disseminating the different SDGs of the Agenda 2030 (University of Murcia, 2019). In the same line, Gijon developed a mobility plan in 2004 focused on the promoting of more sustainable mobility systems in the city centre (City council of Gijon, 2014). Seville, which also has its own mobility plan, has established a series of objectives and strategies to achieve sustainable city status by 2030. Examples of these measures are the generation of employment and economic development and the fight against poverty and social inequalities, among others (City Council of Seville, 2019). Finally, Zaragoza has implemented several actions within the framework of Agenda 21, within four specific objectives: Integrating nature in the city and its Area of Influence, improving air quality, promoting the development of clean technologies and adopting operational systems for waste management and improving water quality, reducing its inappropriate use and promoting its study (City Council of Zaragoza, 2005).

8.3.2 Relevance of the study

Concern about assessing urban sustainability has grown since the Rio 1992 summit, from which the Agenda 21 program emerged (Tanguay et al., 2010). Moreover, in 2015 the 193 member states of the United Nations agreed on complying with the 2030 Agenda Action Plan with one target goal focused on driving cities towards sustainability (United Nations, 2015). As a result, several studies focusing on the assessment of indicators in cities have been carried out in the last years (Feleki et al., 2018). Furthermore, standardization organizations have recently developed regularization work in the field of smart cities for sustainable development (Marsal-Llacuna, 2016). In addition, outside the scientific field, different city rankings have been published in several journals at both Spanish and European levels, which identify not only the quality of life of their inhabitants but also the socio-economic and environmental impact of the activities carried out in their surroundings (Batten, 2019; El País, 2019; Mercer, 2018). These rankings, further to being a way of comparing a city with others, may contain useful information for interested parties and policy makers on the road to the conception of a city more attractive for people, tourism and business (Mercer, 2019).

However, there are still challenges for the society and researchers, such as the definition of the concept of a sustainable city, as well as the identification of the best indicators set to assess the sustainability (Feleki et al., 2018). Furthermore, the established indicators could be different for each case study because not all cities control the same data due to the differences that may exist between the regions where each city is located (e.g., different climate, culture, …) (Braulio-Gonzalo et al., 2015). With these issues in mind, this chapter proposes a methodology to evaluate the sustainability of Spanish cities based on the creation of an index which was a three-letter label. This three-letter label requires a certain balance in the three pillars of the sustainability to be accredited as a sustainable city. Moreover, this does not coincide with other studies (Análisis e Investigación, 2012; Batten, 2019), where cities are classified in a ranking with a score integrated by the three main pillars of sustainability but not with the same weight, i.e. a high value in the economic pillar can compensate a low value in the environmental one, and the city should be classified as sustainable.

In addition, the classification of cities according to their size avoids comparing large cities with small ones since they may have very different socio-economic realities, such as municipal budget, investment, etc. which also affect the environmental behaviour of the cities. In this sense, the challenges and sustainability plans that can be projected from the results of the application of the methodology could be oriented towards reaching goals within the limits of their size category. This chapter shows the current sustainability picture of the most representative Spanish cities. However, if the time is managed as an additional variable, as well as to study cities for different years, the trend of each city can be seen in a sustainability dimension. For this purpose, collecting and monitoring data at city level is a key factor in sustainability assessment (Ibrahim et al., 2018), as good data quality improves the representativeness and plausibility of results.

In relation to the results obtained at the present chapter, they were in line with other study available in the literature (Análisis e Investigación, 2012), where the cities ranked at the top in the sustainability scale were Bilbao, Logroño, Pamplona and Vitoria-Gasteiz, which have reported good results in our study despite not having used the same set of indicators (see **Table 8.3**). However, there are some differences compared to this study due to the use of different indicators, and the way the ranking was scored. In this document the scoring criterion is considered a three-letter code which is a non-compensatory system; however, in the Siemens study (2012) the scoring criterion was based on a compensatory procedure. Thus, a low score in an indicator can be compensated by a good result on another. Bearing it in mind, that was the reason why cities such as Malaga or Zaragoza which have a good score the study conducted by Siemens (2012), did not reach the category of sustainable city using the three-letter code. Moreover, the three-letter code designed allows to identify the strengths and weaknesses of a city in a simple and fast way. Therefore, the stakeholders and policy makers, using a retrospective analysis, can easily identify the indicators which need to be improved to reach the category of sustainable city.

8.4 CONCLUSIONS

Assessing sustainability at the city level remains a challenge. Many studies focus on environmental aspects. However, sustainability implies three dimensions: social, economic and environmental. Therefore, the use of sustainability indicators can be considered as a potential assessment method that incorporates non only environmental but also socioeconomic factors. With the point to achieve the goals set out in the Agenda 21, the use of sustainability indicators has grown in recent years. However, there are different gaps in this type of analysis, such as the identification of the adequate set of indicators, the scale of application (city, metropolitan area…) and the lack of consensus on the definition of sustainability, which makes it difficult to establish sustainability thresholds. In addition, data collection and monitoring are essential, but not all cities have equivalent level of data, which makes it very difficult to determine the real state of a city.

This chapter adapted a methodology developed in Chapter 6 to assess sustainability in cities considering a set of Spanish cities as case study to demonstrate its applicability. For this purpose, a set of indicators covering the three pillars of sustainability for the set of cities classified by size was selected and measured. Moreover, each indicator was assigned a different weight because of the application of the AHP methodology. A three-letter code was used to define the concept of sustainability, so that to reach the category of sustainability, a balance between the three pillars should be required. The results show that the cities located in the north of the country achieve better scores than the ones located in the south. The rationale behind these differences is associated with economic factors (such as higher unemployment rates and fewer permanent contracts in the south of the country) and social issues derived from the economic ones, such as a high poverty rate in the south.

This three-letter code may be useful to get a quick idea of the state of a city, but policy makers should need a retrospective analysis to know which indicators achieve the worst scores in a certain city. In this sense, sustainability plans and projects could be developed to improve the category of that city from a sustainability approach.

8.5 REFERENCES

Accountability, 2016. Consultation of institutions and accounts (in Spanish). http://www.rendiciondecuentas.es (accessed May 2021).

Ais Group, 2016. Spanish poverty town to town (in Spanish). https://www.ais-int.com/datos-sociodemograficos-economicos-habits-municipios/es/ (accessed May 2021)

Análisis e Investigación, 2012. 25 sustainable Spanish cities (in Spanish) 68.

Barral, S., 2015a. Pontevedra receives the UN award in Dubai (in Spanish). La Voz Galicia.

Batten, J.J., 2019. Citizen Centric Cities. The Sustainable Cities Index 2018.

Beltrán-Tapia, F.J., Martinez-Galarraga, J., 2018. Explorations in Economic History Inequality and education in pre-industrial economies : Evidence from Spain 69, 81–101.

Braulio-Gonzalo, M., Bovea, M.D., Ruá, M.J., 2015. Sustainability on the urban scale: Proposal of a structure of indicators for the Spanish context. Environ. Impact Assess. Rev. 53, 16–30. https://doi.org/10.1016/j.eiar.2015.03.002

Cabello, J.M., Navarro-Jurado, E., Rodríguez, B., Thiel-Ellul, D., Ruiz, F., 2019. Dual weak–strong sustainability synthetic indicators using a double reference point scheme: the case of Andalucía, Spain. Oper. Res. 19, 757–782. https://doi.org/10.1007/s12351-018-0390-5

City council of Gijon, 2014. Gijón Sustainable Urban Mobility Plan. https://movilidad.gijon.es/page/13901-pmus-2004-2016 (accessed May 2021)

City council of Malaga, 2017. Malaga. Sustainable city (in Spanish). http://medioambiente.malaga.eu/opencms/ export/sites/sostenibilidad/.content/galerias/documentos/malaga-sostenible.pdf (accessed March 2019)

City Council of Seville, 2019. Objectives and Strategies. Seville 2030 (in Spanish. https://www.sevilla.org/ planestrategico2030/documentos/sevilla-2030/plan-estrategico-sevilla-2030/objetivos-y-estrategias-sevilla2030.pdf (accessed March 2019)

City Council of Zaragoza, 2005. Zaragoza and sustainable development. http://www.zaragoza.es/ contenidos/medioambiente/agenda21/publicaciones_anteriores/Agenda21.pdf (accessed March 2019)

Directorate General of Traffic, 2016. Vehicle fleet (in Spanish). http://www.dgt.es/es/seguridad-vial/ estadisticas-e-indicadores/parque-vehiculos/tablas-estadisticas/2016/ (accessed May 2021)

El País, 2019. Ranking of the best cities to live (in Spanish). https://elpais.com/elpais/2019/ (accesseed March 2019)

Electoral Commission, 2015. Electoral results (in Spanish). http://www.juntaelectoralcentral.es/cs/jec/elecciones/

Locales_mayo2015 (accessed March 2019)

Expansion, 2019. Unemployment by municipalities: Spain (in Spanish). https://datosmacro.expansion.com/paro/espana/municipios (accessed May 2021)

Feleki, E., Vlachokostas, C., Moussiopoulos, N., 2018. Characterisation of sustainability in urban areas: An analysis of assessment tools with emphasis on European cities. Sustain. Cities Soc. 43, 563–577. https://doi.org/10.1016/j.scs.2018.08.025

Google, 2019. Google Earth Pro (7.3.2.5776).

Government of Spain, 2016. Ranking of expenses in Social Services and social promotion (in Spanish) [WWW Document]. https://presupuestos.gobierto.es/ranking/2016/G/functional/amount_per_inhabitant/

Ibrahim, M., El-Zaart, A., Adams, C., 2018. Smart sustainable cities roadmap: Readiness for transformation towards urban sustainability. Sustain. Cities Soc. 37, 530–540. https://doi.org/10.1016/j.scs.2017.10.008

Idealista, 2016. Evolution of the price of housing for rent (in Spanish).

INE, 2021. Statistics National Institute (in Spanish). Home page. https://www.ine.es/ (accessed May 2021)

INE, 2020. Statistics National Institute. Urban Audit Indicators for Cities (in Spanish). https://www.ine.es/ (accessed May 2021)

INE, 2019. National statistic Institute (in Spanish). https://www.ine.es/ (accessed May 2021)

Marsal-Llacuna, M.L., 2016. City Indicators on Social Sustainability as Standardization Technologies for Smarter (Citizen-Centered) Governance of Cities. Soc. Indic. Res. 128, 1193–1216. https://doi.org/10.1007/s11205-015-1075-6

Martí, P., Nolasco-Cirugeda, A., Serrano-Estrada, L., 2017.

Assessment tools for urban sustainability policies in Spanish Mediterranean tourist areas. Land use policy 67, 625–639. https://doi.org/10.1016/j.landusepol.2017.06.015

Mercer, 2019. City attractiveness. https://mobilityexchange.mercer.com/city-benchmarking-and-consulting (accessed May 2021)

Mercer, 2018. The cities with the highest quality of life in the world (in Spanish). https://www.muyinteresante.es/ cultura/arte-cultura/fotos/las-ciudades-con-mayor-calidad-de-vida-del-mundo/1 (accessed May 2021)

Ministry of Development, 2018. Appraised value of the dwelling (in Spanish). https://apps.fomento.gob.es/ (accessed March 2019)

Ministry of Health Social Services and Equality, 2017. National Catalog of Hospitals (in Spanish), Estadísticas e Información Sanitaria. https://doi.org/978-84-7670-723-4

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., 2008. Handbook of Contructing Compsoite Indicators: Methodology and user guide. https://doi.org/10.1787/9789264043466-en

Planelles, M., 2018. Spain faces a millionaire fine for purifying urban waters badly. El País.

Public Service of State Employment, 2017. Registered unemployment and contracts by municipality (in Spanish). https://www.sepe.es/HomeSepe/que-es-el-sepe/estadisticas/datos-estadisticos/municipios.html (accessed May 2021)

Rico, A., Martínez-Blanco, J., Montlleó, M., Rodríguez, G., Tavares, N., Arias, A., Oliver-Solà, J., 2019. Carbon footprint of tourism in Barcelona. Tour. Manag. 70, 491–504. https://doi.org/10.1016/ j.tourman.2018.09.012

Rioja-Andueza, I., 2019. Vitoria, from green capital of Europe to “global green city” (in Spanish). eldiario.es.

Tanguay, G.A., Rajaonson, J., Lanoie, P., 2010. Measuring the sustainability of cities : An analysis of the use of local indicators. Ecol. Indic. 10, 407–418. https://doi.org/10.1016/j.ecolind.2009.07.013

Tirado, D.A., Díez-Minguela, A., Martinez-Galarraga, J., 2016. Regional inequality and economic development in Spain , 1860 e 2010. J. Hist. Geogr. 54, 87–98. https://doi.org/10.1016/j.jhg.2016.09.005

United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. https://sdgs.un.org/2030agenda (accessed May 2021)

Universia, 2019. Spanish companies guide. https://guiaempresas.universia.es/ (accessed May 2021)

University of Murcia, 2019. ODSesiones. https://www.um.es/web/17odsesiones/proyecto/que-es (accessed March 2020)

Chapter 9: **Three key indicators for the analysis of the sustainability of urban systems**[20]

SUMMARY

In this chapter, a methodology was developed to evaluate the sustainability of urban systems with only three indicators. To do this, the methodologies Classification and Regression Trees (CART) and Random Forest, were applied over the case study considered in Chapter 8. The main goals were to identify the key indicators and to quantify the corresponding thresholds to define a sustainable city. The key indicators identified were: “woman unemployed rate”, “city unemployment rate” and “Municipal Solid Waste collected” and the corresponding thresholds are 14%, 16% and 423 kg·inhabitant^{-1}·year^{-1} respectively. In addition, the sustainability of 32 different Spanish cities was evaluated with these three indicators and thresholds to validate the achievements. According with the results, urban sustainability could be evaluated considering only three indicators with a high degree of accuracy, providing information to policy makers without the requirement of compiling a large amount of data.

[20] Based on the study: Rama, M., Andrade, E., Moreira, M.T., Feijoo, G., González-García, S., 2021. Defining a procedure to identify key sustainability indicators in Spanish urban systems: Development and Application. Sustainable Cities and Society. Vol. 70, 102919. https://doi.org/10.1016/j.scs.2021.102919.

9.1 INTRODUCTION

In the previous chapters, a methodology was developed and applied to analyze the sustainability of urban systems with 33 indicators in the case of cities or municipalities with less than 35,000 inhabitants, and with 38 indicators for cities with more than 35,000 inhabitants. This methodology turned out to be robust and useful for analyzing different urban systems of a region, a country, and could even be used considering different cities in different countries. However, this methodology requires case studies from several cities and requires a large compilation of data which is time and resource consuming. Thus, the starting hypothesis was raised: *is it possible to reduce the set of indicators to one indicator for each pillar of sustainability while maintaining the reliability and robustness?*

With the purpose of solving this hypothesis in this chapter, two analysis models were used on the case study analyzed in Chapter 8: Classification and Regression Trees (CART) and Random Forest (RF), in order to identify which were the key indicators of each of the pillars of sustainability when defining a sustainable city. Therefore, the main objective of this chapter was to develop a methodology that allows evaluating the sustainability of a city using only three indicators with the same reliability as if the methodology developed in Chapter 6 was used. In addition, once the methodology was developed, it was applied to a new case study composed of the 32 Spanish cities with more than 100,000 inhabitants that were not considered in the initial case study.

Consequently, this study has been structured in two sections: firstly, the development of the methodology divided in four stages: 1) description of the analysis models; 2) description of the case study as a baseline reference; 3) identification of key sustainability indicators; and 4) calibration of the methodology; and secondly, the application to a new sample, with the objective of determining its sustainability ranking.

9.2 MATERIALS AND METHODS

The methodology developed in this chapter consisted of two analysis models applied to a sample of 31 cities in which 38 indicators were previously measured in Chapter 8. Bearing in mind which cities were sustainable and which were not, according to the values reached in the indicators, the two analysis models predicted which indicators had the greatest predictive capacity to determine the sustainability profile of each city. Moreover, they made it possible to determine the thresholds for distinguishing a sustainable city from a non-sustainable one.

9.2.1 Description of the analysis models: CART and Random Forest

With the aim of identifying the indicators that best predict the sustainability profile of a city, two analysis models based on decision trees were used: Classification and Regression Trees (CART) and Random Forest. These analysis models have been used in different research fields to predict the behavior of a dependent variable, and to identify which independent variables that most influence this behavior. Examples of applications were predicting the electricity and gas consumption in London residences (Gassar et al., 2019) and the flood susceptibility in the vicinity of the Putna river in Romania (Costache and Tien, 2019).

The CART model is a statistical analysis that evaluates the interactions between a response variable or dependent variable (predicted variable) and the corresponding independent variables (predictor variables) (Giraldo et al., 2019; Serrano-López et al., 2018). Accordingly, it predicted the values of the response variable when the independent variables change. Thus, for example, based on a series of parameters characteristic of flooded areas, CART model could identify which of them best help to predict a flood (Costache and Tien, 2019).

Each single tree had a predictive accuracy according to the correct classification with respect to the database (Serrano-López et al., 2018). Hence, if the predicted response was ranked the same as the observed response in the database, the highest value of predictive accuracy would be reached. Thus, for cases with binary response variables – e.g. Yes or No, four possible scenarios can be identified whether the response of the analysis model coincided to the response observed in the database. In the case that both responses were “Yes”, or both responses were “No”, they were defined as true positive (TP) and true negative (TN) respectively, so that these scenarios were considered a correct classification of the analysis model. On the contrary, when the response observed in database was “Yes”, but the response of the analysis model was “No”, it should be classified as false negative (FN). Finally, false positive (FP) was identified when the response of the analysis model was “Yes” while the observed response was “No” (Hu et al., 2011). **Table 9.1** summarizes the different scenarios detailed above according to the responses obtained.

Table 9.1. Four possible scenarios according with the coincidence between the responses observed and predicted.

Observed	Predicted	
	Yes	**No**
Yes	True Positive (TP)	False Negative (FN)
No	False Positive (FP)	True Negative (TN)

In the present chapter, predictive accuracy indicated the predictive capacity of an indicator to determine whether a city was sustainable or not by considering a threshold given by the model. Therefore, with the definitions of FP and FN, these thresholds were calculated so that the number of both was the minimum possible. Consequently, the number of TP and TN should also be the maximum possible. For example, an indicator obtained three values: 15, 9 and 6 was used in a case study of several cities. When the indicator scored a value of 15, it classified 10 of the cities as FP and FN. However, when the indicator obtained a value of 9, it classified 7 cities as FP and FN. Finally, when the indicator obtained a value of 6, it classified 13 cities as FP and FN. Therefore, the analysis model set the threshold when the indicator has a value of 9 because it was the value at which the fewest cities were misclassified with respect to the original case study. Considering this, predictive accuracy was calculated following the **Equation 9.1**:

$$predictive\ accuracy = \frac{TP + TN}{n} \qquad \textbf{(Equation 9.1)}$$

Where n represents the sample size. In this sense, predictive accuracy indicated the rate of correct classifications for a given threshold. Hence, the best predictor variables were those that have the thresholds with the highest predictive capacity. The main disadvantage of this model was the loss of predictive accuracy when extrapolating the results to other cities outside the original sample. For this reason, the Random Forest model was also used in combination with CART (Serrano-López et al., 2018). Random Forest combined many classification trees, typically draws 500 bootstrap samples. It also used square root of the number of variables managed in the analysis, randomly selecting variables as candidates in each division. Both parameters can be adapted to improve the accuracy (Kanin et al., 2019).

Accuracy was estimated by the OOB error (Out of Bag error), i.e., for each bootstrap iteration and related tree, the method estimates the prediction error using data that were not in the sample. Hence, the model identified the variables out of the division that made OOB increase. Therefore, this model considered four parameters: i) number of trees (normally 500), ii) number of variables in each split, iii) estimation of the error rate and iv) estimation of accuracy (Krebs et al., 2019). Moreover, Random Forest had many advantages over other machine learnings, such as low variance due the use of many trees, low correlation between individual trees, robust error estimation and high prediction performance (Ahmed II and Pradhan, 2019). The best predictor variables in Random Forest were determined according to the highest values of Mean Decrease Accuracy (MDA) and Mean Decrease Gini (MDG). MDA determined how less accurate the model was when a variable was discarded from the model and it was calculated taking into account the OOB (Zaimes et al., 2019). MDG indicated the impurity of the model, i.e., the discriminative capacity that a variable had on the response. Accordingly, a high value of MDG, indicated a more homogeneous model (Gounaridis et al., 2019). Thus, the use of both MDA and MDG made it possible to achieve greater robustness than when only one was considered (Han et al., 2016).

The advantage of using those two models was their complementarity (Serrano-López et al., 2018). In the present study, these two models of analysis were used to identify the key indicators to define a sustainable city. Hence, the CART model established the corresponding thresholds of the key indicators which determine if a city was considered sustainable or not. Additionally, Random Forest reduces the error when the model was extrapolated to other case of studies. In this sense, the sustainability of a city can be evaluated analyzing only the key indicators provided by both models.

These models of analysis were available as packages in the calculation software R (R Core Team, 2019), which allows the graphs and trees to be plotted as result.

9.2.2 Case study as baseline reference

The case study considered as the baseline for the application of the described analysis models was based on a previous case study considered in Chapter 8 where the ranking of sustainability of a sample constituted by 31 representative Spanish cities was determined according to the evaluation of 38 mixed indicators. This sample of urban systems was made up of the capitals of each Spanish region, administratively relevant cities and those with an important historical heritage. The set of indicators consisted of social, economic and environmental indicators, as shown in **Table 9.2**.

Table 9.2. Indicators and respective codification.

Pillar	Indicator	Code
Social	High school graduate population	var001
	Number of registered gender violence cases	var002
	Women unemployed rate	var003
	Population rate at risk of poverty	var004
	People per household	var005
	Rate of population that participated in the last municipal election	var006
	Population under 16 years old	var007
	Population over 65 years old	var008
	Annual population net growth	var009
	Ratio of immigrants	var010
	Population Density	var011
	Number of leisure facilities	var012
	Number of hospital beds	var013
	Total expense in social services	var014
Economic	GDP per capita	var015
	City unemployment rate	var016
	Average household income	var017
	Number of permanent contracts signed per 1000 inhabitants	var018
	Number of businesses per 1000 inhabitants	var019
	Municipal budget per inhabitant	var020
	Non-financial total incomes	var021
	Surplus/Deficit	var022
	Indebtedness	var023
	Investment	var024
	Average rental price per m^2	var025
	Average sale price per m^2	var026
	Number of hotel places	var027

Table 9.2 (cont.). Indicators and respective codification.

Pillar	Indicator	Code
Environmental	Ratio of public/private vehicles	var028
	Ozone	var029
	NO_2	var030
	PM10	var031
	Total domestic water consumption per dwelling	var032
	Total electrical use per capita	var033
	Surface of green area	var034
	Surface of pedestrian zone	var035
	MSW collected	var036
	Non-Compliance Wastewater Treatment	var037
	Sustainability plan, participation in projects and awards	var038

In addition, each indicator was considered as an independent variable (*x*), therefore, a change in nomenclature was made as shown in **Table 9.2**. Hence, indicator 1 was identified as var001, indicator 2 as var002, etc. On the other hand, the response variable (*y*) was corresponded to an estimated score according to the sustainability of each city. Thus, a value of 1 was assigned to cities considered sustainable and 0 to non-sustainable cities, bearing in mind the results from Chapter 8. **Table 9.3** shows the selected cities in Chapter 8 and the corresponding sustainability score.

Table 9.3. Cities considered in Chapter 8 and their sustainability considering 1 as sustainable city and 0 as non-sustainable city.

Cities	Sustainability
Valencia	1
Seville	0
Zaragoza	0
Malaga	0
Murcia	0
Palma de Mallorca	0
Las Palmas de Gran Canaria	1
Bilbao	1
Alicante	0
Cordoba	0
Valladolid	1
Vigo	0
Gijon	0
L'Hospitalet de Llobregat	1
Vitoria-Gasteiz	1
A Coruña	0
Oviedo	0
Santa Cruz de Tenerife	0
Pamplona	1
Burgos	1
Albacete	0
Santander	0
Logroño	1
Badajoz	0
Huelva	0
Tarragona	0
Ourense	0
Lugo	1
Santiago de Compostela	1
Toledo	1
Pontevedra	1

Moreover, the three dimensions of sustainability (environmental, economic and social) were studied separately. In this chapter, data taken from Chapter 8 were rearranged into three new matrixes of independent variables ($x_{i,j}$), one per sustainability pillar and including all 31 rows (one per city). Each column in the matrices should correspond to a specific indicator j. Thus, the social matrix (X_{social}) should include 14 columns, the economic matrix (X_{econom}) 13, and the environmental matrix ($X_{environ}$), 11. The sustainability scores of the sample obtained in Chapter 8, i.e., the response variable (y_i), were included in the sustainability vector Y (corresponding with values shown in **Table 9.3**). This vector was made up of 31 rows and 1 column. The different matrices and sustainability vector were represented below:

$$X_{social} = \begin{pmatrix} x_{1,1} & \cdots & x_{1,14} \\ \vdots & \ddots & \vdots \\ x_{31,1} & \cdots & x_{31,14} \end{pmatrix} \qquad \text{(Social matrix)}$$

$$X_{econom} = \begin{pmatrix} x_{1,15} & \cdots & x_{1,27} \\ \vdots & \ddots & \vdots \\ x_{31,15} & \cdots & x_{31,27} \end{pmatrix} \qquad \text{(Economic matrix)}$$

$$X_{environ} = \begin{pmatrix} x_{1,28} & \cdots & x_{1,38} \\ \vdots & \ddots & \vdots \\ x_{31,28} & \cdots & x_{31,38} \end{pmatrix} \qquad \text{(Environmental matrix)}$$

$$Y = \begin{pmatrix} y_1 \\ \vdots \\ y_{31} \end{pmatrix} \qquad \text{(Sustainability vector)}$$

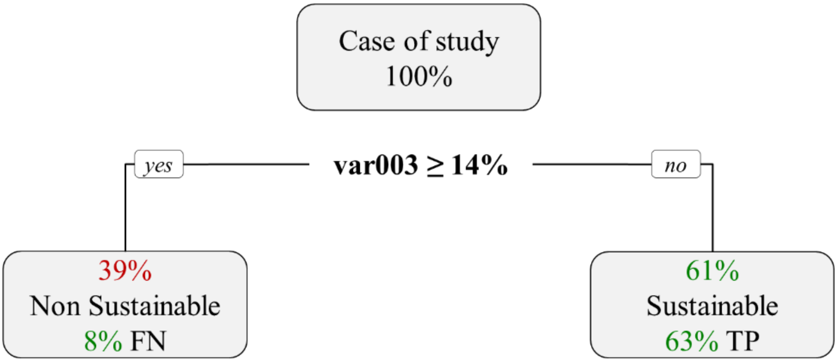
Hence, once the data corresponding to the indicators and the cities were reorganized into the matrixes defined, the analysis models were applied.

9.3 RESULTS AND DISCUSSION

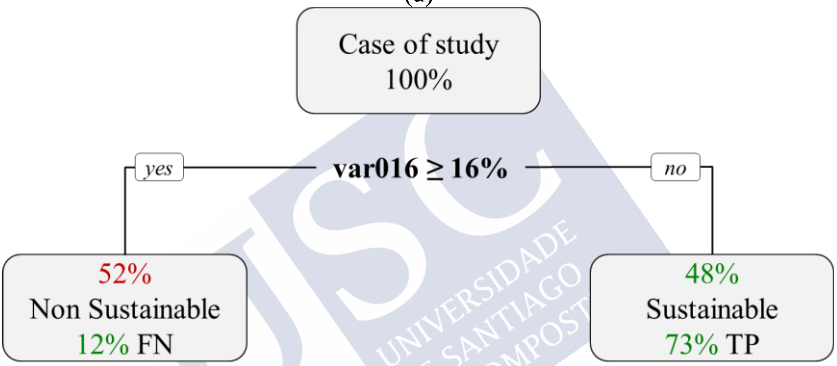
This section has been divided into three sub-sections considering the goals of this chapter. Firstly, the key indicators and corresponding thresholds resulting from the application of the analysis models were identified. Secondly, the sustainability scores of these cities were again recalculated using only the key indicators and the corresponding thresholds to calibrate the method. Finally, a new case study composed of another set of Spanish cities was assessed by applying the abovementioned indicators and thresholds.

9.3.1 Identification of key indicators and thresholds

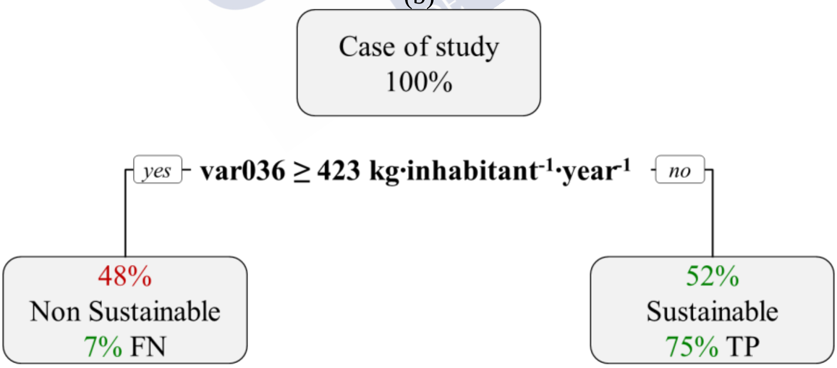
Initially, the mentioned analysis models (CART and Random Forest) were applied to the set of cities considered as starting point for identifying the best predictor variables or key indicators and sustainability values. As a result of CART, the predictor variables identified with the highest predictive accuracy were var003 (woman unemployed), var016 (city unemployment rate) and var036 (municipal solid waste - MSW collected). It should be noted that var003 was considered a social indicator, unlike var016, which was considered an economic indicator. The rationale behind this assumption was that female unemployment was considered an equality indicator that analyzes equal employment opportunities between men and women (Feleki et al., 2018). In addition, this variable was proportionally related to the female poverty rate, and a high value of this indicator could even lead to the risk of child poverty (Kiaušienė, 2015). The city unemployment rate indicator, which corresponds to var016, was considered as the percentage of unemployed persons with respect to the total active population (population aged 16 to 65 years). On the other hand, the var036 that corresponded to the MSW collected indicator, indicates the amount of waste in kg that a city dweller generates in a year. These three variables (var003, var016 and var036) were negative indicators and, consequently, a high value of these indicators negatively affected the sustainability profile of the city. Consequently, and considering the definition of false negative and false positive, the model determined the thresholds that allow the minimum number of FN and FP as explained in Section 9.2.1. Therefore, the thresholds for these key indicators were estimated as shown in **Figure 9.1**. The threshold for var003 was 14%, so that 39% of the cities analyzed presented a woman unemployed rate higher than the threshold, so they were classified by the model as non-sustainable. However, 8% of them were classified as sustainable in the case of study, so they were considered FN. 61% of the cities reported values below the threshold that the model classified as sustainable and 63% of them were identified as TP. Regarding the city unemployment rate (var016), 52% of the cities presented a value higher than 16%, of which 12% were identified as FN. Finally, 48% of the cities presented a flow of MSW collected (var036) greater than 423 $kg\cdot inhabitant^{-1}\cdot year^{-1}$, so only 7% of them were identified as FN. Moreover, in **Figure 9.1**, the percentages of cities classified as sustainable were represented in green while non-sustainable cities were depicted in red.



(a)



(b)



(c)

Figure 9.1. Single trees of the variables with the best predictive accuracy and corresponding thresholds: (a) var003 woman unemployed rate; (b) var016 city unemployment rate; (c) var036 MSW collected.

The predictive accuracy of an indicator was calculated considering the number of TP and TN identified for that indicator and according to the corresponding threshold. Hence, in the case of var003, if cities with values above 14% were classified as non-sustainable, and cities with values below 14% were classified as sustainable, 74.19% (predictive accuracy) of these cities would be correctly classified. **Table 9.4** shows the indicators with the best predictive accuracy and their respective thresholds.

Table 9.4. Indicators with the best predictive accuracy (key indicators) and the corresponding thresholds considering CART model.

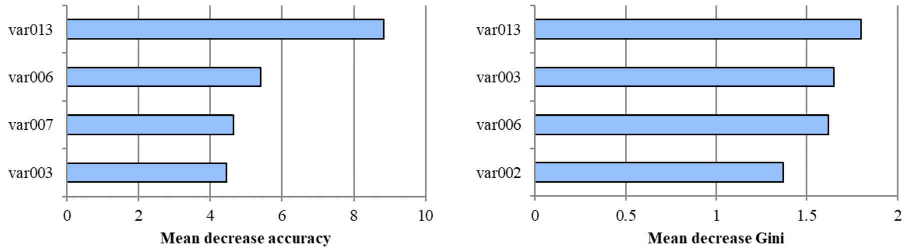
Indicator	Threshold	Units	Predictive accuracy
Woman unemployed (var003)	14	%	74.19 %
City unemployment rate (var016)	16	%	80.65 %
MSW collected (var036)	423	$kg·inhabitant^{-1}·year^{-1}$	83.87 %

The results obtained with the Random Forest model were similar to those obtained with the CART model. **Table 9.5** shows the number of decision trees built and the number of variables considered by the model to obtain the lowest OOB error values. Nevertheless, the values of the predictive accuracy were lower than those obtained with CART. While CART considered all the variables in a single tree, Random Forest considered different groups of variables and many trees. In this sense, the number of the variables for each tree was calculated by the model to obtain the minimum OOB error. In this case, the number of variables selected was 6 for social and economic indicators and 3 for environmental indicators. As a result, the predictive accuracy of the Random Forest model was lower than that obtained using the CART model. The rationale behind this result was that the error increases when not all predictor variables were used. Nevertheless, when extrapolating to other case studies, the error generated with Random Forest was less than that generated with CART (Ahmed II and Pradhan, 2019).

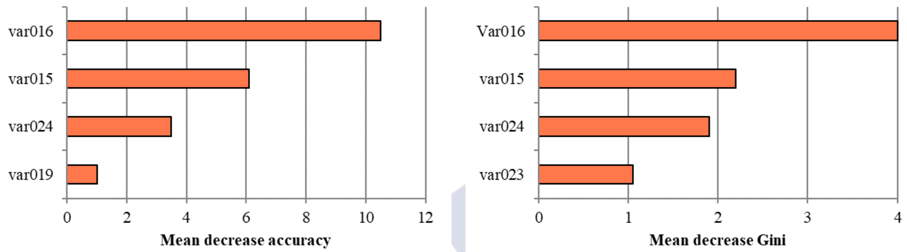
Table 9.5. Parameters used in Random Forest model for social, economic and environmental indicators.

	Social	Economic	Environmental
Number of decision trees	500	450	500
Number of variables at each split	6	6	3
OOB error	29.03%	35.48%	22.58%
Predictive accuracy	70.97%	64.52%	77.42%

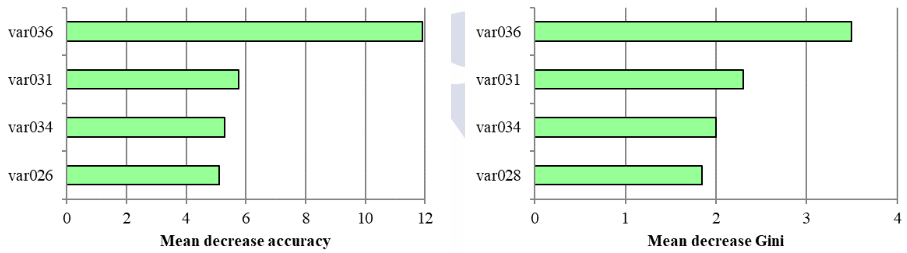
The indicators with the highest predictive accuracies were determined according to MDA and MDG. **Figure 9.2** shows the four main variables with the best predictive capacity, based on the best values of MDA and MDG for each dimension of sustainability analyzed. In line with the CART model, city unemployment rate (var016) and MSW collected (var036) were among the indicators with the best predictive capacity in the economic and environmental pillars, respectively. In the case of social indicators, number of hospital beds (var013) reported the highest predictive capacity in terms of MDA. On the other hand, the MDG value of var013 was closely followed by woman unemployed rate (var003) and rate of population that participated in the last municipal election (var006). With respect to the economic and environmental indicators, the difference was much more noticeable when attributing the highest predictive capacities to city unemployment rate and MSW collected for the economic and environmental indicators, respectively as displayed in **Figure 9.2**. The main difference between the results obtained with CART and Random Forest, was that in the first model, the best predictor variable corresponding to the social indicators was woman unemployed rate and in Random Forest, this indicator was preceded by number of hospital beds. Finally, only one of these two indicators was selected based on their joint contribution with the other selected indicators (var016 and var036) according to general predictive capacity once the model was calibrated.



(a)



(b)



(c)

Figure 9.2. Mean decrease accuracy and mean decrease Gini of the four best predictor variables of each sustainability dimension: (a) social variables, (b) economic variables and (c) environmental variables.

The thresholds corresponding to the key indicators previously identified by MDA and MDG were represented with partial dependence plots. Thus, **Figure 9.3** displays the graphs for the indicators number of hospital beds (var013), city unemployment rate (var016) and MSW collected (var036) to determine their thresholds. Furthermore, woman unemployed rate (var003) was depicted to compare the thresholds obtained with the Random Forest and CART models. Accordingly, the value taken by the indicator at the point where the trend of the slope changes was considered as threshold since this shift constitutes a change of the sustainability category. In the case of the indicator woman unemployed rate (var003), the change in trend was observed from approximately the value 0.14; for MSW collected, it was observed over the value 420. In the graph corresponding with city unemployment rate two changes in trend were observed as displayed in **Figure 9.3c**, one between values 0.14 and 0.15, and another one very close to the value 0.16, which was more pronounced. Bearing in mind the results of CART, these values were very similar. For the indicator of number of hospital beds, the threshold identified was observed at a value of 9. Moreover, the clear changes in trend of the partial dependence graph indicated a good discriminatory capacity of these variables.

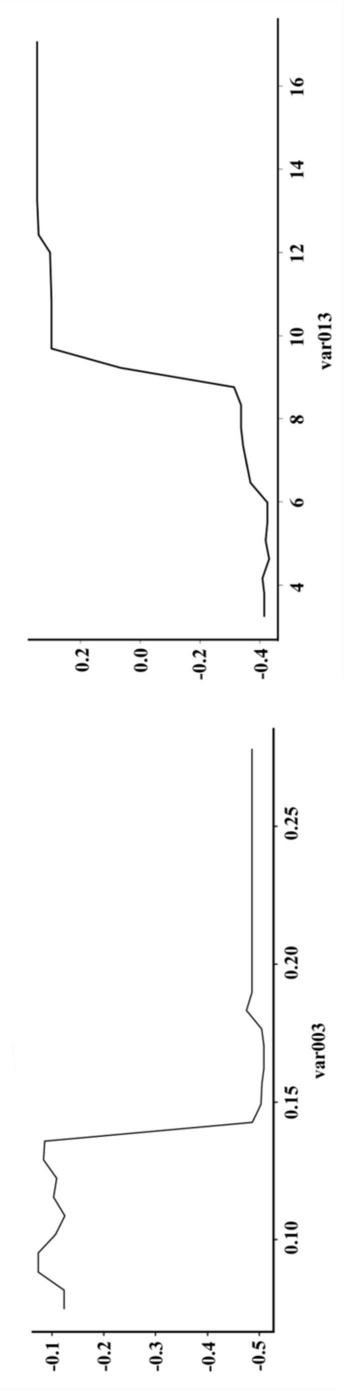
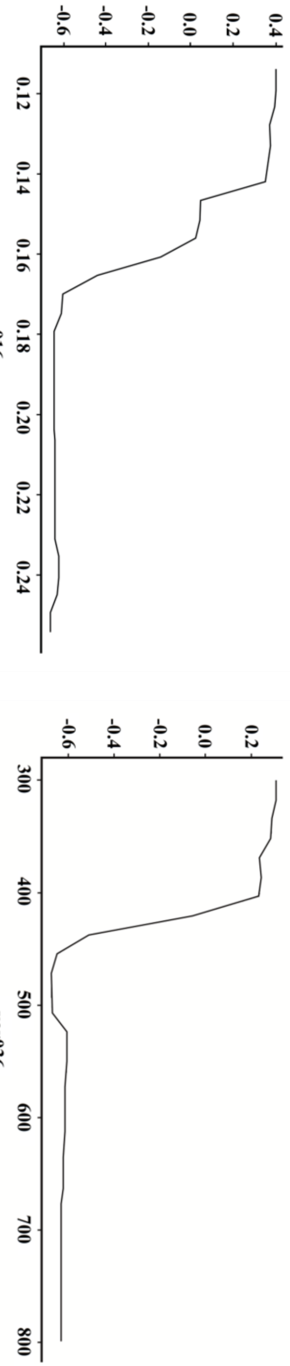


Figure 9.3. Partial dependence plots shown as sustainability changes based on predictors variables: (a) var003, (b) var013.



(c) (d)

Figure 9.3 (cont.). Partial dependence plots shown as sustainability changes based on predictors variables: (c) var016, (d) var036.

9.3.2 Calibration of the method

Once the indicators with the best predictive accuracy resulting from the application of the CART and Random Forest models have been identified, the method has been calibrated on the same case study calculating the general predictive accuracy. These selected indicators were woman unemployed rate, city unemployment rate and MSW collected, corresponding to variables var003, var016 and var036 in the case of the CART model, and number of hospital beds, corresponding to var013, var016 and var036 in the case of the Random Forest model. In this sense, the sustainability of the cities was analyzed with the values of the estimated thresholds for the selected key indicators under each analysis model and then the findings were compared with those obtained in Chapter 8. Therefore, the established thresholds were those resulting from the CART model. Furthermore, as a criterion for defining a sustainable city, it has been established that it should not exceed any of the defined thresholds. In addition, the overall predictive accuracy was calculated as indicated in Equation 1.

Considering the variables var003, var016 and var036, three FN and one FP were identified, so the predictive capacity was 87%. On the contrary, considering variable var013 instead of variable var003, the predictive capacity was reduced to 74%.

Consequently, the best set of key indicators, with the best predictive accuracy, was composed of woman unemployed rate (var003), city unemployment rate (var016) and MSW collected (var036). The use of these three indicators were considered frequently in many research studies and in the composition of several indices (Feleki et al., 2018; Gonzalez-Garcia et al., 2018; Tanguay et al., 2010) which involved that they were relevant indicators and provide greater robustness to the results. **Table 9.6** shows the corresponding values of these key indicators, and the sustainability of each city defined in the case of study and the predicted sustainability considering the respective thresholds of the predictor variables. In addition, cities in which both definitions of sustainability coincide were also shaded. According to **Table 9.6**, 27 cities have been correctly classified. Only the cities of Zaragoza, Las Palmas, Bilbao and Lugo did not have a coincidence between the sustainability definitions of both methods.

Table 9.6. Values of the variables var003, var016 and var036 for each city included in the case study, and their corresponding sustainability values defined by the case of study and the predicted sustainability.

City	var003	var016	var036	Sustainable City in Chapter 8	Predicted Sustainable city
Valencia	13.3	16.0	366	Yes	Yes
Seville	18.0	22.9	481	No	No
Zaragoza	10.9	12.6	367	No	Yes
Malaga	18.7	24.2	509	No	No
Murcia	12.7	15.9	486	No	No
Palma de Mallorca	7.5	14.7	744	No	No
Las Palmas de Gran Canaria	18.2	24.0	397	Yes	No
Bilbao	13.7	15.6	528	Yes	No
Alicante	14.2	18.9	439	No	No
Cordoba	19.7	23.0	461	No	No
Valladolid	12.6	15.8	327	Yes	Yes
Vigo	14.5	18.6	414	No	No
Gijon	16.6	19.6	799	No	No
L'Hospitalet de Llobregat	9.1	11.4	372	Yes	Yes
Vitoria-Gasteiz	13.2	11.9	419	Yes	Yes
A Coruña	12.3	16.3	416	No	No
Oviedo	10.0	16.2	799	No	No
Santa Cruz de Tenerife	17.9	25.4	699	No	No
Pamplona	12.4	12.9	400	Yes	Yes
Burgos	9.9	12.5	412	Yes	Yes
Albacete	15.5	19.2	425	No	No
Santander	11.1	16.8	496	No	No
Threshold	**14.0**	**16.0**	**423**		

Table 9.6 (cont.). Values of the variables var003, var016 and var036 for each city included in the case study, and their corresponding sustainability values defined by the case of study and the predicted sustainability.

City	var003	var016	var036	Sustainable City in Chapter 8	Predicted Sustainable city
Logroño	10.7	13.5	407	Yes	Yes
Badajoz	18.2	22.4	456	No	No
Huelva	27.8	25.4	495	No	No
Tarragona	10.1	14.8	502	No	No
Ourense	14.1	17.5	419	No	No
Lugo	11.6	16.5	419	Yes	No
Santiago de Compostela	10.2	13.7	421	Yes	Yes
Toledo	11.5	14.5	300	Yes	Yes
Pontevedra	12.9	14.5	419	Yes	Yes
Threshold	**14.0**	**16.0**	**423**		

In the case of Zaragoza, the values of the three indicators denote that Zaragoza could be a sustainable city, so this result was classified as a FP, because in the case study, Zaragoza was ranked as non-sustainable city. The other cities have been classified as a FN, due were considered sustainable in the case study, but the model predicted that these cities were not sustainable using only the three indicators. Nevertheless, the predictive capacity achieved by the model was in line with other studies (Hu et al., 2011; Li et al., 2010), so it was considered a good result. In addition, considering the results in terms of sustainable cities, the case study categorized 42% of the cities as sustainable. However, the percentage of the sustainable cities decreased to 35% considering the results obtained with the three indicators. This fact made the second method more restrictive.

9.3.3 Application to a new case study

Once the methodology was developed, it was applied to a new sample of urban systems. Thus, in this section the sustainability of a new set of cities in accordance with the set of the three indicators identified in the previous sections was predicted. In order to define the new case study and select the cities, the population size has been taken as a reference. Accordingly, all Spanish cities with more than 100,000 inhabitants, which have not been studied previously, have been chosen. Therefore, considering these criteria, 32 cities with populations between 101,486 and 234,765 inhabitants were selected. In all the cities selected, the female population exceeds 50% of their population, reaching almost 55% in the cases of León and Salamanca. Moreover, the population of most of these 32 cities grew in the period between 2008 and 2018 between 0 and 6%, and even 7 cities (Marbella, Girona, Mataró, Alcobendas, Getafe, Parla and Torrejon de Ardoz) raised more than 6%. However, the population of 6 of the cities decreased between 0 and 7% between 2008 and 2018, and three of them lost more than 7% of their population in the same period (Cádiz, León and Salamanca) (INE, 2020). As for the level of education, only the population of 5 cities exceeded 9% of people with no education in 2011 (Badalona, Mataro, Santa Coloma de Gramenet, Leganes and Elche) (EsriEspaña, 2018). Finally, the income level of these cities was between 17,500 and 24,000 $€\cdot person^{-1}$ of disposable income in 2018, except in the cases of Girona and Donostia/San Sebastian, which were 25,965 € and 25,577 $€\cdot person^{-1}$ respectively, and in the case of Alcobendas, which was the city with the highest income, exceeding 45,580 $€\cdot person^{-1}$ (Eustat, 2018; Expansion, 2018).

Accordingly to the indicators previously identified as key indicators, the data sources used for the collection of the required information were the website of Spanish statistics institute (INE, 2019), different regionals statistics of Andalusia (Instituto de estadística y cartografía de Andalucía, 2019), Basque Country (Eustat, 2019), Canary Islands (ISTAC, 2019), Castile and Leon (Junta de castilla y Leon, 2019), Catalonia (Idescat, 2019), Madrid (Instituto de estadística de la Comunidad de Madrid, 2019) and Valencia (PEGV, 2019). The data regarding unemployed woman rates have been collected from the Spanish public employment service (SEPE, 2020), and the general unemployment rate from the observatory on-line datosmacro (Expansion, 2019). **Table 9.7** shows the 32 cities selected and the data collected corresponding to each indicator. Most of the cities were located in the most populated regions of Spain: Madrid, Catalonia and Andalusia due to the influence of cities such as Madrid and Barcelona, and in the case of Andalusia due to the available agricultural resources (Gómez-Losada et al., 2019; Ojo et al., 2019; Rico et al., 2019). In terms of sustainability, 31% of the cities included in the group were identified as sustainable, and all of them were located close to the two largest Spanish cities: Madrid and Barcelona. Moreover, there were 13 cities that overpass the threshold of woman unemployed rate, 15 cities exceeded the threshold of city unemployment rate and 18 cities overtaken the MSW collection threshold. Considering the social and economic indicators, 46% of the cities that surpass the established thresholds were from the Autonomous Community of Andalusia. This fact shows that regional labor policies must be implemented to ensure that both indicators were reduced to reach the threshold. In addition, 56% of the cities studied exceed the threshold defined for the indicator of MSW collected. Consequently, national policies on waste collection should be improved.

Table 9.7. Indicators data for the new case of study and the corresponding sustainability value.

City	Region	Woman Unemployed rate (2017)	Unemployment rate (2017)	MSW Collected (2016)	Sustainability
Alcala de Henares	Madrid	11.9	12.4	382	Yes
Alcobendas	Madrid	07.4	08.2	382	Yes
Alcorcon	Madrid	11.6	11.7	382	Yes
Algeciras	Andalusia	20.1	28.7	557	No
Almeria	Andalusia	17.7	19.9	472	No
Badalona	Madrid	11.2	13.1	420	Yes
Barakaldo	Basque Country	13.6	14.7	528	No
Cadiz	Andalusia	19.1	28.9	557	No
Cartagena	Murcia	14.3	18.5	472	No
Castellon de la Plana	Valencia	15.0	17.4	446	No
Donostia/San Sebastian	Basque Country	08.5	9.0	548	No
Elche	Valencia	20.8	24.9	446	No
Fuenlabrada	Madrid	12.4	12.3	382	Yes
Getafe	Madrid	11.5	11.6	382	Yes
Girona	Catalonia	07.8	11.0	456	No
Granada	Andalusia	16.0	22.3	475	No

Table 9.7 (cont.). Indicators data for the new case of study and the corresponding sustainability value.

City	Region	Woman Unemployed rate (2017)	Unemployment rate (2017)	MSW Collected (2016)	Sustainability
Jaen	Andalusia	15.1	16.1	423	No
Jerez de la Frontera	Andalusia	23.9	33.0	557	No
Leganes	Madrid	11.9	12.6	382	Yes
Leon	Castilla and Leon	12.9	18.8	422	No
Lleida	Catalonia	8.9	13.2	445	No
Marbella	Andalusia	11.6	19.1	548	No
Mataro	Catalonia	12.8	14.7	460	No
Mostoles	Madrid	11.8	12.4	382	Yes
Parla	Madrid	14.3	14.8	382	No
Reus	Catalonia	10.9	16.8	438	No
Sabadell	Catalonia	10.8	12.5	427	No
Salamanca	Castilla and Leon	15.0	20.3	400	No
San Cristobal de la Laguna	Canary Islands	17.0	23.7	592	No
Santa Coloma de Gramenet	Catalonia	11.7	14.0	380	Yes
Telde	Canary Island	20.2	24.9	592	No
Torrejon de Ardoz	Madrid	12.7	12.6	382	Yes

In addition, there were 11 cities whose values exceed the thresholds of the three key indicators, most of them located in the south of the country, i.e., in the regions of Andalusia, Canary Islands and Murcia. These results were in line with another study available in the literature which have reported a high poverty rate in the south of the country (Ais Group, 2016). **Figure 9.4** and **Figure 9.5** details the location of the 32 cities analyzed, classified in colors considering the number of indicators that exceed the corresponding thresholds. Therefore, cities marked in green were the cities considered as sustainable; in yellow, cities were indicated with only one indicator that exceeds the threshold; in orange, the cities that had two indicators that exceed the thresholds, and finally, in red those cities in which the three indicators had values above the thresholds. Moreover, in black, Madrid and Barcelona as the largest cities in Spain were pointed out.

Thus, the differences between the north and the south of the country were remarkable. According to the results, the presence of large cities in the vicinity could have a positive effect on the nearest cities in terms of sustainability. This is an important point to share, since if a large city establishes social, economic and environmental measures towards sustainability, the surrounding cities or urban systems could be positively affected to encourage these measures. With this hypothesis in mind, large cities should be encouraged to adopt sustainable development measures so that surrounding cities are positively affected. In addition, large cities usually have more resources to implement sustainable improvement plans and actions, which would involve a smaller city or even a small town nearby. However, this phenomenon should be investigated further. In addition, there were differences in terms of sustainability between the south and the north of the country. In part, this was due to the high total unemployment rate in southern Spain. As a result, the poverty rate and inequality were also high in these regions.

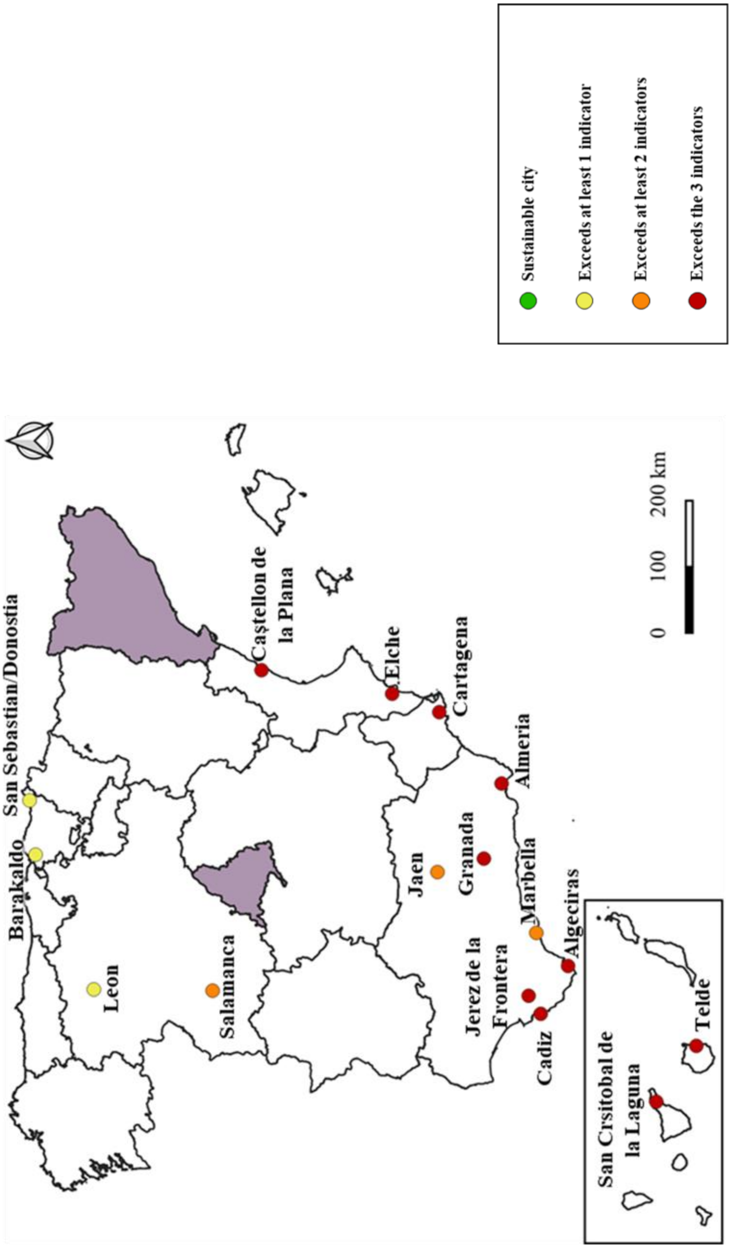


Figure 9.4. Spatial distribution of the cities selected for analysis and sustainability except cities located in the regions of Madrid and Catalonia (in purple).

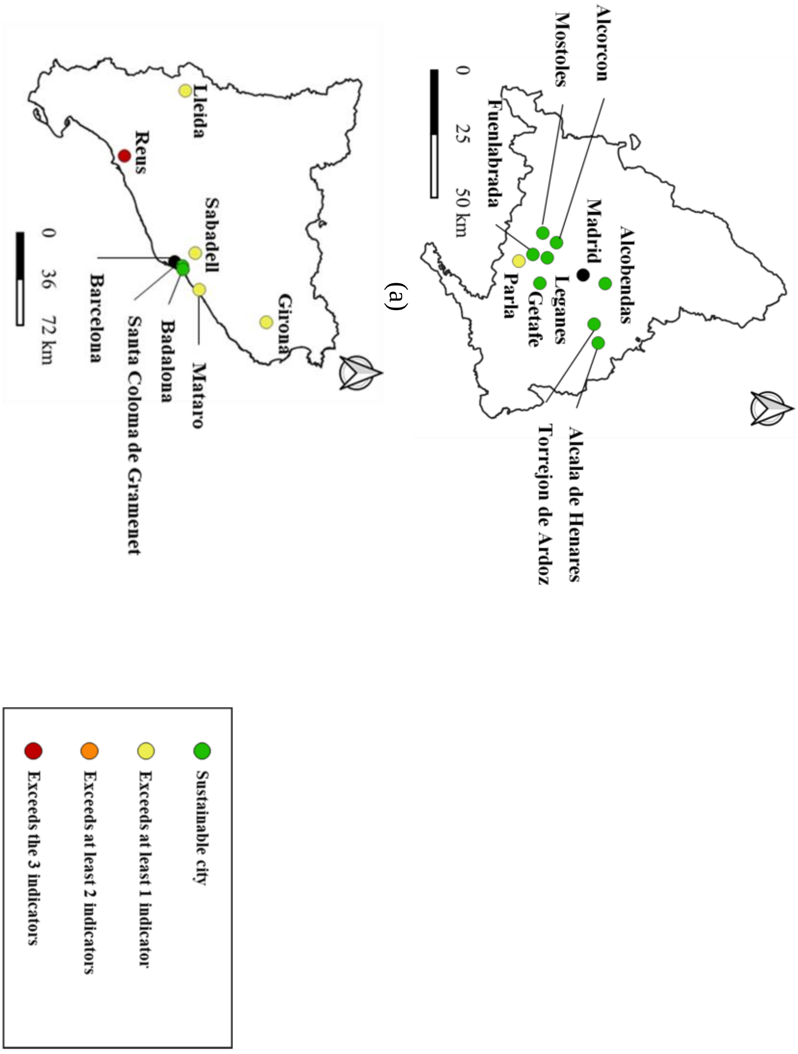


Figure 9.5. Spatial distribution of the cities and sustainability rate located in the regions of (a) Madrid and (b) Catalonia.

The sustainability of these 32 cities was predicted using three indicators, but do these results correspond to real situation? There are no studies that consider the same list of selected cities as those considered in this case study. However, the method developed in this study was calibrated, obtaining 87% overall accuracy. In other words, using these 3 key indicators with the corresponding thresholds, the same results were obtained at 87% accuracy as those using the 38 indicators. This implies that the developed method had high reliability.

9.4 CONCLUSIONS

The methodology developed in Chapter 6 requires the compilation of a large amount of data, which is therefore time and resource consuming. So, this chapter proposes a methodology that allows predicting the sustainability of a Spanish city based on three key indicators with an overall accuracy of 87%. Hence, the method developed allows a quick analysis of the sustainability of urban systems and it can be adapted to other countries and it could be applied on a global scale. Furthermore, this methodology can be used to monitor the sustainability of cities. In this way, trends can be observed within the same city and it can be used by policy makers, since it is very simple to apply and does not require a large compilation of data. However, for a more detailed and in-depth analysis of an urban system, it is advisable to use a methodology that considers more indicators, such as the one developed and proposed in Chapter 6. Accordingly, this method is recommended as initial analysis in which policy makers can identify weaknesses or strengths, but to design plans and measures that improve the sustainability of a city, an in-depth analysis must be carried out.

9.5 REFERENCES

Ahmed II, J.B., Pradhan, B., 2019. Spatial assessment of termites interaction with groundwater potential conditioning parameters in

Ke ffi , Nigeria. J. Hydrol. 578, 124012. https://doi.org/10.1016/j.jhydrol.2019.124012

Ais Group, 2016. Spanish poverty town to town (in Spanish). https://www.ais-int.com/datos-sociodemograficos-economicos-habits-municipios/es/ (accessed May 2019)

Costache, R., Tien, D., 2019. Spatial prediction of flood potential using new ensembles of bivariate statistics and arti fi cial intelligence : A case study at the Putna river catchment of Romania. Sci. Total Environ. 691, 1098–1118.

EsriEspaña, 2018. Municipalities of Spain. Level of studies. Census2011 (in Spanish).

Eustat, 2019. Statistic Institute of Basque Country (in Spanish). http://www.eustat.eus/indice.html (accessed May 2021)

Eustat, 2018. Basque Institute of Statistics. Average personal income of the C.A. of the Basque Country by territorial area, according to sex and type of income (euros) (in Spanish). https://www.eustat.eus/ (accessed May 2021)

Expansion, 2019. Unemployment by municipalities: Spain (in Spanish). https://datosmacro.expansion.com/paro/espana/municipios (accessed May 2021)

Expansion, 2018. Rent by municipalities: Spain (in Spanish). https://datosmacro.expansion.com/mercado-laboral/renta/espana/municipios/ (accessed May 2021)

Feleki, E., Vlachokostas, C., Moussiopoulos, N., 2018. Characterisation of sustainability in urban areas: An analysis of assessment tools with emphasis on European cities. Sustain. Cities Soc. 43, 563–577. https://doi.org/10.1016/j.scs.2018.08.025

Gassar, A.A.A., Yun, G.Y., KIm, S., 2019. Data-driven approach to prediction of residential energy consumption at urban scales in London. Energy 187, 115973. https://doi.org/10.1016/

j.energy.2019.115973

Giraldo, M.A., Dark, S., Pendleton, P., Stein, E.D., Mazor, R., Andreas, J., 2019. Environmental predictors of stream flow in semi-arid watersheds for biological assessments. Ecol. Indic. 104, 429–438. https://doi.org/10.1016/j.ecolind.2019.05.019

Gómez-Losada, Á., Santos, F.M., Gibert, K., Pires, J.C.M., 2019. A data science approach for spatiotemporal modelling of low and resident air pollution in Madrid (Spain): Implications for epidemiological studies. Comput. Environ. Urban Syst. 75, 1–11. https://doi.org/10.1016/j.compenvurbsys.2018.12.005

Gonzalez-Garcia, S., Manteiga, R., Moreira, M.T., Feijoo, G., 2018. Assessing the sustainability of Spanish cities considering environmental and socio-economic indicators. J. Clean. Prod. 178, 599–610. https://doi.org/10.1016/j.jclepro.2018.01.056

Gounaridis, D., Chorianopoulos, I., Symeonakis, E., Koukoulas, S., 2019. A Random Forest-Cellular Automata modelling approach to explore future land use / cover change in Attica (Greece), under different socio- economic realities and scales. Sci. Total Environ. 646, 320–335.

Han, H., Guo, X., Yu, H., 2016. Variable Selection Using Mean Decrease Accuracy And Mean Decrease Gini Based on Random Forest. 2016 7th IEEE Int. Conf. Softw. Eng. Serv. Sci. 219–224. https://doi.org/10.1109/ICSESS.2016.7883053

Hu, W., Leary, R.A.O., Mengersen, K., Choy, S.L., 2011. Bayesian Classification and Regression Trees for Predicting Incidence of Cryptosporidiosis 6, 1–8. https://doi.org/10.1371/journal.pone.0023903

Idescat, 2019. Estatistic Institute of Catalonia (in Spanish). https://www.idescat.cat/?lang=es (accessed May 2021)

INE, 2020. Statistics National Institute. Official population figures resulting from the revision of the Municipal Register as of January 1 (in Spanish).

https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736177011&menu=resultados&idp=1254734710990 (accessed May 2021)

INE, 2019. National statistic Institute (in Spanish). https://www.ine.es/index.htm (accessed May 2021)

Instituto de estadística de la Comunidad de Madrid, 2019. Statistic Institute of the region of Madrid. http://www.madrid.org/iestadis/ (accessed May 2021)

Instituto de estadística y cartografía de Andalucía, 2019. Statistics and cartography Institute of Andalusia (in Spanish). https://www.juntadeandalucia.es/institutodeestadisticaycartografia/ (accessed May 2021)

ISTAC, 2019. Statistic Institute of Canary Islands (in Spanish). http://www.gobiernodecanarias.org/istac/ (accessed May 2021)

Junta de castilla y Leon, 2019. Statistic institute of Castilla and Leon (in Spanish). https://estadistica.jcyl.es/web/es/estadistica.html (accessed May 2021)

Kanin, E.A., Osiptsov, A.A., Vainshtein, A.L., Burnaev, E. V, 2019. A predictive model for steady-state multiphase pipe flow : Machine learning on lab data. J. Pet. Sci. Eng. 180, 727–746. https://doi.org/10.1016/j.petrol.2019.05.055

Kiaušienė, I., 2015. Comparative assessment of women unemployment and poverty in European Union. Intelekt. Ekon. 91–101.

Krebs, M.A., Reeves, M.C., Baggett, L.S., Service, U.F., Mountain, R., Ave, E.B., States, U., 2019. Predicting understory vegetation structure in selected western forests of the United States using FIA inventory data. For. Ecol. Manage. 448, 509–527. https://doi.org/10.1016/j.foreco.2019.06.024

Li, H., Sun, J., Wu, J., 2010. Predicting business failure using classification and regression tree : An empirical comparison with popular classical statistical methods and top classification mining methods. Expert Syst. Appl. 37, 5895–5904. https://doi.org/10.1016/j.eswa.2010.02.016

Ojo, O.O., Zigan, S., Orchard, J., 2019. Advanced Technology Integration in Food Manufacturing Supply Chain Environment : Pathway to Sustainability and Companies ' Prosperity. 2019 IEEE Technol. Eng. Manag. Conf. 1–7.

PEGV, 2019. Statistics of Region of Valencia (in Spanish). http://pegv.gva.es/es (accessed May 2021)

R Core Team, 2019. R: A Language and Environment for Statistical Computing.

Rico, A., Martínez-Blanco, J., Montlleó, M., Rodríguez, G., Tavares, N., Arias, A., Oliver-Solà, J., 2019. Carbon footprint of tourism in Barcelona. Tour. Manag. 70, 491–504. https://doi.org/10.1016/j.tourman.2018.09.012

SEPE, 2020. Public Service of State Employment. Registered unemployment and contracts by municipalities (in Spanish). https://www.sepe.es/HomeSepe/que-es-el-sepe/estadisticas/datos-estadisticos/municipios.html (accessed May 2021)

Serrano-López, A.L., Freire-Chaglla, S.A., Espinoza-Figueiroa, F.E., Andrade-Tenesaca, D.S., Villafuerte-Pucha, M.E., 2018. Modeling of Tourist Profiles with Decision Trees in a World Heritage City : The Case of Cuenca (Ecuador). Tour. Plan. Dev. 0, 1–21. https://doi.org/10.1080/21568316.2018.1501731

Tanguay, G.A., Rajaonson, J., Lanoie, P., 2010. Measuring the sustainability of cities : An analysis of the use of local indicators. Ecol. Indic. 10, 407–418. https://doi.org/10.1016/j.ecolind.2009.07.013

Zaimes, G.N., Gounaridis, D., Symenonakis, E., 2019. Assessing the impact of dams on riparian and deltaic vegetation using remotely-sensed vegetation indices and Random Forests modelling 103, 630–641.

Chapter 10: **Towards a sustainable tourism: Evaluating the impact of tourism in Santiago de Compostela**[21]

SUMMARY

A sustainable city implies socio-economic characteristics that allow citizens to maintain a certain quality of life. However, the effect of overtourism in some tourist cities negatively affects to the community. In this chapter, a methodology was developed to analyze how tourism affects the way of life of residents in Santiago de Compostela. Hence, a set of indicators was created based on surveys carried out among the three groups involved in the tourism sector: citizens, traders and visitors. Finally, this set of indicators was aggregated to a sustainability score on a scale of 1 to 10. The results show a sustainability score of 6.84, and the main weak points were the mobility of the residence from citizens to peripheral areas, and the change of the offer by the commerce promoted by tourism. Consequently, this methodology is useful for policy makers when making decisions and propose actions to foster sustainable tourism.

[21] Based on manuscript: Manuel Rama, Emilio Carral, Sara González-García, Elías Torres Feijó, Maria Luisa del Rio, María Teresa Moreira, Gumersindo Feijoo. "Balance between Hosts and Guests: the key to sustainable tourism in a heritage city". Tourism Management Perspectives. Submitted to the Journal.

10.1 INTRODUCTION

The Agenda 2030 action plan established by the United Nations in 2015, defined 17 Sustainable Development Goals (SDGs) to be achieved by 2030. This action plan, in which all members committed to meet these objectives, contains, among others, a specific goal focused on making cities and human settlements inclusive, safe, resilient and sustainable. It is the SDG number 11 and is entitled Sustainable cities and Communities (United Nations, 2015). This goal implies that policymakers must not only act on the environmental impacts of cities, but also ensure the social and economic well-being of their citizens. Consequently, the main function of a city should be to be able to maintain or improve the quality of life of its residents (Marans, 2015).

City tourism is a sector that has been growing since the 1960s, with an increase in travel to cities of 82% between 2007 and 2014 (Postma et al., 2017). In Spain, the tourism sector contributed about 12% to its GDP, being one of the most important sectors (OECD, 2020). The arrival of tourism in a city can be beneficial both socially and economically (increase in services and supply, economic growth of the city, etc.), but in excess it can also be one of the driving factors that can affect the quality of life of its citizens (Biagi et al., 2020; López Pena et al., 2020; Torres Feijó et al., 2020). Therefore, some researchers have studied the consequences of overtourism in cities, and how it affects the lives of their residents. Overtourism is a problem that affects several European cities such as Barcelona, Seville or Venice (Claudio et al., 2018). The way in which this phenomenon can affect the quality of life of a city can be evidenced in several ways. For example, in Venice, the massive use of boats in the canals damages the stability of the city's buildings (Trancoso González, 2018). In Seville, the concentration of tourism in its old city displace citizens to other areas (Diaz-Parra and Jover, 2021). In addition, excessive tourism creates feelings of rejection among citizens in relation to visitors (López Pena et al., 2020; Ramos and Mundet, 2020; Torres Feijó et al., 2020). Moreover, in economic terms, cities with large tourist flows and with a strong economic dependence on tourism, may have major economic problems when external factors cause tourism to fall such as the economic crisis or the recent pandemic caused by COVID-19 (Cristiano and Gonella, 2020).

The evaluation of the impact of tourism in cities through indicators has been used to determine how the city and citizens are affected by tourism and to provide information to design sustainable tourism strategies and avoid overtourism (Biagi et al., 2020; Choi et al., 1999; Stylidis et al., 2014; Tsaur et al., 2006). The dynamics followed in this type of work has been to determine a series of indicators, obtaining the corresponding information through specifically designed surveys. These surveys can be addressed to citizens (Biagi et al., 2020; Stylidis et al., 2014), tourists (Choi et al., 1999), or even other stakeholders such as the resource administration as detailed by Tsaur et al. (2006). However, one of the main deficiencies in this field of research is the evaluation of sustainability considering not only residents or tourists separately, but also analyzing these two groups together.

The purpose of this chapter was to develop a methodology that allows to know how tourism affects the way of life of the citizens of Santiago de Compostela, one of the most important touristic cities in Spain, which is the destination of the St. James Way[22]. This methodology was based on the use of multiple socioeconomic indicators selected from a specific survey of three population groups involved: citizens, traders and tourists. The main novelty of the study developed in this chapter was that, for the first time, the behavior of these interrelated actors was integrated to determine the impact and consequences of tourism in this historical city. Moreover, this methodology could be applied to other cities with similar characteristics (growing tourism, relevance of its historical area, etc.) to assess the impact of tourism on the well-being of its residents. On the other hand, it could also provide policy makers with valuable

[22] https://www.caminodesantiago.gal/en

information that would be useful for proposing actions towards a more integrated and sustainable tourism.

10.2 MATERIALS AND METHODS

10.2.1 Case Study

Santiago de Compostela is a city located in the region of Galicia (NW Spain) **(Figure 10.**). According to the number of inhabitants, Santiago de Compostela is the fifth most populated city in Galicia with 97,260 inhabitants registered in 2019 (IGE, 2020). It is the Galician city with the highest GDP per inhabitant with 37,508 € per capita in 2018 and the service sector is the largest contributor to its economy with more than 80% (IGE, 2019a). The large flow of tourists visiting the city is behind these figures and highlights the important role that tourism plays in the local economy. **Figure 10.1** represents the boundaries of the municipality composed of the rural area and the city, which is distributed in three subareas: Old Town (Historical Center), Industrial and Residential areas.

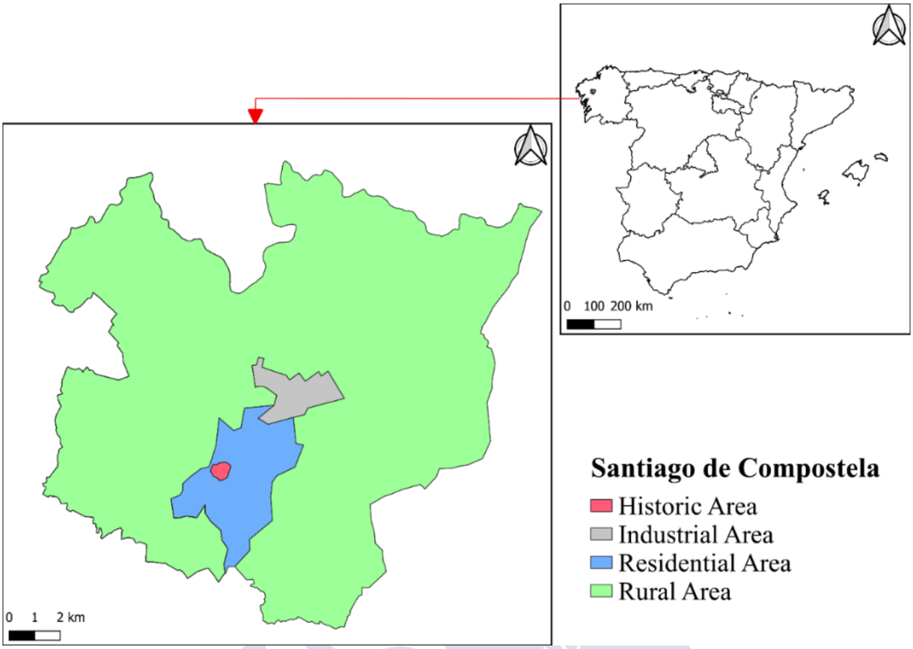


Figure 10.1. Location of Santiago de Compostela in Spain and distribution of the different areas of the municipality.

Three main reasons support the growing tourism in the city: first, the city was declared a UNESCO World Heritage Site in 1985[23]. Secondly, it is a historic university city with one of the oldest universities in Spain (founded in 1495), which contributes to the mobility of students and researchers and, consequently, to the celebration of congresses and different related businesses. Finally, Santiago de Compostela is the final destination of the St. James Way, one of the most important pilgrimage routes in Europe (Lopez et al., 2019).

Since 1993, the regional government promoted the St. James Way as a tourist destination, considerably increasing the arrival of pilgrims, especially in the Holy Year or "*Xacobeo*" (celebrated the year when July 25th is Sunday). Thus, while the number of pilgrims in the

[23] https://whc.unesco.org/en/list/347

"*Xacobeo*" year 1993 was 99,436, the figure rose to 327,378 in 2018 (which was not a "*Xacobeo*" year). In addition, not only the arrival of pilgrims to the city increased, but the number of tourists visiting the city also increased, reaching a peak of 842,895 visitors in 2017 (68% more than in 2005) (IGE, 2019b).

Considering this economic growth in the tourism sector, a proportional growth in the size of the city could be expected. However, while other Galician cities with a similar size compared to Santiago de Compostela, such as Lugo and Pontevedra, grew in population size by 13% and 12% respectively in the period between 1998 and 2018, the population of Santiago de Compostela only grew by 3% in the same period (IGE, 2020). However, this growth was evident in some municipalities bordering the city such as Oroso, Teo and Ames, which increased their population by 57%, 33% and 120% respectively, indicating that their population more than doubled in the period between 1998 and 2018 (IGE, 2020). Thus, from these data, some questions arise in this regard: *why do citizens prefer to reside in peripheral cities? Is tourism related to this mobilization of citizens?* Thus, the starting hypothesis was that the tourist pressure on the city is affecting the lifestyle of its citizens. Therefore, the main objective of this work was to determine to what extent this pressure affects the lifestyle of citizens and how to obtain relevant information when planning integrated and sustainable tourism strategies.

10.2.2 Indicator selection

The starting point was the elaboration of three specific surveys performed by Galabra Research Group to the three most potential collectives directly related to tourism: citizens, traders and visitors. These surveys were part of the project led by Galabra Research Group[24] "*Speeches, images and cultural practices about Santiago de Compostela as the goal of the Caminos"* and *"Narratives, Uses and Consumptions by Visitors as Allies or Menaces for the Community Well-Being: The Case of Santiago de Compostela"* (Rede Galabra, 2019). The aim of the questionnaires was to obtain information about

[24] https://redegalabra.org/

the discourses, images and referenced practices of traders, residents and visitors. Thus, the socio-economic indicators used in this chapter were selected from the questions posed. Consequently, a two-stage selection method was used to identify the questions that contained the information necessary for the purpose of this work. First, the questions were classified according to the information contained considering the approach from a sustainable city and integrated tourism. Information such as i) the socioeconomic situation of residents and visitors, ii) the use that citizens make of the different areas of the city, iii) the social commitment of residents, iv) the economic relationship between residents, tourism, and the city's services and offer was established as reference frameworks (Biagi et al., 2020; Tournois and Rollero, 2020). In this way, all questions containing information within these defined frameworks were selected in this first step.

Nevertheless, most of these questions contained qualitative information. Thus, and with the objective of obtaining quantitative data from these questions, it was necessary to classify the answers to each question into different categories and give each of them a numerical value (Guttman, 2016). However, some of the questions selected in the previous stage cannot be directly quantified. For this reason, a second screening stage was carried out in which questions that could not be quantified or categorized and scaled were discarded.

Finally, the number of questions selected was 19, 19 and 13 for the groups of citizens, traders and visitors, respectively. These selected questions were renamed to be transformed into indicators as shown in **Table 10.1**. To simplify reading and comprehension, each indicator was coded with a letter C, T or V depending on whether citizens, traders or visitors are involved and with a number.

Table 10.1. Indicators selected from Rede Galabra questions and their description corresponding to citizens

Cod.	Indicator	Description
C1	Level of education	Educational level of citizens
C2	Municipality of residence	Residence in the city, in the metropolitan area or in a more distant location
C3	Residence within the city	How far from the city center you live
C4	Family income level	Household income level according to high or low income
C5	Employment Situation	Employment situation: Worker, unemployed, student etc.
C6	Leisure places	Areas frequented during leisure time
C7	Affective areas	Places that have affection for citizens
C8	Coincidence in significant places	Citizen's perception of the coincidence of the most affective areas.
C9	Alternative tourist elements	Citizens believe if there are elements that should be part of the image of the city
C10	City use time	Years that a citizen has been using the city daily
C11	Shopping establishments	Types of favorite establishments
C12	Shopping Site	Place where purchases are made with respect to the district of residence
C13	Use of the historic area	Part of the daily life of the citizens takes place in the historic area
C14	Place attachment	How a citizen perceives his/her belonging to the city
C15	Community participation	Participate actively within the community (Neighborhood Association, municipal policy, charity, etc.)
C16	Economic dependence on tourism	Degree of economic dependence on tourism
C17	Tourist image of the city	How much is in accordance with the image of the city
C18	Citizen lifestyle	How much tourism affects the way of life of citizens
C19	City evolution	Opinion on whether citizens prefer the city in the early 1990s, when there were few tourists, or today.

Table 10.1 (cont.). Indicators selected from Rede Galabra questions and their description corresponding to traders.

Cod.	Indicator	Description
T1	Level of education	Educational level of traders
T2	Municipality of residence	Residence in the city, in the metropolitan area or in a more distant location
T3	Employment Situation	Employment situation: Worker, unemployed, student etc.
T4	Family income level	Household income level according to high or low income
T5	Offering evolution	Whether or not the commercial and economic offer improved with the increase in tourism
T6	Perception of changes in the offer	How much the offer changes due to tourism
T7	Perception of changes in the offer (other establishments)	How much the offer changes due to tourism in other establishments
T8	Customers in the early 90's	Type of customers that frequented the business in the early 90's
T9	Customers at present	Type of customers that frequented the business at present
T10	Difference in most demanded products	Visitors and citizens do or do not consume different types of products
T11	Evolution in most demanded products	The most demanded products changed with the increase in tourism or not
T12	Community participation	Participate actively within the community (Neighborhood Association, municipal policy, charity, etc.)
T13	Place attachment	How a trader identifies who belongs to the city
T14	Income from tourism	Percentage of income from tourism at present
T15	Income from tourism (early 90's)	Percentage of income from tourism in the early 90's
T16	Economic dependence on tourism	Degree of economic dependence on tourism
T17	Tourist image of the city	How much is in accordance with the image of the city
T18	Type of visitor	How much do you like the type of visitor who comes to city
T19	Camino de Santiago as Public Image	How much is the Camino de Santiago part of the identity of the city

Table 10.1 (cont.). Indicators selected from Rede Galabra questions and their description corresponding to visitors.

Cod.	Indicator	Description
V1	Level of education	Educational level of visitors
V2	Employment Situation	Employment situation: Worker, unemployed, student etc.
V3	Family income level	Household income level according to high or low income
V4	Transport used	Means of transport used
V5	Satisfaction with the visit	How satisfied are you with the visit?
V6	Discovered activities	Activities and places that surprised the visit
V7	Places to plan to eat and drink	Places where visitors eat and drink
V8	Expenditures on food products	Consumption of local gastronomic products
V9	Shopping in the city	Do visitors make purchases?
V10	Shopping places	Places where visitors shopping
V11	Accommodation in the city	Visitors stay in or out of town
V12	Spending on visit	Spending on leisure and transport/ accommodation
V13	Total spending per person	Total spending per person on the trip

10.2.3 Sustainability score calculation

The objective of this chapter was to determine a sustainability score for Santiago de Compostela in relation to its tourism situation. This sustainability score, which reflects the degree of sustainability of tourism and its relationship with residents and traders, was calculated from the selected indicators. The score takes values on a scale of 0 to 10. Thus, a high score should mean that the relationship of citizens and traders with tourism was good, so that visitors should be integrated without harming the quality of life of residents. **Figure 10.** shows schematically how this sustainability score was calculated, which consisted of several steps. First, the different indicators were categorized and scaled by transforming the qualitative values (i.e., the answers to the questions to which each indicator corresponds) into numerical ones. Second, the indicator values within the same group (i.e., citizens, traders or visitors) were summed to assign a score to each of the groups. Finally, the sustainability score of the city was the result of the weighted average of the scores of the aforementioned groups. These steps are explained in more detail below.

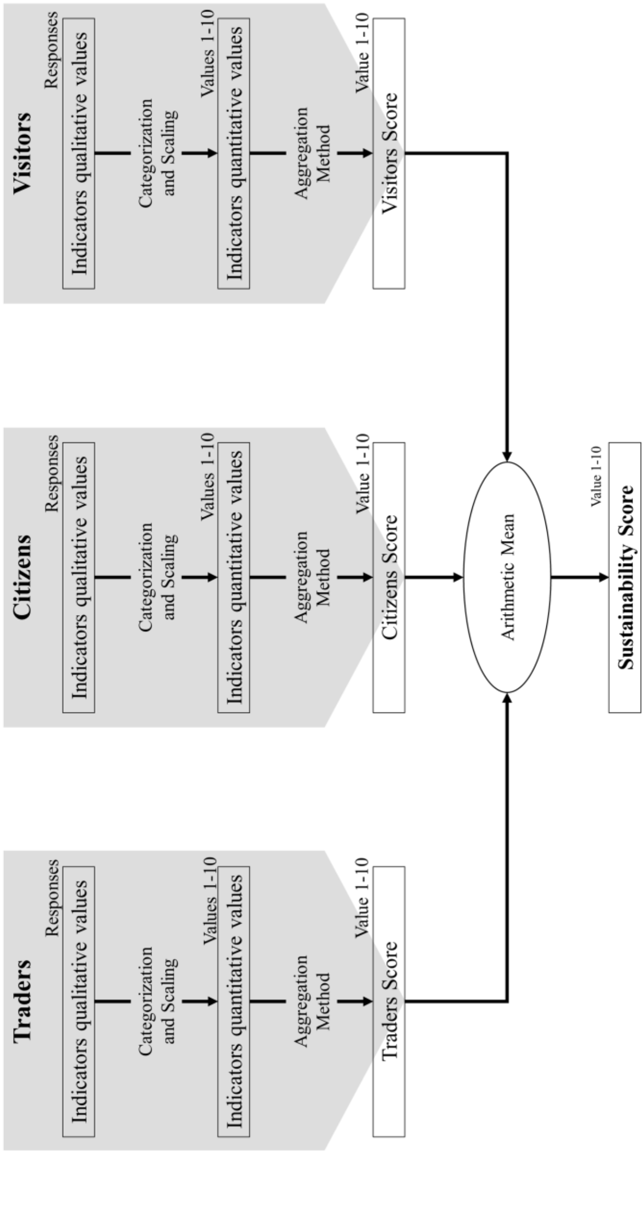


Figure 10.2. Scheme of the methodology used: (a) calculation of the values of each group assessed: citizens, traders and visitors (b) calculation of the Integrated Tourism Score of Santiago de Compostela.

10.2.3.1 Categorization and scaling of indicators

The information provided by the indicators was mostly qualitative, as mentioned above. Following the method described by Guttman (2016), it was possible to scale the qualitative data. Therefore, to obtain quantitative values for these selected indicators, the responses for each indicator were grouped into different categories. Therefore, for each indicator, a certain number of categories were identified based on how the responses were grouped. The minimum number of categories identified in an indicator was two, corresponding to indicators with binary responses such as "Yes" or "No". On the other hand, the maximum number of categories identified was 8. In the case of indicators with two categories, score 1 was assigned to one of the categories and score 10 to the other. For indicators where more than two categories were identified, the values assigned to each category were calculated according to **Equation 10.1**.

$$Y = X + \frac{(Max - Min)}{(n - 1)} \qquad \textbf{(Equation 10.1)}$$

Where *Y* was the value of the category, *X* was the value of the lower category, *Max* was the maximum value of the scale (i.e.,10), *Min* was the minimum value of the scale (i.e., 1) and *n* was the number of categories identified in that indicator. For example, an indicator in which 4 categories were identified (*n* = 4), Category 1 was assigned the lowest value on the scale (1), then the value of Category 2 was calculated considering the value of *X* (lower Category value) corresponded with the Category 1 value (1), and therefore the Category 2 value was:

$$Category\ 2 = 1 + \frac{(10 - 1)}{(4 - 1)} = 4$$

Table 10.2. Relation between the number of categories and the values assigned to each of them on a scale of 1 to 10.

	Values							
Number of Categories	**Category 1**	**Category 2**	**Category 3**	**Category 4**	**Category 5**	**Category 6**	**Category 7**	**Category 8**
2	1	10						
3	1	5.5	10					
4	1	4	7	10				
5	1	3.3	5.5	7.8	10			
6	1	2.8	4.6	6.4	8.2	10		
7	1	2.5	4	5.5	7	8.5	10	
8	1	2.3	3.6	4.9	6.1	7.4	8.7	10

Thus, depending on the number of categories that were identified in each indicator, the value of each category was assigned. **Table 10.2.** Relation between the number of categories and the values assigned to each of them on a scale of 1 to 10. shows the values of all the categories according to the number of categories identified according to the indicator.

The assignment of values to each category was based on whether the responses within a category were in line with the social, economic and environmental principles of sustainability (Feleki et al., 2018). Therefore, the highest values were assigned to categories implying tourism that does not negatively influence the quality of life of residents (Biagi et al., 2020), the economic offer of the city does not vary (Barata-Salgueiro and Guimarães, 2020), tourists use low-emission transport and consume local products (Gössling et al., 2011). Regarding the citizens and traders, the highest category values were assigned to those who have a high educational level, a high economic level, reside in the city (near the areas with greater tourist pressure), their economy does not depend on tourism, their purchases are made in the nearest local stores, their place attachment and their use of the areas with greater tourist pressure, and their social commitment to the city (Tournois and Rollero, 2020).

For example, if the question is "*Where in the city do you shop?*" The category with the highest score (10) was the one that considers the closest establishments since from an environmental approach it considerably reduces the emission of greenhouse gases (quantified as Carbon Footprint), which is linked to the distance between the home and the store (Shahmohammadi et al., 2020). In this sense, in some indicators the Carbon Footprint was also considered as a criterion to assign values to the categories, considering that it is a widely used environmental parameter and for which society is sensitized.

Once the responses to each question were categorized, all the indicators were scaled according to the number of responses, classified in each category and received the value assigned to that category as shown in **Equation 10.2**.

$$I_j = \sum_{i=2}^{n} C_i \cdot \frac{R_i}{TR_j}$$ (**Equation 10.2**)

Where I_j was the Indicator j (C1-C19, T1-T19 or V1-V13 in the case of citizens, traders or visitors respectively), n was the total number of categories in I_j, C_i was a category identified within the indicator I_j, R_i the number of responses classified within C_i and TR_j was the number of responses considered valid in I_j. In all indicators some of the responses were not accounted for because they could not be classified within the categories. These responses correspond with answers such as "*do not know*" and "*no answer*". Accordingly, each indicator I_j was quantified obtaining a value on a scale between 1 and 10.

10.2.3.2 Aggregation

The aggregation method allowed, first, to calculate the scores of each population group (citizens, traders and visitors) and then from these scores to estimate the sustainability score of the city. To do so, it was necessary to define the specific aggregation method and the weight of each indicator (Nardo et al., 2008). In this chapter, the arithmetic mean of the value of the selected indicators for each separate group was considered as the aggregation method, and equal weight was attributed to all indicators. Thus, to calculate the scores for each group, the indicators belonging to each of the groups were first aggregated into Level 1 composite indicators (level 1 CI), and then these were aggregated into Level 2 composite indicators (level 2 CI). These composite indicators were defined considering the relationship of some of the indicators to each other. **Table 10.3** shows which Level 1 CI and Level 2 CI were defined for each of the population groups.

Table 10.3. Level 1 composite indicators and level 2 composite indicators of the corresponding groups considered.

Level 1 Composite Indicators	**Level 2 composite indicators**
Citizens	
Home Incomes	Personal Characteristics
Affective area City Shopping	Use of the city
	Social Commitment
Affinity for visitors	Tourism
Traders	
Incomes	Personal Characteristics
Offering evolution Customers Products	Customers and products
	Social Commitment
Economy from tourism Affinity for visitors	Tourism
Visitors	
Incomes	Personal Characteristics
	Visit
Gastronomic products Products Expenses	Leisure

In Addition, **Figure 10.3** shows how the indicators were grouped into these composite indicators. All indicators were part of Level 2 CI, which were more generic. However, not all the indicators were grouped into Level 1 CI because they were not sufficiently related to be grouped. For example, C16, C17, C18 and C19 were grouped within the Level 2 composite indicator "Tourism" since all of these are related to the link between tourism and citizens, however, C17, C18 and C19 are related with the image perceived by citizens of tourism while C16 with an economic aspect. For this reason, C17, C18 and C19 were grouped in the Level 1 composite indicator "Affinity for visitors" which together with C16 were part of the "Tourism" level 2 composite indicator. In this way, some indicators were added directly with Level 2 CI, as they were not grouped into Level 1 CI. These were within the group of citizens: C1, C6, C10, C13, C14, C15 and C16; in the group of traders: T1, T2, T12 and T13; and in the group of visitors: V1, V4, V5, V6 and V11.

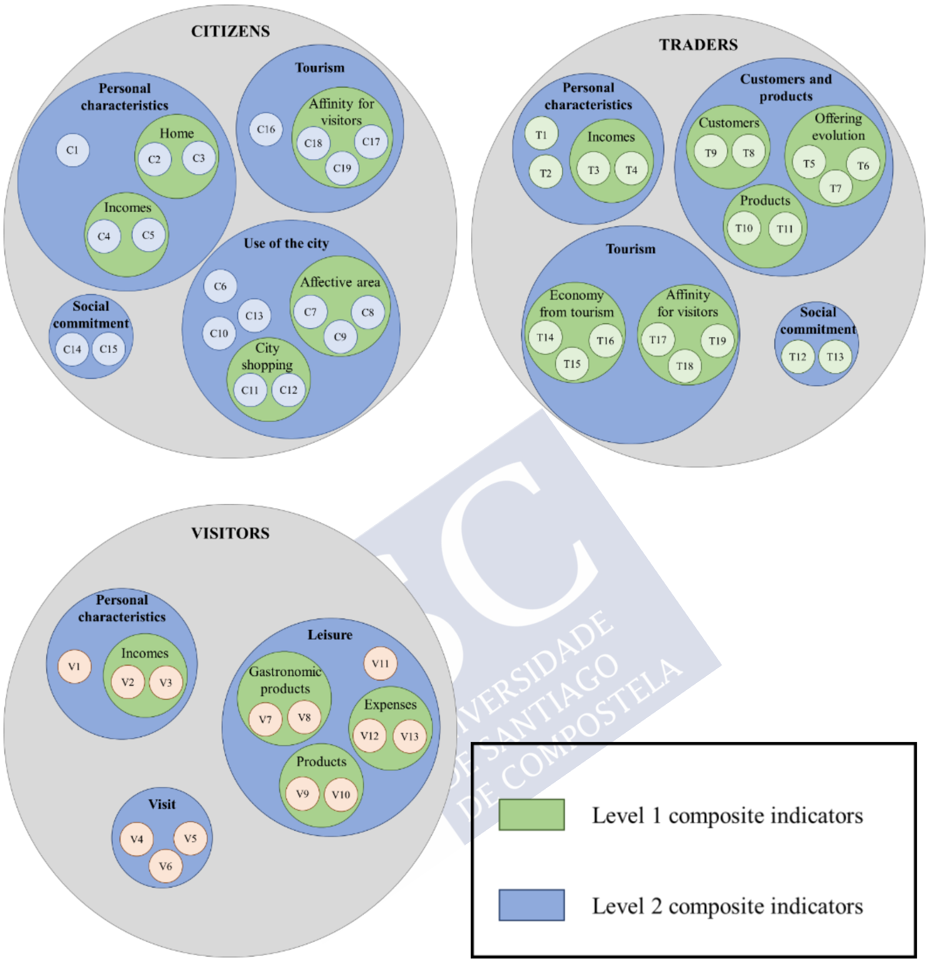


Figure 10.3. Aggregation of the indicators into their respective composite indicators for each group: citizens, traders and visitors.

Hence, the values of the Level 1 CI were calculated as the arithmetic mean of those from the corresponding indicators within of each composite indicator. Values of the Level 2 CI were calculated as the arithmetic mean of those indicators and level 1 CI which were grouped in each level 2 CI. Thus, both Level 1 CI and Level 2 CI obtained values between 1 and 10. Accordingly, the scores of each population group were calculated as the average value of the Level 2 CI. Finally, the sustainability score for the city of Santiago de Compostela was calculated as the average of the scores that each group obtained.

10.3 RESULTS AND DISCUSSION

10.3.1 Scaling and categorization

As explained previously in the *Material and Methods* section, all the responses obtained for each question or indicator were classified into different categories. **Table 10.4** shows the categories considered of each indicator. The values of each category corresponded to those stated in **Table 10.2** according to the number of categories for each indicator. Thus, the categories that appear on the left of Table 4 were the categories with the lowest score, and those that are on the right were the categories with the highest scores. Therefore, the responses from C1 and T1, for example, were classified into 3 different categories, and according to **Table 10.2** a value was assigned: "No education or primary education" with a value of 1, "Secondary education" with a value of 5.5, and "University education" with a value of 10. The highest value in this category was assigned taking into account that the degree of education positively influences the social aspect of the sustainability of an urban system (Egger, 2006; González-García et al., 2019). In the case of "place of residence", implicit in indicators C2, C3 and T2, the highest values were assigned to residents in the city and near the Old Town. This implies to favor the city model where to live in the most touristic areas was economically affordable and comfortable. In terms of income level, the categories with the highest values were those that imply a high level of income (C4, T3 and V3) or an income-earning employment situation (C5, T4 and V2).

Table 10.4. Categories considered to classify the responses to the questions of the Rede Galabra surveys equivalent to each indicator.

Ind.	**Nº Cat.**	**Categories**							
		Low Score categories							**High Score Categories**
Citizens									
C1	3	No or Primary education	Secondary education	University education					
C2	3	Others	Ames/Teo	Santiago de Compostela					
C3	5	Most far	Far	Medium Distance	Near	City center			
C4	2	Low	High						
C5	4	Unemployed	Students	Pensioners	Workers				
C6	7	Any area	Sports Cult. Area	Leisure	Resid. Area	Green Area	Historic area	Cathedral	
C7	5	Industrial area	Residential area	Restoration and Leisure	Green areas	Historic area			
C8	2	No	Yes						
C9	2	No	Yes						
C10	5	< 2 years	2-5 years	6-10 years	11-20 years	>20 years			
C11	3	Shopping Center	Hypermarket or Supermarket	Market or traditional shop					
C12	3	Other districts	Other districts and in the district	In the district					
C13	2	No	Yes						
C14	8	1	2	3	4	5	6	7	8
C15	2	No participation	Participation						
C16	3	Total dependence	Partial dependence	Non dependence					
C17	8	1	2	3	4	5	6	7	8
C18	8	8	7	6	5	4	3	2	1
C19	3	Early 90's	Early 90's and at present	At present					

Table 10.4 (cont.). Categories considered to classify the responses to the questions of the Rede Galabra surveys equivalent to each indicator.

Ind.	Nº Cat.	Categories: Low Score categories → High Score Categories							
Traders									
T1	3	No or Primary education	Secondary education	University education					
T2	3	Others	Ames/Teo	Santiago de Compostela					
T3	4	Unemployed	Students	Pensioners	Workers				
T4	2	Low	High						
T5	3	Early 90's	Early 90's and at present	At present					
T6	8	8	7	6	5	4	3	2	1
T7	8	8	7	6	5	4	3	2	1
T8	3	Mostly visitors	Mix of visitors and citizens	Mostly citizens					
T9	3	Mostly visitors	Mix of visitors and citizens	Mostly citizens					
T10	2	Yes	No						
T11	2	Yes	No						
T12	2	No participation	Participation						
T13	8	1	2	3	4	5	6	7	8
T14	3	High	Medium	Low					
T15	3	High	Medium	Low					
T16	3	Total dependence	Partial dependence	Non dependence					
T17	8	1	2	3	4	5	6	7	8
T18	8	1	2	3	4	5	6	7	8
T19	8	1	2	3	4	5	6	7	8

Table 10.4 (cont.). Categories considered to classify the responses to the questions of the Rede Galabra surveys equivalent to each indicator.

Ind.	Nº Cat.	Categories (Low Score categories → High Score Categories)							
Visitors									
V1	3	No education or primary education	Secondary Education	University Education					
V2	4	Unemployed	Students	Pensioners	Workers				
V3	8	1	2	3	4	5	6	7	8
V4	5	Plane	Car	Bus	Train	Walk/Bike			
V5	8	1	2	3	4	5	6	7	8
V6	3	Cathedral	City/City Size	Other					
V7	3	Fast food chains	Hotels, Hospital canteens	Local restaurants					
V8	3	Fast food	Other	Traditional food					
V9	2	No	Yes						
V10	3	Shopping center	Residential area	Historic area street markets					
V11	2	No	Yes						
V12	2	Travel expenses	Leisure expenses						
V13	5	0-99 €	100-332 €	333-665 €	666-1099 €	> 1,100 €			

10.3.1.1 Citizens

Based on the indicators selected for the group of citizens, the values of the categories corresponding to the indicators of "use of the city" and "the affective areas" (C6, C7 and C13), were assigned to favor the use of the areas with more tourist intensity (Old Town, cathedral, etc.). Moreover, the categories of indicators C8 and C9, a value of 10 was assigned to the answers in which citizens declared that the affective places selected by them would coincide with those selected by other citizens for the indicator C8, and those who stated that there are elements in the city that should be known as the image of Santiago de Compostela in the case of indicator C9. In addition, the categories of the indicator C10 were scaled assigning the highest values to the categories that represent more years residing in the city. This implies favoring citizens with longer stays in Santiago, which was considered a good indicator of the quality of life (Tournois and Rollero, 2020).

The categories of indicators related to commerce and purchases of citizens C11 and C12 were scaled so that the categories involving local products and commerce received the highest values. The rationale was that local trade and consumption of local products have a lower carbon footprint (Gössling et al., 2011; Handy and Clifton, 2001). Additionally, a high degree of place attachment as well as social commitment among citizens are symptoms of good health within a community (Tournois and Rollero, 2020). For this reason, the categories belonging to indicators C14 and C15 were assigned higher values based on the higher degree of place attachment or community engagement. Finally, the citizen group indicators within the level 2 composite indicator "Tourism" C16, C17, C18 and C19 defined the relationship of citizens to tourism. Consequently, whether there is a high economic dependence, whether they agree with the image sold of the city, whether tourism modifies their way of life, or whether they prefer the current type of city compared to the early 90's, when there was not yet so much tourist intensity. The categories of these indicators were scaled, assigning the highest values to the categories that indicated in the case of C16 a non-economic dependence on tourism, so that if tourism falls it does not affect the city's economy to a large extent. Regarding the image of the city of C17, the categories with the highest values were those that reflect the responses of the citizens who most agree with the social perception of Santiago de Compostela, because it is a symptom that they like the type of tourism that visits the city. For the lifestyle of citizens in C18, the highest values were assigned to the responses in which tourism does not modify the lifestyle of citizens. In other words, the less tourism modifies the lifestyle of citizens, the higher the score for this indicator. Finally, the values assigned to the C19 categories were established considering that if citizens prefer the city when tourism intensity is lower, tourism is negatively affecting citizens. Thus, the highest values were assigned to the categories that indicate a preference for the city at present.

10.3.1.2 Traders

Considering the indicators selected for the group of traders, the values of the categories of those indicators within the level 2 composite indicator “customers and products” (T5, T6, T7, T8 T9, T10 and T11) were assigned to favor the categories which included responses that consider that the offer has not changed with tourism, most of the customers were city residents, and the products demanded by citizens and visitors are the same. In other words, these answers were in line with the idea that tourism plays an important role within the city but was not the main source of incomes for traders. On the other hand, as in the case of citizens, the categories belonging to the indicators of place attachment, as well as of social commitment T12 and T13, the highest values were assigned to the categories that encompass the responses greater place attachment and a high degree of social commitment.

In addition, the categories of those indicators within the level 1 composite indicator “Economy from tourism” (T14, T15 and T16) were scaled considering that a trade that depends mainly on tourism is a vulnerable and fragile trade. In fact, currently due to the global pandemic caused by COVID-19, the economy of tourist cities such as Venice has been seriously affected (Cristiano and Gonella, 2020). In other way, to the indicators grouped in level 1 composite indicator “Affinity for visitors” T17, T18 and T19 the categories were scaled considering something positive that traders agree with the image of the city that is sold and that they like the type of tourist who visits the city.

10.3.1.3 Visitors

Finally, of the indicators selected for the group of visitors, the indicator related to the transport used to get to the city (V4) was categorized, assigning the lowest values to visitors arriving by plane and the highest to visitors who traveled by bicycle or walking. These values were established considering CO_2 emissions and the contribution to climate change of each means of transport. The categories of the V5 and V6 indicators were scaled by assigning higher values to the categories that imply that the visit was satisfactory, as well as that the visitors discovered interesting activities that they were not aware of. As for the group of citizens, the categories of indicators within the level 1 composite indicator "Gastronomic products" V7 and V8, and within the level 1 composite indicator "Products" V9 and V10, which are related to commerce and consumption in bars and restaurants, were scaled, evaluating more favorably those categories that involve consumption in local trade and local products.

Regarding the accommodation contemplated in indicator V11, it was categorized by valuing more positively that tourists stayed within the city limits. Finally, from the economic perspective of the visitor, indicators within level 1 composite indicator "Expenses" V12 and V13 were scaled considered the total expenses of the visitors in the city. For the first (V12), the expenses were classified into two types of expenses: expenses such as accommodation and transportation and leisure expenses. The objective of this classification was to identify the amount of spending that was allocated only to accommodation and transport, which was favorable that it was low and affordable, and the spending on leisure, cultural, gastronomic activities, etc. This type of leisure spending was favorable if it was higher because it economically benefits more sectors of the city. The categories of indicator V13 were designated considering the average expenditure per visit and person in Galicia, which is approximately 1,100 €. In this sense, the values were assigned to the different categories considering the most favorable category the one that the expense exceeds the amount of 1,100 €.

10.3.2 Indicators and sustainability scores

Once the categories of each indicator were defined and scaled, it was calculated the score for the indicators. These scores of the indicators were quantified on a scale from 1 to 10, and then they were added by means of the arithmetic mean as explained above in **Section**

10.2.3 to calculate the score for each group. **Table 10.5** shows the scores for the groups identified in this chapter and the total score for Santiago de Compostela. All groups have obtained similar values between 6.95 and 6.69 so there was no specific group with a limiting score or a key factor to improve the overall score of the city. Considering that the maximum value that could be reached was 10, these values indicate the possibility of a wide improvement in terms of sustainability.

Table 10.5. Scores for the different groups and the total score for the average profile of Santiago de Compostela.

	Score
Citizens	6.95
Trader	6.88
Visitors	6.69
Santiago de Compostela	**6.84**

With the aim of proposing improvement actions to the sustainability score of the city, attention should be paid into the indicators that received the lowest marks so that specific actions should be defined. **Figure 10.4 to 10.6** shows how the indicators were aggregated to obtain the score for each group. The width of each line corresponds to the scores calculated of each indicator; therefore, the thinnest lines show indicators that obtained the lowest scores. So, in the case of citizens, the indicators with the lowest values were C4, C15 and C18 which correspond with “Family income level”, “Community Participation” and “Citizen Lifestyle” respectively.

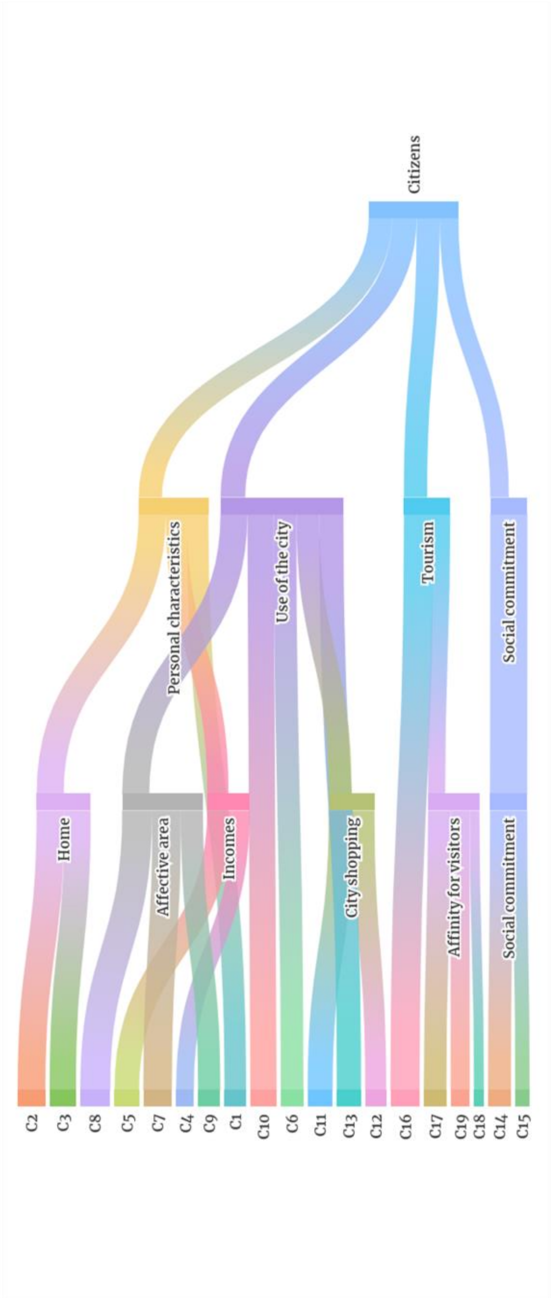


Figure 10.4. Contribution of the indicators to the scores of each of the composite indicators in the group of citizens.

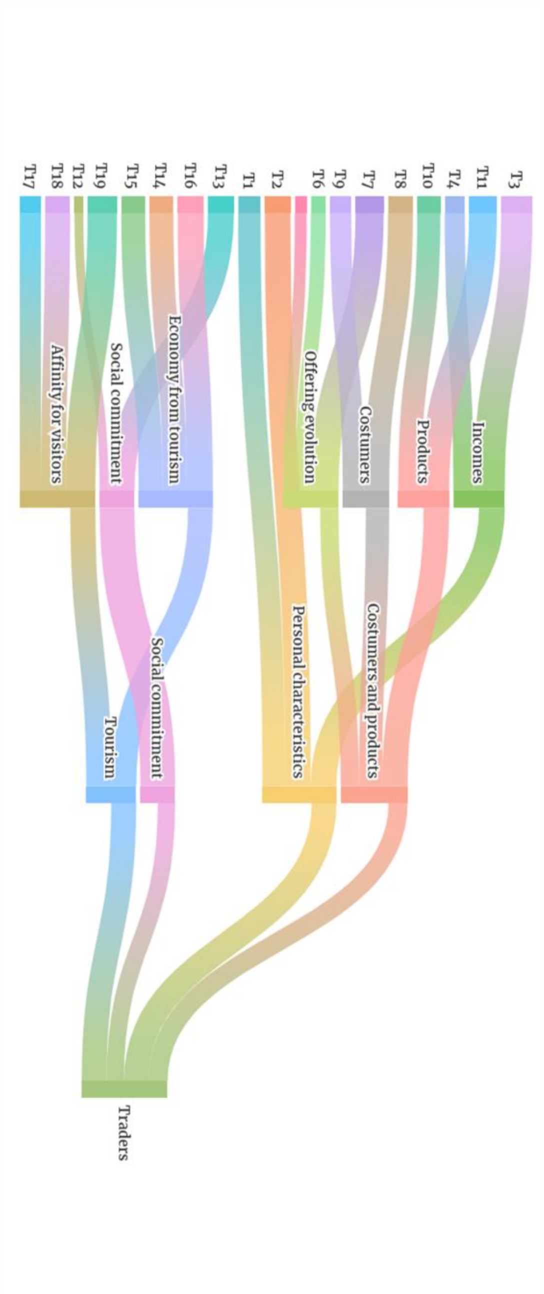


Figure 10.5. Contribution of the indicators to the scores of each of the composite indicators in the group of traders.

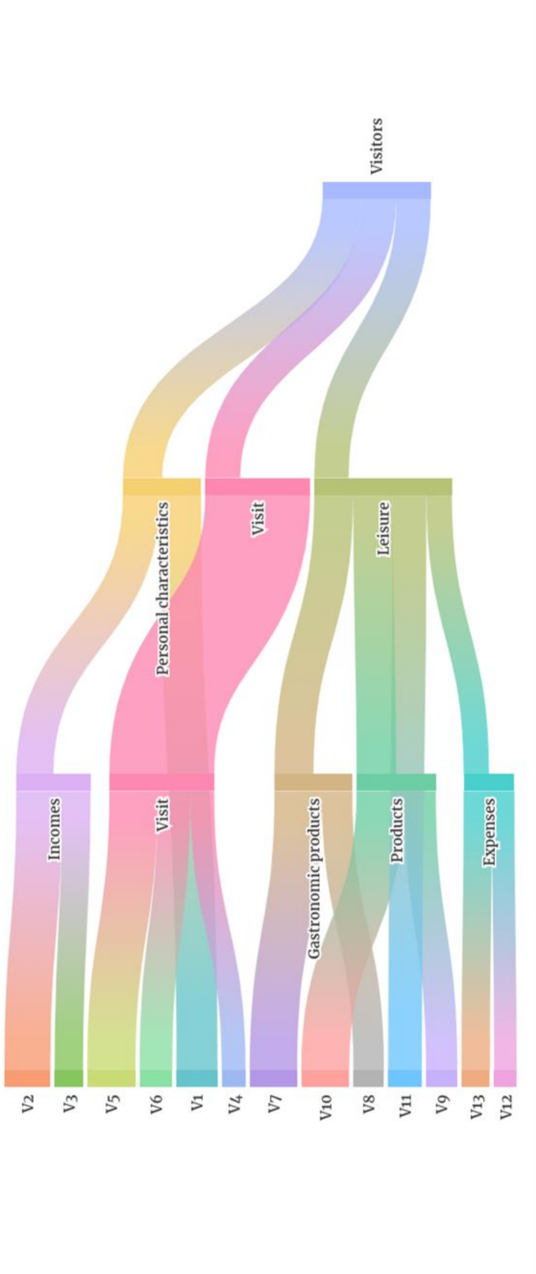


Figure 10.6. Contribution of the indicators to the scores of each of the composite indicators in the group of visitors.

The values obtained from each indicator are detailed in **Table 10.6**, which complements **Figure 10.4 to 10.6**. This table shows that the value for the indicator "Family income level" was approximately 5.5, which indicates a medium level of income among the respondents. The "Community Participation" indicator was referred to the level at which citizens participate in community activities (sports and cultural associations, politics, etc.). Citizen participation in these types of activities creates social ties with the city, generating a healthier community (Egger, 2006). Moreover, high values in this indicator as well as in "Place attachment" were related to durable settlements allowing the growth of the city (Tournois and Rollero, 2020). On the other hand, most of the citizens consider that tourism affects their lifestyle as indicated by "Citizen Lifestyle". However, how was it affecting their lifestyle? According to the respondents, the main reason is the saturation of tourism in the old town. This phenomenon is currently displacing the citizens of the historic area. Even though the indicators for "Residence within the city" and "Leisure places" received both high values, most of the citizens do not reside in the city center, and the use of green areas by citizens increased in detriment of the use of the historic area (Rede Galabra, 2019). Consequently, it is observed a trend towards depopulation of the Old Town.

Table 10.6. Scores calculated for the indicators.

Cod.	Indicator	Score
	Citizens	
C1	Level of education	6.70
C2	Municipality of residence	8.59
C3	Residence within the city	8.17
C4	Family income level	5.46
C5	Employment Situation	7.65
C6	Leisure places	7.05
C7	Affective areas	8.85
C8	Coincidence in significant places	9.30
C9	Alternative tourist elements	6.89
C10	City use time	8.10
C11	Shopping establishments	7.72
C12	Shopping Site	6.48
C13	Use of the historic area	7.50
C14	Place attachment	7.07
C15	Community participation	4.46
C16	Economic dependence on tourism	9.05
C17	Tourist image of the city	6.99
C18	Citizen lifestyle	3.07
C19	City evolution	5.92

Table 10.6 (cont.). Scores calculated for the indicators.

Cod.	Indicator	Score
	Traders	
T1	Level of education	7.19
T2	Municipality of residence	8.23
T3	Employment Situation	9.99
T4	Family income level	6.47
T5	Offering evolution	3.79
T6	Perception of changes in the offer	4.76
T7	Perception of changes in the offer (other establishments)	9.04
T8	Customers in the early 90's	8.02
T9	Customers today	6.82
T10	Difference in most demanded product	7.43
T11	Evolution in most demanded product	8.90
T12	Community participation	2.84
T13	Place attachment	8.30
T14	Income from tourism	7.70
T15	Income from tourism (early 90's)	7.69
T16	Economic dependence on tourism	8.33
T17	Tourist image of the city	6.77
T18	Type of visitor	7.99
T19	Camino de Santiago as Image	9.44

Table 10.6 (cont.). Scores calculated for the indicators.

Cod.	Indicator	Score
	Visitors	
V1	Level of education	7.75
V2	Employment Situation	8.71
V3	Family income level	5.35
V4	Transport used	4.51
V5	Satisfaction with the visit	9.14
V6	Discovered activities	6.18
V7	Places to plan to eat and drink	8.96
V8	Expenditures on food products	5.77
V9	Shopping in the city	5.93
V10	Shopping places	9.07
V11	Accommodation in the city	6.38
V12	Spending on visit	4.25
V13	Total spending per person	5.36

In the case of traders, the indicators T5, T6 and T12 which corresponded to “Offering evolution”, “Perception of changes in the offer” and “Community Participation” were identified as the indicators with the lowest scores. As would be expected after the result of the "Community participation" indicator obtained in the group of citizens, this indicator has also a low score in the group of traders, because most of the traders are residents in the city. Regarding the evolution of the offer, this indicates how the trade adapted according to the demand of the clients. When this change in the offer is encouraged by the tourism sector, as in the case of Santiago de Compostela, it may cause the variety of products offered to decrease. As a consequence, all restaurants adapt to this demand by increasing the difference between the menu of a restaurant with respect to the daily diet of a resident (Carral et al., 2020). Furthermore, as the demand for the same products increases drastically, local production may not be enough to supply this demand, and therefore many of the products offered were imported from other countries with the environmental implications that this implies such as a higher CF (Gössling et al., 2011). In addition, the change in the offer promoted by tourism is one more way in which tourism affects the lifestyle of residents, since the offer was more appropriated to the profile of a visitor than to a resident.

Finally, considering visitors the indicators with the lowest scores were V3, V4, V12 and V13 which corresponded with “Family income level”, “Transport used”, “Spending on visit” and “Total spending per person”. As in the case of citizens, the score for the indicator "Family income level" was approximately 5.5 (**Table 10.6**). This indicates that the income of the interviewed visitors was adjusted to the normal income. Regarding the low score that results in the "Transport used" indicator that referred to the means of transport used to visit the city, it indicates that the most used means are plane, private car and bus, which are means with a great contribution to climate change (Lenzen et al., 2018). Even though many visitors came to Santiago on foot or by bicycle following the Way of St. James, most of the tourists arrived in this type of transport. Tourism mobility is not only an environmental problem in Santiago de Compostela as in isolated cities or countries, but it is also an international problem (Dwyer et al., 2010; Rico et al., 2019; Sharp et al., 2016). A possible solution, to reduce the emissions associated to air transport trips, is to promote domestic tourism, that is, tourism without leaving the country or the region, without the need for long-distance trips (Becken, 2009).

On the other hand, the low scores obtained in indicators V12 and V13 related to spending could be since the cost of living in Santiago is lower than in other cities. However, considering the scores of indicators V8 and V9, which correspond to spending in the city's establishments, which were 5.77 and 5.93 respectively (**Table 10.6**), which exceed 5.50 but are also quite low. This indicates that the daily spending in the city of the visitors is low. One of the reasons could be that the product offering was not attractive to most visitors. Considering that traders perceive that the offer of the trade has changed as tourism in the city increased, it is possible that this evolution was promoted for a minority of visitors. Better advertising and an expansion of the offer could favor consumption and thus increase the expenditures of visitors. Even though spending on gastronomic products is low, indicators V7 and V10 show that the consumption of local products prevails over other products, and that these gastronomic products are purchased in local stores, which favors the local economy and is more sustainable.

10.4 CONCLUSIONS

Tourism in Santiago de Compostela has markedly increased in the last thirty years. In addition, the Old Town and the cathedral of the city are the main tourist attraction, making it the area with the greatest tourist pressure. In this chapter was presented the development of a methodology based on a series of indicators to determine the impact that this growth in tourism has on the three groups involved: citizens, traders and visitors.

The result obtained on a scale of 1 to 10 was 6.84, which indicates that despite not being a bad value, tourism's relationship with city residents can be considerably improved. Considering the values obtained for the indicators, in this chapter was concluded that the way of life of the citizens was altered significantly due to the tourism. One of the main consequences was the displacement of the citizens' residence to more peripheral places of the city, moving away from the Historical Center. Another is the change in the places of leisure, where the use of green areas increased as the use of the Historical Area decreased. In addition, commerce varied the offer available for tourism, leaving aside the demand of residents. However, despite this, visitor expenditure was low in relation to the regional average expenditure per visitor. Thus, the variation in this supply was detrimental to residents and unattractive to visitors.

Some possible solutions to better integrate tourism in the city could be to dilute the pressure of the Old Town and enhance tourism in the different neighborhoods of Santiago de Compostela. In addition, the range of products on offer (poor gastronomic example) should be expanded and the advertising of the products offered by the city should be improved to encourage consumption and increase visitor spending. Accordingly, local and regional governance could improve the reach and impact of online advertising of Galician products, which could be a good way to publicize more products and broaden the range of offerings.

This chapter analyzes the impact of tourism in Santiago de Compostela, but the methodology used can be applied to other cities on the St. James Way, or to cities with an important historical area with similar characteristics. Moreover, it can be applied by updating the data so that the trends adopted by the indicators over time can be observed. Therefore, this work may be of interest to policy makers, as it provides useful information to design strategies for a future integrated and more sustainable tourism.

10.5 REFERENCES

Barata-Salgueiro, T., Guimarães, P., 2020. Public Policy for Sustainability and Retail Resilience in Lisbon City Center.

Becken, S., 2009. The Carbon Footprint of Domestic Tourism, LEaP Research Centre.

Biagi, B., Ladu, M.G., Meleddu, M., Royuela, V., 2020. Tourism and the city: The impact on residents' quality of life. Int. J. Tour. Res. 22, 168–181. https://doi.org/10.1002/jtr.2326

Carral, E. V., Del Río, M., López, Z., 2020. Gastronomy and tourism: Socioeconomic and territorial implications in santiago de compostela-galiza (NW Spain). Int. J. Environ. Res. Public Health 17, 1–25. https://doi.org/10.3390/ijerph17176173

Choi, W.M., Chan, A., Wu, J., 1999. A qualitative and quantitative assessment of Hong Kong's image as a tourist destination. Tour. Manag. 20, 361–365. https://doi.org/10.1016/S0261-5177(98)00116-2

Claudio, M., Joseph, M.C., Marina, N., 2018. Overtourism: a growing global problem. Conversat.

Cristiano, S., Gonella, F., 2020. 'Kill Venice': a systems thinking conceptualisation of urban life, economy, and resilience in tourist cities. Humanit. Soc. Sci. Commun. 7, 1–13. https://doi.org/10.1057/s41599-020-00640-6

Diaz-Parra, I., Jover, J., 2021. Overtourism, place alienation and the right to the city: insights from the historic centre of Seville, Spain. J. Sustain. Tour. 29, 158–175. https://doi.org/10.1080/09669582.2020.1717504

Dwyer, L., Forsyth, P., Spurr, R., Hoque, S., 2010. Estimating the carbon footprint of Australian tourism. J. Sustain. Tour. 18, 355–376. https://doi.org/10.1080/09669580903513061

Egger, S., 2006. Determining a sustainable city model. Environ. Model. Softw. 21, 1235–1246. https://doi.org/10.1016/j.envsoft.2005.04.012

Feleki, E., Vlachokostas, C., Moussiopoulos, N., 2018. Characterisation of sustainability in urban areas: An analysis of assessment tools with emphasis on European cities. Sustain. Cities Soc. 43, 563–577. https://doi.org/10.1016/j.scs.2018.08.025

González-García, S., Rama, M., Cortés, A., García-Guaita, F., Núñez, A., Louro, L.G., Moreira, M.T., Feijoo, G., 2019. Embedding environmental, economic and social indicators in the evaluation of the sustainability of the municipalities of Galicia (northwest of Spain). J. Clean. Prod. 234, 27–42. https://doi.org/10.1016/j.jclepro.2019.06.158

Gössling, S., Garrod, B., Aall, C., Hille, J., Peeters, P., 2011. Food management in tourism: Reducing tourism's carbon "foodprint." Tour. Manag. 32, 534–543. https://doi.org/10.1016/j.tourman.2010.04.006

Guttman, L., 2016. A Basis for Scaling Qualitative Data Author (s): Louis Guttman Source : American Sociological Review , Vol . 9 , No . 2 (Apr ., 1944), pp . 139-150 Published by : American Sociological Association Stable http://www.jstor.org/stable.

Handy, S.L., Clifton, K.J., 2001. Local shopping as a strategy for reducing automobile travel. Transportation (Amst). 28, 317–346. https://doi.org/10.1023/A:1011850618753

IGE, 2020. Galician Institute of Statistics (in Galician). Municipal Population Census. Statistical exploitation. 1998-2019. http://www.ige.eu/web/ (accessed May 2021)

IGE, 2019a. Galician Institute of Statistics (in Galician). Municipal gross domestic product. Statistical review 2019. https://www.ige.eu/web/ (accessed May 2021)

IGE, 2019b. Galician Institute of Statistics (in Galician). Travelers, nights and average stay in hotel establishments by tourist points-municipalities. Monthly data. http://www.ige.eu/web/ (accessed May 2021)

Lenzen, M., Sun, Y.Y., Faturay, F., Ting, Y.P., Geschke, A., Malik, A., 2018. The carbon footprint of global tourism. Nat. Clim. Chang. 8, 522–528. https://doi.org/10.1038/s41558-018-0141-x

Lopez, L., Pazos Otón, M., Piñeiro Antelo, M. de los Á., 2019. Is there overtourism in Santiago de Compostela? Contributions for an ongoing debate. Boletín la Asoc. Geógrafos Españoles 83, 1–48. https://doi.org/https://doi.org/10.21138/bage.2825

López Pena, Z., Samartim, R., Bello Vázquez, R., Pazos-Justo, C., Iriarte Sanromán, Á., Sotelo Docío, S., 2020. Visitar, comerciar e habitar a cidade. Desenvolvemento do proxecto expositivo e participación social en Santiago de Compostela. Andavira.

Marans, R.W., 2015. Quality of urban life & environmental sustainability studies: Future linkage opportunities. Habitat Int. 45, 47–52. https://doi.org/10.1016/j.habitatint.2014.06.019

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., 2008. Handbook of Contructing Compsoite Indicators: Methodology and user guide. https://doi.org/10.1787/9789264043466-en

OECD, 2020. Tourism GDP. https://data.oecd.org/industry/tourism-gdp.htm (accessed May 2021)

Postma, A., Buda, D.M., Gugerell, K., 2017. The future of city tourism. J. Tour. Futur. 3, 95–101. https://doi.org/10.1108/JTF-09-2017-067

Ramos, S.P., Mundet, L., 2020. Tourism-phobia in Barcelona: dismantling discursive strategies and power games in the construction of a sustainable tourist city. J. Tour. Cult. Chang. 0, 1–19. https://doi.org/10.1080/14766825.2020.1752224

Rede Galabra, 2019. Impacts of the Camino on the local community of Santiago de Compostela. https://redegalabra.org/impactos-caminho-comunidade-local-santiago-compostela/ (accessed May 2021)

Rico, A., Martínez-Blanco, J., Montlleó, M., Rodríguez, G., Tavares, N., Arias, A., Oliver-Solà, J., 2019. Carbon footprint of tourism in Barcelona. Tour. Manag. 70, 491–504. https://doi.org/10.1016/j.tourman.2018.09.012

Shahmohammadi, S., Steinmann, Z.J.N., Tambjerg, L., Van Loon, P., King, J.M.H., Huijbregts, M.A.J., 2020. Comparative Greenhouse Gas Footprinting of Online versus Traditional Shopping for Fast-Moving Consumer Goods: A Stochastic Approach. Environ. Sci. Technol. 54, 3499–3509. https://doi.org/10.1021/acs.est.9b06252

Sharp, H., Grundius, J., Heinonen, J., 2016. Carbon footprint of inbound tourism to Iceland: A consumption-based life-cycle assessment including direct and indirect emissions. Sustain. 8. https://doi.org/10.3390/su8111147

Stylidis, D., Biran, A., Sit, J., Szivas, E.M., 2014. Residents' support for tourism development: The role of residents' place image and perceived tourism impacts. Tour. Manag. 45, 260–274. https://doi.org/10.1016/j.tourman.2014.05.006

Torres Feijó, E., del Rio Araujo, M.L., Carral, E. V., Rodríguez Prado, M.F., Pichel Iglesias, I., 2020. A cidade, o Camiño e nós.

Desenvolvemento do proxecto expositivo e participación social en Santiago de Compostela. Andavira.

Tournois, L., Rollero, C., 2020. “Should I stay or should I go?” Exploring the influence of individual factors on attachment, identity and commitment in a post-socialist city. Cities 102, 102740. https://doi.org/10.1016/j.cities.2020.102740

Trancoso González, A., 2018. Venice: The problem of overtourism and the impact of cruises. Investig. Reg. 2018, 35–51.

Tsaur, S.H., Lin, Y.C., Lin, J.H., 2006. Evaluating ecotourism sustainability from the integrated perspective of resource, community and tourism. Tour. Manag. 27, 640–653. https://doi.org/10.1016/j.tourman.2005.02.006

United Nations, 2015. Sustainable Development Goals. https://sustainabledevelopment.un.org/?menu=1300 (accessed May 2021)

CONCLUSIONS

Chapter 11: **Conclusions and future perspectives**

The main objective of this thesis is to evaluate the sustainability of urban systems and thus identify the main weaknesses of each case study. In this sense, this knowledge is crucial to be able to establish plans and take specific measures for the transformation of urban systems with a view to a future of sustainable development. Therefore, different methodologies to evaluate the sustainability of cities and municipalities were developed and adapted to different case studies. In a first section, Life Cycle Assessment (LCA) and Environmentally Extended Input-Output Analysis (EEIOA), which are environmental methodologies, were used to perform an analysis of the environmental profile of urban systems (Chapters 2 to 5). On the contrary, sustainability-based methodologies were developed in Section 2 that allow obtaining information not only on the environmental situation but also on the social and economic pillars of different urban systems using Sustainable Development Indicators (Chapters 6 to 9). Moreover, in Section 2 a set of indicators and a methodology was developed to analyze how an external factor such as tourism affects the sustainability of a city, based on a specific case study (Chapter 10).

11.1 SECTION 1: RELATIONSHIP OF URBAN SYSTEMS WITH THE ENVIRONMENT

Section 1 of this thesis has the objective of adapting the LCA and EEIOA methodologies to analyze the environmental impacts of urban systems, thus identifying the main causes of those impacts. Chapter 2 explained in detail the procedures and steps required by both methodologies in their application at the local level and the main challenges within the investigation. The use of both methodologies in urban systems is quite recent, so that many of the data that are required are not available at the local scale, so it is necessary to use downscaling methods and approximations. For this reason, it is important to establish what type of downscaling approach to use so that the results obtained adjust as closely as possible to the reality of the case study. On the other hand, there are also methodological shortcomings when it comes to establish the flows that need to be studied in the LCA or the criteria followed to relate the spending groups with the economic sectors in the EEIOA. For this reason, in Chapters 3 and 4 alternatives are proposed to solve these main challenges of these methodologies by applying them to different case studies.

In Chapter 3 LCA was used to analyze the environmental profile of the municipality of Madrid. Hence, different impact categories related to discharges, emissions, resource exploitation and toxicity were analyzed considering the activity and the consumption of materials and energy within the municipality. Some of these materials and energy data are not available at the local level, so different assumptions were made depending on whether data were collected at the regional or national level. These assumptions are frequent in this type of study, and the results do not differ excessively in orders of magnitude with other case studies. The consumption of energy, manufacturing and food (especially of animal origin) were the main causes of the impacts in most of the impact categories. In this way, LCA allows us to know which are the main flows that must be addressed when mitigating environmental burdens.

In Chapter 4 the two methodologies LCA and EEIOA were compared to calculate the carbon footprint of the city of Cadiz. Once again, due to the lack of data at the local level, some assumptions were considered when taking data at the regional or national level in some cases. Furthermore, two downscaling factors were considered in EEIOA to transform regional data to local scale. Another of the EEIOA's methodological weaknesses was to create relationships between citizens' spending groups with the industrial sectors considered in the Input-Output Table. The main conclusions of Chapter 4 were that EEIOA is a good alternative to calculate the CF of an urban system with respect to LCA, because it is a faster method, it does not need a compilation of large amounts of data, and it is not necessary to use private database. Nevertheless, LCA allows a better disaggregation of the flows, thus allowing more information about which are the flows that most affect the CF. In addition, EEIOA with these databases is limited only to calculate the CF while LCA considers more impact categories without the need to obtain more data. Therefore, depending on the depth of analysis required by the case study, it can be considered to use one methodology or another or a combination of both, using EEIOA for a quick analysis and LCA to evaluate in more detail the contributions of each flow.

11.2 SECTION 2: SUSTAINABILITY INDICES OF URBAN SYSTEMS

In Section 2, three different methodologies were developed to evaluate the sustainability of urban systems, considering, in addition to environmental factors, social and economic ones. These methodologies are based on using indicators and obtaining indices from the aggregation of the indicators. Therefore, the crucial stages in these methodologies are the selection of a set of indicators, the weighting and aggregation of the indicators and the thresholds from which a sustainable urban system is defined.

The methodology developed in Chapter 6, which was adapted and applied in Chapters 7 and 8, proposes a set of 38 indicators selected from national and international databases. Consequently, it has a wide range of application. Hence, this methodology was applied at the regional and national level and was also valid for using on urban systems with different population sizes. This makes the method robust and can be easily adapted for application in other case studies. Moreover, the results are expressed through an index composed of a three-letter label which represents each of the pillars of sustainability: social, economic and environmental. This makes the results easy to interpret and requires a balance between these three pillars to consider a sustainable urban system.

Sin this methodology was developed to be able to analyze the sustainability of several urban systems simultaneously, it can give a vision of how the cultural or climatic differences that exist between various cities or municipalities affect sustainability. However, the information obtained from an index, despite being easy to interpret, is relatively little. Therefore, when taking sustainable development measures, it is necessary to carry out a retrospective analysis and to evaluate in depth the indicators that need to be improved.

In Chapter 9 a methodology was developed to analyze the sustainability of urban systems using only three indicators: women unemployed, city unemployment rate and municipal solid wastes generated. This methodology can predict the sustainability of an urban system with an error of 13% with respect to the methodology developed in Chapter 6. In addition, each indicator has a threshold associated, which means that it is not necessary to collect large amounts of data for several cities. In this sense, this methodology allows to quickly know the state of a city with respect to its sustainability. Furthermore, the method can be adapted and applied on a global scale. However, by only considering three indicators, it does not have specific and sufficient information to develop actions and measures to improve sustainability. Nevertheless, this methodology is a fast and reliable and requires little time and resources. Moreover, this methodology can be complementary to the methodology described in Chapter 6, which analyzes each case study in more detail.

Finally, in Chapter 10 a methodology was developed to analyze how tourism affects the sustainability of a city with a historical heritage, selecting Santiago de Compostela as a case study. The final result that was expressed through a sustainability score with a scale from 1 to 10 was 6.84 for the case study. The results show that tourism affects the way of life of the citizens of the city and causes a displacement of the residence of the inhabitants to more peripheral areas. Moreover, the use of the historic area as a leisure area decreases among citizens, and the use of green areas increases. On the other hand, visitors vary the offer of products in the city, reducing the variety. To solve these problems, tourism should be better integrated into the city, diluting the tourist pressure in the historic area. Furthermore, measures must also be taken to make the variety of products that the city offers visible to diversify the offer.

This methodology developed in Chapter 10, can also be applied in cities with similar characteristics to Santiago de Compostela that is, tourist cities with an important historical heritage. In this way, it can help policy makers to understand the main problems derived from tourism within the city that affect both commerce and citizens and be able to create specific actions in favor of an integrated and sustainable tourism development.

List of Publications

Scientific Journals

The publications contained in this thesis which belong to Elsevier journals, have permission for the author to include their articles in full or in part in a thesis or dissertation for non-commercial purposes[25]. The author wants to show his appreciation to publishers for granting these permissions. The list of publications that this thesis contains is the following:

Sara González-García, Manuel Rama Caamaño, María Teresa Moreira, Gumersindo Feijoo (2021). "Environmental profile of the municipality of Madrid through the methodologies of Urban Metabolism and Life Cycle Analysis". Sustainable Cities and Society. Vol. 64, 102546. IF in 2019: 5.268, Q1. ISSN: 2210-6707. **Chapter 2** and **Chapter 3** are based on this publication. The author of this doctoral thesis contributed in this article to obtaining results, developing the methodology and reviewing in the publication process.

Manuel Rama, Eduardo Entrena-Barbero, Ana Cláudia Dias, María Teresa Moreira, Gumersindo Feijoo, Sara González-García (2021). "Evaluating the carbon footprint of a Spanish city through environmentally extended input output analysis and comparison with life cycle assessment". Science of the Total Environment. Vol. 762, 143133. IF in 2019: 6.551, Q1. ISSN: 0048-9697. **Chapter 2** and **Chapter 4** are based on this publication. The author of this doctoral thesis contributed in this article to writing, developing the methodology and reviewing in the publication process.

Sara González-García, Manuel Rama, Antonio Cortés, Fernando García-Guaita, Andrés Núñez, Lucía González Louro, Maria Teresa Moreira, Gumersindo Feijoo (2019). "Embedding environmental, economic and social indicators in the evaluation of the sustainability

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of the municipalities of Galicia (northwest of Spain)". Journal of Cleaner Production. Vol. 234, 27-42. IF in 2019: 7.246, Q1. ISSN: 0959-6526. **Chapter 6** and **Chapter 7** are based on this publication. The author of this doctoral thesis contributed in this article to obtaining results and reviewing in the publication process.

Manuel Rama, Sara González-García, Elena Andrade, Maria Teresa Moreira, Gumersindo Feijoo (2020). "Assessing the sustainability dimension at local scale: Case study of Spanish cities". Ecological Indicators. Vol. 117, 106687. IF in 2019: 4.229, Q1. ISSN: 1470-160X. **Chapter 8** is based on this publication. The author of this doctoral thesis contributed to obtaining results, developing the methodology, writing and reviewing in the publication process.

Manuel Rama, Elena Andrade, María Teresa Moreira, Gumersindo Feijoo, Sara González-García (2021). "Defining a procedure to identify key sustainability indicators in Spanish urban systems: Development and application". Sustainable Cities and Society. Vol. 70, 102919. IF in 2019: 5.268, Q1. ISSN: 2210-6707. **Chapter 9** is based on this publication. The author of this doctoral thesis contributed to obtaining results, developing the methodology, writing and reviewing in the publication process.

Manuel Rama, Emilio Carral, Sara González-García, Elías Torres Feijó, Maria Luisa del Rio, María Teresa Moreira, Gumersindo Feijoo. "Balance between Hosts and Guests: the key to sustainable tourism in a heritage city". Tourism Management Perspectives. Submitted to the Journal. IF in 2019: 3.648, Q1. **Chapter 10** is based on this publication. The author of this doctoral thesis contributed to obtaining results, developing the methodology, writing and reviewing in the publication process.

Congress proceedings

Manuel Rama, Andrés Núñez, Lucía González Louro, Maria Teresa Moreira, Gumersindo Feijoo and Sara González-García. "Exploring the Sustainability Dimensions of Spanish Cities". Oral. Conference: 3rd International Congress of Chemical Engineering. Santander, Spain. 19-21 June 2019.

Manuel Rama, Elena Andrade, Maria Teresa Moreira, Gumersindo Feijoo, Sara González-García. “A methodology to identify sustainability indicators in small, medium and large cities in Spain”. Poster. Conference: SETAC Europe 30th Annual Meeting. Online meeting. 3-7 May 2020.