LIFE CYCLE ASSESSMENT OF CITIES - THE FIRST STEPS FOR STANDARDIZATION

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Universitat de Girona

DOCTORAL THESIS:

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MINES Saint-Étienne

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A la mare i al pare,
que s'esforçaren a donar-me unes arrels fortes i profundes.
A la Iana, companya de viatge,
que ajuda a que el tronc no es trenqui quan bufa la tramuntana.
Als fruits que vinguin,
per a que visquin en un món millor!

“To waste this opportunity […] would compromise our last best chance to stop runaway climate change. It would not only be immoral, it would be suicidal”

United Nations Secretary General António Guterres, COP24, December 12th 2018.

“If I am not for myself who is for me? And being for my own self, what am 'I'? And if not now, when?”

Attributed to Hillel the Elder, 1st century BC

“Si no és ara, quan? Si no som nosaltres, qui?”
“If not now, when? And if not us, who?”

David Fernàndez Member of the Catalan Parliament, during the debate on the State of the Nation, citing Primo Levi, September 16th 2014.

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List of Acronyms

AFOLU	Agriculture, Forestry, and Other Land Use
AP	Acidification Potential
BC	Bilan Carbone
BCN	Barcelona
BSI	British Standards Institution
BUWAL	Federal office for the environment, forests, and landscape
CB	Consumption-Based
CDP	Carbon Disclosure Project
CED	Cumulative Energy Demand
CF	Characterization Factor
CFP	Carbon Footprint
CML	Institute of environmental sciences, Leiden University, Netherlands
CO_2-eq	CO_2 equivalent emissions
COP	Conference of the Parties
CPI	City Prosperity Index
CPS	City Protocol Society
DHW	Domestic Hot Water
DPSC	Direct Plus Supply Chain
DSHW	Domestic Solar Hot Water
EC	European Commission
EEIO	Environmentally Extended Input-Output
EIA	Environmental Impact Assessment
EP	Eutrophication Potential
EPA	Environmental Protection Agency of the United States
EPD	Environmental Product Declaration
ESI	Environmental Sustainability Index
EU	European Union
EUROSTAT	Statistical office of the European Union
EVI	Environmental Vulnerability Index
FAO	Food and Agriculture Organization of the United Nations
FU	Functional unit
GDP	Gross Domestic Product
GER	Gross Energy Requirement
GHG	Greenhouse Gas
GNNP	Green Net National Product
GPC	Global Protocol for Community-Scale Greenhouse Gas Emission Inventories
GWP	Global Warming Potential
HD	Human Development
HDI	Human Development Index
HWI	Human Well-Being Index
IHDI	Inequality adjusted Human Development Index

ILCD	International reference Life Cycle Data system
IPPU	Industrial Processes and Product Use
ISCAM	Integrated Sustainable Cities Assessment Method
ISEW	Index of Sustainable Economic Welfare
ISO	International Organization for Standardization
JRC	Joint Research Centre
LC	Life Cycle
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Initiative
LCIA	Life Cycle Impact Assessment
LCM	Life Cycle Management
LCSA	Life Cycle Sustainability Analysis
LCT	Life Cycle Thinking
LPI	Living Planet Index
MDG	Millennium Development Goal
Mth	Method
NR-CED	Non-Renewable Cumulative Energy Demand
NUTS	Nomenclature des Unités Territoriales Statistiques
OAM	Organizational Assessment Method
ODP	Ozone Depletion Potential
OECD	Organization for Economic Cooperation and Development
OEF	Organization Environmental Footprint
OLCA	Organizational Life Cycle Assessment
P	Population
PA	Paris Agreement
PCR	Product Category Rule
PEF	Product Environmental Footprint
PV	Photovoltaic
RF	Reference Flow
SCI	Sustainability Cities Index
Sdev	Standard Deviation
SDG	Sustainable Development Goal
SEA	Strategic Environmental Assessment
SETAC	Society of Environmental Toxicology and Chemistry
SI	International System of units
SLC	Social Life Cycle
S-LCA	Social Life Cycle Assessment
SNBI	Sustainable Net Benefit Index
UK	United Kingdom
UN	United Nations
UN Habitat	United Nations Human Settlements Programme
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme

UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USI	Urban Sustainability Index
WB	World Bank
WBCSD	World Business Council on Sustainable Development
WBI	Well-Being Index
WF	Water Footprint
WRI	World Resources Institute
WU	Water Use
ZRH	Zurich

Summary

Cities are recognised as great generators of impacts and, consequently, seen as an opportunity for reducing them Worldwide. Cities are environmentally relevant because of two reasons. Firstly, because they are responsible, for example, for more than 60% of global warming or more than 78% of world's energy consumption, which is said to take place within cities. Secondly, cities are very relevant because more than half of the world's population is living in cities. Therefore, any environmental impact that is affecting cities may be affecting more than half of the population of the world.

Life Cycle Assessment (LCA) is being recognised as the best available methodology to assess environmental burdens and to avoid problem shifting. However, as LCA is environmentally focused, burden exchange between the three dimensions of sustainability - environment, economy, and society - may still happen.

The research objectives of this thesis are:

1. To propose criteria on how to frame city LCA methodology.
2. To review the existing environmental assessment methods and to analyse their compliance with the criteria set in objective 1.
3. To review the existing city assessment methods and analyse their compliance with the criteria set in objective 1.
4. To propose definitions and procedures for the main items within the goal and scope of a city LCA, such as: the function, the function unit, the reference flow, the system boundary, and allocation.
5. To contribute to the understanding of the validity of LCA along time.
6. To explore the environmental consequences on the choices of substitution of parts of a city system.

The outcomes of the thesis can be found in each of the subsections of Chapter 3. Section 3.1 includes research on the state of the art of current assessment methods is performed, including LC based methods and city focused methods, and checking the fulfilment of relevant criteria. Solutions to gaps and inconsistencies are proposed in the following section (3.2), which suggests some basis for working on LCA of cities with a sustainability perspective. A systematic literature review is performed so as to extract the procedure for defining the goal, function, functional unit, and reference flow of a complex system. Social and economic aspects are proposed to be introduced as technical performance within the FU of the city LCA through the use of the City Prosperity Index (CPI).

Section 3.3 is another step forward in the definition of the scope of city LCA, by proposing procedures (i) to set city boundaries and (ii) for allocating burdens among cities. Three methods for setting the boundaries for a city LCA and four allocation procedures are assessed.

Being a city a very long lasting system, section 3.4 focuses on finding if an old LCA study remains valid or not after a long period of time. To answer this we re-perform an LCA of

a bus stop in the city of Barcelona that was performed about 20 years ago. LCAs validity along time has been found to be dependent, at the inventory level, on the ever-changing techno-sphere and the improvement of the environmental policies; while, at impact level, on the evolution of impacts models and characterization factors.

Cities are complex systems which can evolve. In fact, energy supply of cities is currently quickly evolving. Section 3.5 assesses how to preview emissions reduction when the technology mix changes.

Cities are absolutely relevant both as causing and solving impacts and LCA is the proper assessment methodology. An adaptation to what a city is for such a methodology is essential but not a single methodology or standard for city LCA has been found to include all the following aspects: (i) holistic point of view, (ii) multi-criterial environmental impact assessment, (iii) analysis from a LC perspective, and (iv) the adequacy for comparison among different cities or urban regions. This thesis provides answers to the first steps to solve these challenges, including a shift from producer based to a category-based impact accountability. This change on the allocation procedure could affect, if accepted, the way national emissions inventories are performed.

Resum

Les ciutats són reconegudes com a grans generadores d'impactes i, com a conseqüència, són vistes com una oportunitat per a reduir-los arreu del món. Les ciutats són mediambientalment rellevats degut a dues raons. La primera és que són responsables, per exemple, d'un 60% de l'escalfament global o de més del 78% del consum mundial d'energia. La segona raó de la seva rellevància és que en elles hi viu més de la meitat de la població mundial. Conseqüentment, qualsevol impacte ambiental que afecti a les ciutats podrà afectar potencialment a més de la meitat de la població mundial. Alhora, l'Anàlisi de Cicle de Vida (ACV) s'està reconeixent com el millor mètode disponible per avaluar les càrregues ambientals i per evitar "l'intercanvi del problema". No obstant, l'intercanvi de problemes entre les tres dimensions de la sostenibilitat (mediambiental, econòmica i social) poden seguir succeint ja que l'ACV té un abast que considera només els aspectes ambientals.

Els objectius de recerca d'aquesta tesi són:

1. Proposar un criteri que estableixi les condicions que l'ACV de ciutats hauria de complir.
2. Revisar els mètodes d'avaluació ambiental existents i analitzar la seva adequació als criteris definits a l'objectiu 1.
3. Revisar els mètodes d'avaluació de ciutats existents i analitzar la seva adequació als criteris definits a l'objectiu 1.
4. Proposar definicions i procediments per als ítems principals dins de l'objectiu i abast de l'ACV en ciutats tals com: la funció, la unitat funcional, el flux de referència, les fronteres del sistema i els mètodes d'assignació.
5. Contribuir a la comprensió de la validesa dels ACV en el temps.
6. Explorar les conseqüències de l'elecció de sistemes substituïts quan es calculen crèdits ambientals.

Els resultats d'aquesta tesi es poden trobar en cadascuna de les subseccions del capítol 3. La secció 0 inclou recerca de l'estat de l'art dels mètodes d'avaluació actuals incloent-hi mètodes que utilitzen la perspectiva de cicle de vida i mètodes que tenen les ciutats com a objecte d'estudi. S'utilitza aquesta revisió per a comprovar si els mètodes estudiats compleixen amb criteris rellevants. Les inconsistències i mancances que es troben en els mètodes revisats són detectades i es proposen solucions per a resoldre-les en la següent secció de la tesi (3.2). Aquesta secció suggereix una base comuna per treballar els ACV en ciutats amb una perspectiva de sostenibilitat. Es realitza una revisió sistemàtica de la literatura per a extreure el procediment que defineixi l'objectiu, la funció, la unitat funcional i el flux de referència per a sistemes complexos. Es proposa introduir aspectes socials i econòmics com a paràmetres d'ajust de la funció de la ciutat mitjançant l'ús de l'Índex de Prosperitat de Ciutats.

La secció 0 és un altre pas endavant en la definició de l'abast dels ACV de ciutats per a (i) determinar les fronteres de les ciutats i (ii) assignar càrregues entre ciutats. Es

proposen i avaluen tres mètodes per a determinar les fronteres i quatre per a assignar càrregues.

Essent les ciutats sistemes que perduren en el temps, la secció 0 es centra en descobrir si un ACV antic es manté vàlid o no al cap d'un llarg període de temps. Per tal de respondre a aquesta pregunta refem un ACV, elaborat fa 20 anys, d'una parada d'autobús de la ciutat de Barcelona. S'ha detectat que la validesa dels ACV en el temps depèn, a nivell d'inventari, de la sempre canviant tecnosfera i de la modificació (millora) de polítiques ambientals, mentre que, a nivell d'impacte, depèn de l'evolució dels models d'avaluació d'impactes i dels factors de caracterització.

Les ciutats són sistemes complexos que evolucionen. De fet, el subministrament d'energia a les ciutats està evolucionant ràpidament. La secció 0 avalua com preveure una reducció d'emissions quan hi ha canvis tecnològics.

Les ciutats són absolutament rellevants tant en la causa com en la solució dels impactes, i l'ACV és la metodologia adequada per a avaluar-les. Es necessària una adaptació del concepte de ciutat per a aplicar-lo a la metodologia, no obstant, no s'ha trobat cap metodologia o estàndard per realitzar ACV de ciutats que inclogui els següents aspectes: (i) un punt de vista holístic, (ii) una avaluació d'impactes ambientals multi-criteri, (iii) un anàlisi amb perspectiva de cicle de vida i (iv) que permeti comparar diferents ciutats o regions urbanes. Aquesta tesis proporciona respostes a com desenvolupar les primeres passes per a superar els reptes, incloent-hi passar de la responsabilitat basada en el productor a la basada en la categoria d'impacte. Aquest canvi en els procediments d'assignació podria afectar, si s'acceptés, la manera en què es realitzen els inventaris d'emissions nacionals.

Resumen

Las ciudades están siendo reconocidas como grandes generadoras de impactos y, como consecuencia, son vistas como una oportunidad para reducirlos. Las ciudades son medioambientalmente relevantes debido a dos razones. La primera es que son responsables, por ejemplo, de un 60% del calentamiento global o de más del 78% del consumo mundial de energía. La segunda razón de su relevancia es que en ellas vive más de la mitad de la población mundial. Por consiguiente, cualquier impacto ambiental que afecte las ciudades puede afectar potencialmente a más de la mitad de la población mundial. A su vez, el Análisis de Ciclo de Vida (ACV) se está reconociendo como el mejor método disponible para evaluar las cargas ambientales y para evitar el "intercambio del problema". No obstante, el intercambio de problemas entre las tres dimensiones de la sostenibilidad (medioambiental, económica y social) puede seguir sucediendo ya que el ACV tiene un alcance que considera solo los aspectos ambientales.

Los objetivos de investigación de esta tesis son:

1. Proponer un criterio que establezca las condiciones que el ACV de ciudades debería cumplir.
2. Revisar los métodos de evaluación ambiental existentes y analizar su adecuación a los criterios definidos en el objetivo 1.
3. Revisar los métodos de evaluación de ciudades existentes y analizar su adecuación a los criterios definidos en el objetivo 1.
4. Proponer definiciones y procedimientos para los ítems principales dentro del objetivo y alcance del ACV de ciudades tales como: la función, la unidad funcional, el flujo de referencia, las fronteras del sistema y los métodos de asignación.
5. Contribuir a la comprensión de la validez de los ACV en el tiempo.
6. Explorar las consecuencias de la elección de sistemas substituidos cuando se calculan créditos ambientales.

Los resultados de esta tesis se pueden encontrar en cada una de las subsecciones del capítulo 3. La sección 3.1 incluye investigación del estado del arte de los métodos de evaluación actuales incluyendo métodos que utilizan la perspectiva de ciclo de vida y métodos que tienen las ciudades como objeto de estudio. Se utiliza esta revisión para comprobar si los métodos estudiados cumplen con criterios relevantes. Las carencias que se encuentran en los métodos revisados son detectadas y se proponen soluciones para solventar carencias e inconsistencias en la siguiente sección de la tesis (3.2). Ésta sugiere una base común para desarrollar los ACV en ciudades con una perspectiva de sostenibilidad. Se realiza una revisión sistemática de la literatura para extraer el procedimiento que defina el objetivo, la función, la unidad funcional y el flujo de referencia para sistemas complejos. Se propone introducir aspectos sociales y económicos como parámetros de ajuste de la función de la ciudad mediante el uso del Índice de Prosperidad de Ciudades.

La sección 3.3 es otro paso adelante en la definición del alcance de los ACV en ciudades proponiendo procedimientos para (i) determinar las fronteras de las ciudades y (ii) asignar cargas entre ciudades. Se proponen y evalúan tres métodos para determinar las fronteras y cuatro para asignar cargas.

Siendo las ciudades sistemas que perduran en el tiempo, la sección 3.4 se centra en descubrir de un ACV antiguo se mantiene válido o no después de un largo período de tiempo. Para responder a esta pregunta se rehace un ACV, elaborado hace 20 años, de una parada de autobús de la ciudad de Barcelona. Se ha detectado que la validez de los ACV en el tiempo depende, a nivel de inventario, de la siempre cambiante tecnosfera y de la modificación (mejora) de políticas ambientales; mientras que, a nivel de impacto, depende de la evolución de los modelos de evaluación de impactos y de los factores de caracterización.

Las ciudades son sistemas complejos que evolucionan. De hecho, el suministro de energía a las ciudades está evolucionando rápidamente. La sección 3.5 evalúa como prever una reducción de emisiones cuando hay cambios tecnológicos.

Las ciudades son absolutamente relevantes tanto en la causa como en la solución de los impactos y el ACV es la metodología adecuada para evaluarlas. Es necesaria una adaptación del concepto de ciudad para aplicarlo en la metodología pero no se ha encontrado ninguna metodología o estándar para realizar ACV de ciudades que incluya los siguientes aspectos: (i) un punto de vista holístico, (ii) una evaluación de impactos ambientales multi-criterio, (iii) un análisis con perspectiva de ciclo de vida y (iv) que permita comparar diferentes ciudades o regiones urbanas. Esta tesis proporciona respuestas a cómo desarrollar los primeros pasos para superar los retos, incluyendo pasar de la responsabilidad basada en el productor a la basada en la categoría de impacto. Este cambio en los procedimientos de asignación podría afectar, si se aceptase, a la forma en que se realizan los inventarios de emisiones nacionales.

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El meu doctorat, no només aquesta tesi doctoral, va començar a mitjans de setembre de 2005. En aquell moment vaig entrar a formar part de l'equip de recerca de l'Institut d'Enginyeria Civil de TECNUN, l'escola d'enginyeria de la Universitat de Navarra.

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Personal Introduction – The agglomeration of the species

Before the thesis starts, I would like to express how I think that the historical evolution of human beings has influenced the way human agglomerations are shaped nowadays and why, from my perspective, cities will play a relevant role in sustainable development. This chapter is thus a personal writing mainly inspired by the book from Yuval Noah Harari: "Sapiens: A Brief History of Humankind" published in Random House (2014).

This book includes information about how the first humans appeared. The author states that first Homo genera differentiate its evolution from that of the chimpanzees around 6,000,000 years before present (BP). Since then, I think that the way our species, the Homo sapiens, has organized itself in society has also matured. Curiously, Harari explains that Homo sapiens, who evolved in East Africa around 200,000 years BP, started to expand out of Africa and cohabitate with Homo Neanderthalensis and Homo Floresiensis around 70,000 years BP.

I think that during that time, daily humans' activity was probably focused on finding their basic needs covered. I imagine that those basic needs were mainly focused on satisfying their physiological requirements (Figure 1), such as their nutrition. To achieve so, I suppose that humans were hunter-gatherers, picking and hunting in places where the conditions where favourable to do so. This brings me to deduce that, once the micro-ecosystem was not providing enough resources to satisfy the needs of the group, our ancestors simply moved out to a new ecosystem. From my perspective, this nomad behaviour of first human groups favoured the expansion of the species, while Harari also attributes to those humans the extinction of the existing megafauna, throughout the world.

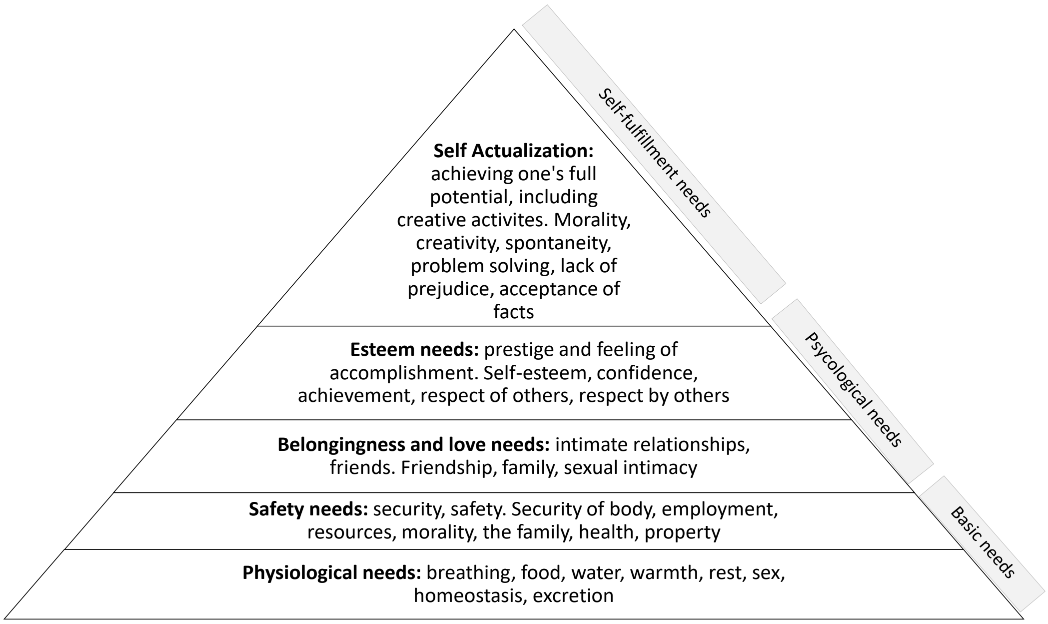

Figure 1. Maslow's hierarchy of needs. Inspired by Maslow (1943)[1]

[1] Maslow AH (1943) A theory of human motivation. Psichol Rev 50:370–396. doi: http://dx.doi.org/10.1037/h0054346

According to Harari, humans lived this way for tens of thousands of years. However, around 12,000 years BP, he states, a change modified the way humans were relating to their surrounding ecosystems, and therefore the way they were relating to the planet: the agricultural revolution happened. I assume that first farmers and shepherds cohabited with hunter-gatherers but Harari specifies that, while the formers were increasing in number, the later were decreasing. I see this fact as a consequence that a nomadic lifestyle was not appropriated for taking care of crops and herds. Thus, a direct consequence of the agricultural revolution was that human beings started to live in geographically fixed settlements.

The book states that a secondary result of the agricultural revolution was an increase of the number of people living in each settlement. I suppose that the increases of human agglomerations in number and density were instigators of specialization because, as more and more people live together, each individual is able to focus on those activities for which he/she has a better performance.

I guess that trade between those "new" settlements boosted the creation of infrastructures and facilitated the governance of groups of cities through the appearance of first realms, such as the Acadian Empire one around 4,250 BC. According to Harari, this evolution also contributed to the appearance of the first forms of accepted coins[2], such as the Sumer barley around 3,000 BC. The author explains how the increase of trade and specialization, and the appearance of coin, evolved into the creation of property and the need of bureaucracy, which, from my perspective, surely fostered the use of writing. I suspect that this iterative feedback is still valid nowadays in the form depicted in Figure 2.

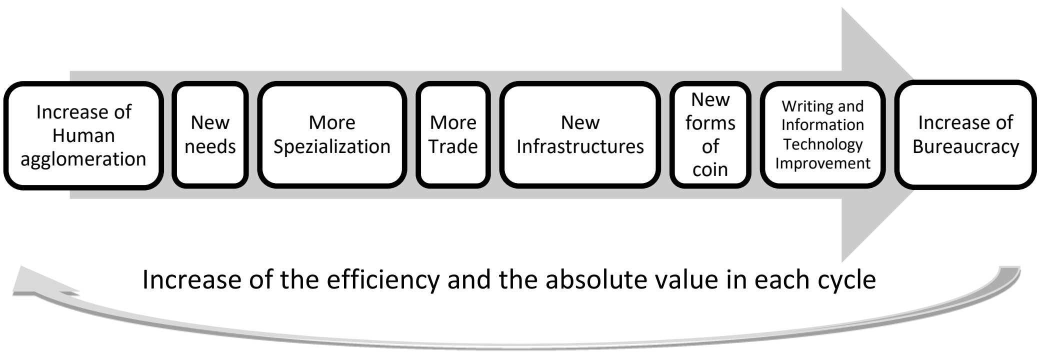

Figure 2. Iterative steps that feedback the increase of population, development, trade, wealth, and management systems

I consider that Cities are a result of the increase of population of these first human settlements. According to Harari, first cities and city states appeared in Sumer, in southern Mesopotamia along 3,000 BC and were followed by the Greek city states, which finally resulted in the generation of the first coin[3] as we understand it nowadays. An eminent Greek, Aristotle, in his Politics Book I, written in the IVth century BC, set the

[2] Here coin means any accepted good between different urban agglomerations which is standardized to be used as the means to exchange other goods.
[3] Here coin means a piece of metal which has value because it fulfils two requirements: (i) has universal convertibility and (ii) it is universally trusted.

first purpose of a city as: to make citizens happiness possible. This shared pursuit of cities citizens makes a city a city[4].

Harari explains how humans continued to be organized through isolated human worlds[5] compounded by empires, realms, city states, more frugal settlements, or agglomeration of these. The book highlights how around 1,500 AC there were five main human worlds from which the Afro-Asian one was the biggest and counted for the 90% of the World population. Meanwhile, most part of the 10% of the remaining population lived in other four worlds: the Australian, the Andean, the Mesoamerican, and the Oceanic ones.

However, according to the book, three events changed the configuration of the World between the late XV century and the XVIII century: (i) the Spanish Kingdom's invasion of America in 1,492; (ii) the first circumnavigation of the World started by Fernão de Magalhães in 1,521 and concluded by Juan Sebastián el Cano in 1,522; and (iii) the invasion of Australia by the British Empire in 1,788. Harari supports that the consequence of these three events was that humans had been able to reduce the socio-cultural differences around the pre-existing worlds on the globe to such an end that those human worlds became unified. The World contains, since then, only one human world whose uniformity, I think, is increasing exponentially.

In this context, I suppose that new needs appeared, and that new technological improvements were developed so as to fulfil those new needs (Figure 1). Following Figure 2, I guess that these new human systems required more bureaucracy which enhanced the capacity of the human societies to support even denser and bigger human agglomerations.

I consider the first industrial revolution, the Age of Steam, which started in the decade of 1,760s[6], as one of the abovementioned technological improvements which it is said that fostered a population explosion. Although until the 1,800, only 3%[7] of the world's population lived in cities, I assume that the age of steam also induced the first massive migration from rural countryside to urban areas, especially in United Kingdom and Western Europe[8].

I see the second industrial revolution, the technological revolution or the Machine Age, between 1870 and 1914[6], as a contributor to the widespread fulfilment of the new needs created due to the massive agglomeration of humans in cities. I suppose that it was mainly based on normalizing the access to telegraph, telephones, railroads, electricity, gas, and water facilities. The mass production started, fostered by the use of petroleum derivatives instead of steam, after the creation of the internal combustion engine[6]. It was finally boosted by efficiency improvements after Henry Ford created the moving

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[4] Clayton E., (2017) Aristotle: Politics. Internet Encycl. Philos. Book I; Bekker sections 1252a to 1342b.

[5] The term world (or human world) refers to those zones of the earth with cultural, political and/or economic bonds.

[6] Klaus S., (2016) The Fourth Industrial Revolution; World Economic Forum.

[7] According to the Population Reference Bureau (2009)

[8] United Nations Population Division (2008). An overview of urbanization, internal migration, population distribution and development in the world. UNDESA (2008).

assembly line in 1913[6]. During the machine age, more people migrated from rural areas to cities, especially in Europe, North America, and Japan[7].

A third industrial revolution, the digital revolution and the beginning of the Information Age, started in the late 1950s[6], when the new findings of electronics fostered the substitution of electric analogue and mechanical devices with computers, cellular phones and the Internet. This revolution caused, again, a massive migration from rural to urban areas, this time especially in Asia[7], being China and India the greatest exponent of this phenomenon.

Nowadays, I usually hear that we are called to be in the fourth industrial revolution which, as far as I understand, is based on emerging ways to embed technology within societies and even the human body. I guess that examples of these achievements are quantum computing, artificial intelligence, nanotechnology, the internet of things, etc. and I think that we are observers of the evolution of communication and connectivity and how they are allowing billions of people to be connected to the Web.

I think that this concurrently evolution of human population, technology developments, and migration from rural to urban areas have increased the capacity of Homo to threaten the ecosystems. From my personal understanding, this threat, which, as far as I deduced from the book, was happening 6,000,000 years BP at a micro-ecosystem level, nowadays has been enhanced to a World level. I hold that Homo has become able to modify the World thermodynamics system being Climate Change one of the biggest challenges of the XXI century. Furthermore, this century is the first one when, since 2,008, more than 50% of the 7,700,000,000 world's population lives in cities[9]. Therefore, I believe that new city management systems have to be generated so as to help policy makers and decision takers to ensure a sustainable and prosperous future to the species.

[9] World Bank Data (2018). Urban Population.
https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS

Chapter 1. Introduction

1.1. Structure of the thesis

This thesis seeks to enhance the knowledge around the sustainability assessment methods of cities. Special effort is put on the revision of existing environmental assessment methods and of city assessment methods highlighting those methods which include life cycle (LC) perspective considerations. The thesis fills in the existing gaps in the scientific literature regarding the methods and the system under study.

In the Results Chapter, the thesis provides the first steps of a new environmental assessment method for cities, which takes into account both a life cycle perspective and the other two dimensions of sustainability: economic and social.

The methodological advancements proposed in this thesis are mainly based on three articles, which shed light on the meaning and linkage between what a city is and how a city can be assessed by means of a life cycle perspective. New methodology has been built on some of those items which have the highest influence on a LCA study.

Section 3.1 is based on Paper 1, "Towards life cycle sustainability assessment of cities. A review of background knowledge", and focuses on existing standards, methods, and guidelines to demonstrate that current methods are not compliant with the ISO standards on LCA. The section includes a revision of the current definitions of what a city or urban area is, so as to allow a coherent description of the system under study.

Section 3.2 is based on Paper 2, "First steps in life cycle assessments of cities with a sustainability perspective: a proposal for goal, function, functional unit, and reference flow", and, following ISO 14040:2006 procedures, focuses on defining the goal and some items of the scope of a city LCA.

Section 3.3 is based on Paper 3, "Allocation and system boundary in life cycle assessments of cities", and focuses on proposing procedures, related to remaining items of the scope, and the inventory phase of an LCA (i) on how to set city boundaries and (ii) for allocating burdens among cities. The article proposes three procedures for the former aim and four for the later, showing pros and cons. The article also includes a survey to a panel of more than 80 international experts, which provided feedback on the proposed procedures.

In addition to these three purely methodological papers, two more contributions have been published in the form of case of studies of specific components of the built environment, contributing to shed light on more applied issues of LCA.

Section 3.4 is based on Paper 4, "Does a Life Cycle Assessment remain valid after 20 years? Scenario analysis with a Bus Stop study". Knowing the high longevity of systems within the built environment, the paper focuses on assessing the validity of LCA along time. As a micro-building or a city energy supply infrastructure, a case study of a Bus Stop was taken as a proxy. This LCA was performed in 1998 and re-performed with up-to-date inventory and impact assessment data and methodologies, so as to check the similarities and differences between the same object of study separated by 20 years. Special focus is put on the causes that make the results of the two studies equal or different.

Section 3.5 is based on Paper 5, "Life Cycle Assessment of a solar thermal system in Spain, eco-design alternatives and derived climate change scenarios at Spanish and Chinese National levels". Environmental assessments are good if they stimulate change. Changes at city level require changes in policy making which can surpass the city boundaries. A case study on these matters was conducted for an important component of a city: house water heating. After assessing impacts with LCA, eco-design strategies of Domestic Solar Hot Water (DSHW) devices were studied, and the consequences of national policies increasing the share of solar energy in the national hot water mix. The article exemplifies the emissions avoided in the case of Spain and China if the DSHW share would raise up to 30%. Furthermore, the methods to be used to displace existing technologies when a share of one of them is increased are discussed.

With this five sections, the document contributes both to LCA methodology for cities and to LCA practise applied to parts of the built environment hierarchy. The LCA of a whole city, following the suggested method in this document, is still a remaining issue. However, the possibility of applying LCA to cities in a standardized way has been demonstrated both at methodological (sections 3.1, 3.2, and 3.3) and applied levels (sections 3.4 and 3.5), being this the essence of the PhD thesis.

A discussion chapter has been added (Chapter 4) so as to link and highlight the findings in each of the results sub-sections. It includes: (i) an introduction to the complexity of cities; (ii) a rationale on the need of holistic perspective in city LCAs; (iii) considerations on the goal and scope of city LCA; and (iv) additional considerations on the simplification needs due to the complexity of both, the method and the object of study.

A Conclusions Chapter has been added (0) so as to summarize the main outcomes. It includes overall conclusions of this thesis, and specific conclusions related to each of the research objectives. Finally, the limitations found during the research period and suggestions for future research are described as well.

1.2. Life Cycle Assessment and the built environment

According to Eco Platform's[10] last position paper (Eco Platform 2016), "it is worth noting that LCAs in the construction sector are somewhat different from other LCAs, as they represent intermediate and long lasting products. Therefore, their environmental assessments have to be carried on a building level. They usually also cover quite a large range of different sizes and formats for products in a specific product category".

The plan of this thesis is to go one step further within the built environment, considering a whole conception of a city. A city is not just built environment, it includes the built environment and the resource flows it transforms and consumes. It can be viewed from an organizational point of view or, beyond this, some authors (Ravetz 2000; Ness et al. 2007; Hillman and Ramaswami 2010; Kennedy et al. 2011; Goldstein et al. 2013; Nel·lo et al. 2016; Mirabella and Allacker 2017; Petit-Boix et al. 2017; Mirabella et al. 2018) consider cities as organisms, and they suggest the use of the term "urban metabolism". Institutions such as City Protocol (2015) also use the term "city anatomy" Figure 3.

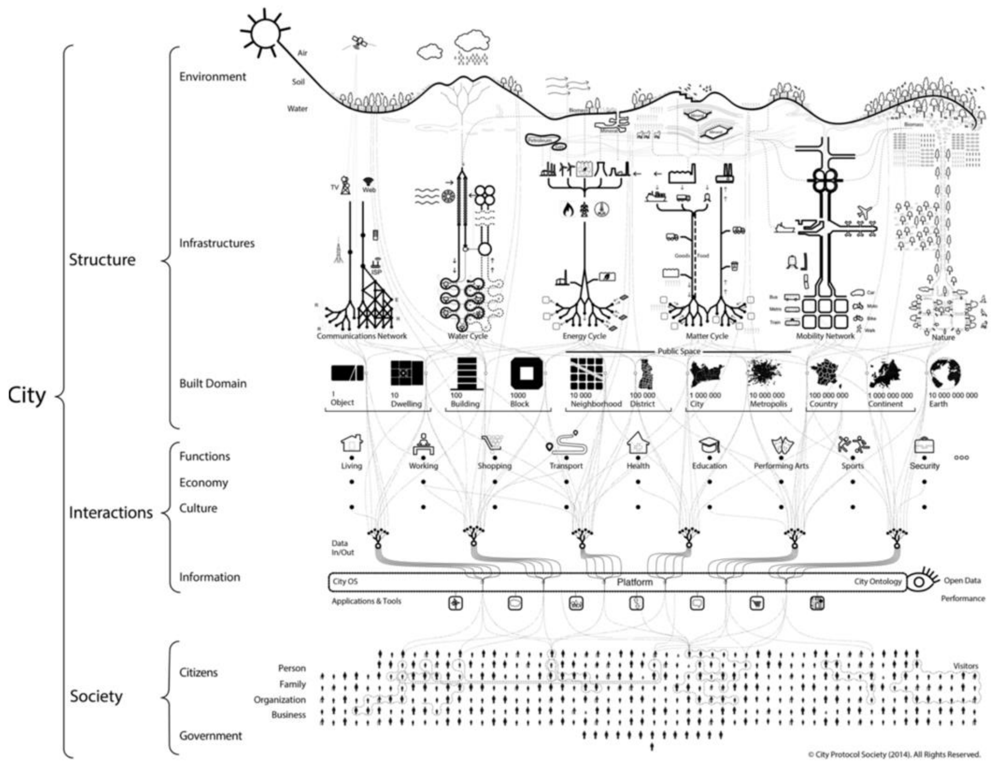

Figure 3. City anatomy as foundation for the City Protocol. Source: URENIO (2015)

[10] ECO Platform is an International Non-Profit Association established by European EPD Programme Operators as well as supporting members from European Trade Associations in the construction sector, Green Building organizations and LCA Practitioners. (Source: www.eco-platform.org)

The life cycle of a construction system (see Figure 4) starts with the extraction of raw materials from the environment and continues with the design and construction of the built system. Then, the use and maintenance stages take place and, finally, the system ends with an end of life, demolishing or deconstructing it, and landfilling or recycling its different materials.

The major contributor of environmental impacts of a building system usually is the use phase (Chau et al. 2015; Anand and Amor 2017). Although this is still true, due to efforts in energy efficiency, new techniques, better insulation, etc., buildings tend to Nearly Zero Energy Buildings (NZEB). NZEB's share of environmental impacts of the use stage are much lower, implying that the other stages are being more and more important in relative terms (Anand and Amor 2017). One example of such a situation was assessed by Blengini and Di Carlo in 2010. These authors compare a NZEB with a building which fulfils the Northern Italy's legal standard requirements (UNI EN 832, 2001). Results show how the inclusion of new materials into the building shell, to reduce energy use during the use stage of the building, make this materials represent the highest relative contributions in all the studied impact categories.

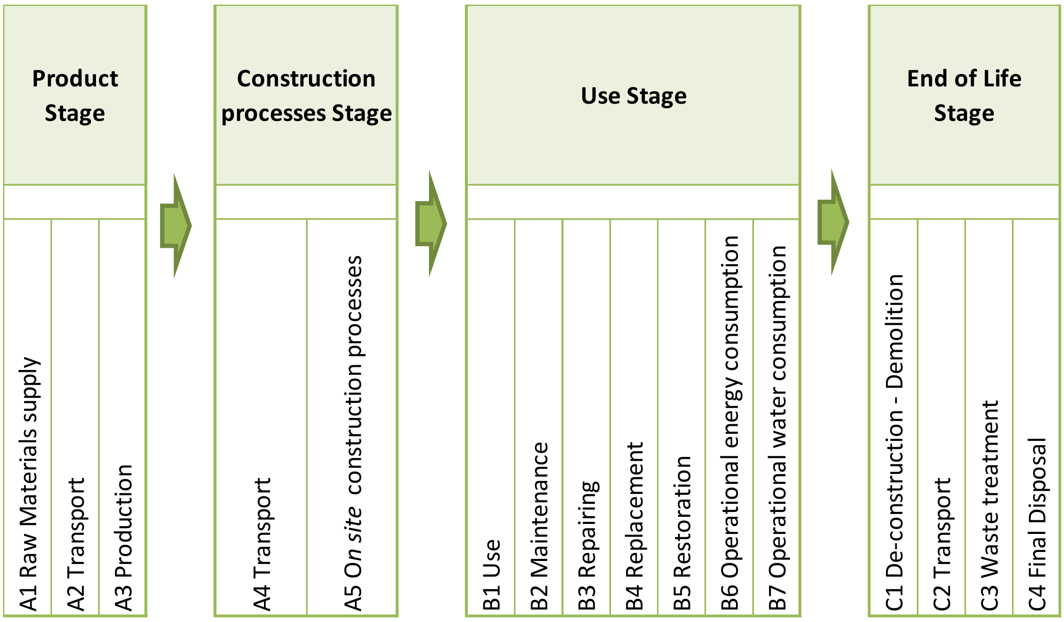

Figure 4. Life Cycle of construction stages. Source: Wittstock et al. (2012a)

The increasing relevance of other LC stages reflects the need to shift the impact analysis to a more LC oriented methodology. There have been some steps taken in this direction (Wittstock et al. 2012a; Li et al. 2013; Kylili and Fokaides 2015a). The analyses for the products of construction sector and buildings themselves are increasing, since LCA methods are already available for construction products (Wittstock et al. 2012b) and simplified LCA tools are being developed (OneclickLCA; EnerBuiLCA 2012; Anand and Amor 2017).New standardised methods have been stablished for developing LCA of different product categories, the so-called Environmental Product Declarations (EPDs), which offer LCA based quantitative information to help producers to apply eco-design to their products and consumers to make informed-based purchases (ISO 14025:2006; EN 2008; Gazulla Santos 2012).

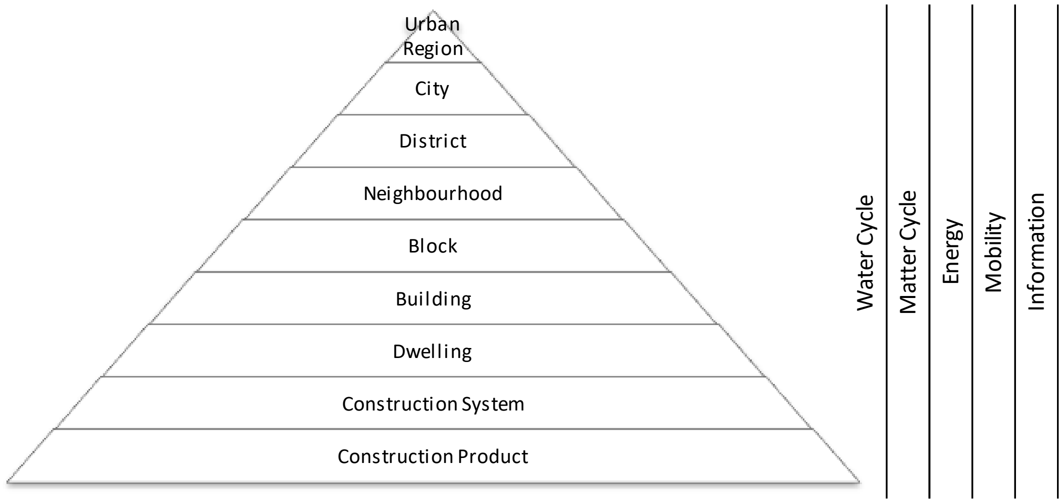

Figure 5. Built environment hierarchy. Inspired by City Protocol (2015)

There has been research on the application of LCA to the built environment, from construction products (Benveniste et al. 2011; Leão Oliveira 2014; Ros-Dosdá et al. 2018), through Constructive Systems, Buildings themselves (Lasvaux et al. 2014) and Neighbourhoods (UrbiLCA 2011; EnerBuiLCA 2012). Despite this, there has not been an LCA of a city from a holistic point of view.

1.3. Problem definition

Cities are getting more and more important in the high level meetings and boards focusing on Climate Change all around the world (Albertí et al. 2017). Moreover, studies show how the number of urban settlements will increase as their population does (Machel 2004). Water Scarcity is becoming a hot topic day by day (UNDESA 2015a) and, in parallel, the concept of Circular Economy has taken off and the use and application of Life Cycle Assessment (LCA) has been boosted.

As it has been stated in Section 1.2, much work has been done in order to create a construction materials database for LCA. There have been studies performed focussing in parts of the built environment hierarchy: from a brick to a building, even to a whole neighbourhood.

The needed further step is to analyse the applicability of current LCA methods, not only to a group of buildings but also to a more complex system such as a City (Albertí et al. 2018a). Cities include more facilities and conceptual differences, which should be tackled from a new perspective as, for instance, cities are geographically fixed systems. Methods, framework, criteria, and concepts developed for the lower levels of study can be useful to see the convergence into standardization. This standardization contributes to avoid the generation of an ad hoc method per each system, which would difficult consensus and results' comparison. However, cities should not be just considered an addition of construction products and buildings. Instead, cities are a more complex concept which could require a more holistic approach which may include the activities that happen within the city and those activities that are induced by the city out of its boundaries.

There is no scientific methodology that sets how to apply the Life Cycle Assessment method to cities. Current methods for impacts of cities measurement in a given period do not allow comparison among their results. Moreover, there are no common references/databases to facilitate results benchmarking and to extract best available solutions which have included a life cycle perspective.

This thesis is part of a bigger project carried out by the UNESCO Chair in Life Cycle and Climate Change at ESCI-UPF, with the aim to set, apply, refine, and foster a widespread use of cities LCA, and which follows LCA projects at different levels of the built environment hierarchy: material, product, building and neighbourhood.

The execution of the activities involved in the development of this part of the project can be divided in three phases. The first phase focuses on a state of the art review and, from here, a methodology is proposed. This phase will be concluded, after the publication of the present work. However, in order to complete the methodological development, started with the setting of the goal and scope, and the allocation procedures, additional study will be needed related to other issues such as:

a) Within the Goal and Scope: additional allocation procedures, data and data quality requirements, cut-off rules, impact categories recommendations, critical review considerations, reporting format;
b) Within the Inventory Analysis: data collection alternatives, unit process descriptions, process exclusions;
c) Within the Impact Assessment: need of new categories, normalisation and weighting recommendations, introduction of other areas of sustainability; and
d) Within Interpretation: indications on gravity analysis, uncertainty analysis, sensitivity analysis, completeness analysis, consistency check, limitations, etc.

In the second phase, the methodology would be applied to a specific city. The success of this pilot exercise brings the project to the third phase, which is the comparison of the results obtained from different cities, which should lead into a ranking where cities are valued in sustainability behaviour terms.

Throughout the thesis development, a stakeholders' consultation has been carried out and their feedback has been used in order to complement the scientific basis with practical and useful characteristics to increase the usability of the method. The experience acquired on future pilot case of studies shall contribute to refine the methodology.

A background goal that has guided all the development of this thesis is the capacity to compare results among cities. This has been kept in mind so as to allow benchmarking, best available solutions sharing, and the realization of a ranking to publish different cities' environmental behaviour.

First environmental approaches to cities date back to the 1960s (Rotmans et al. 2000). However the number of approaches developed raised during the nineties (Rees and Wackernagel 1996; Fullana et al. 1998; Newman and Kenworthy 1999; or Rieradevall et al. 1999, among others) and was boosted during the first decade of this century (Ache 2000; Ravetz 2000; Ferrarini et al. 2001; UN Habitat 2001, 2002; van Kamp et al. 2003; Newman 2006; Lee and Huang 2007; Okpala et al. 2007; or UNEP 2009, among others). In section 3.1, this and other procedures are reviewed, presented, and analysed.

1.4. Alignment of this thesis to the Sustainable Development Goals

This thesis hopes to follow and contribute to concerns set in international fora. The Millennium Development Goals, which, according to UN (2018), "set an historic and effective method of global mobilisation to achieve a set of important social priorities worldwide", were agreed by all countries setting targets for 2015. In 2016, the Sustainable Development Goals (SDGs) replaced the MDGs. The SDGs are a call for action by all countries to follow the 2030 Agenda for Sustainable Development (UN 2015). They are a "universal set of goals, targets, and indicators that UN member states have committed to use to frame both domestic and international development policies over the next 15 years" (Kanuri et al. 2016). SDGs include life cycle and supply chain considerations and, although the scope is national, some actions to achieve and improve SDGs' targets will be taken at a city level (UN Habitat 2016a).

In 2017 the UN Department of Economic and Social Affairs (UNDESA) lead a survey on the implementation of the SDGs which were the base for consideration for the high level political forum on sustainable development (UN 2018). The survey results were used to create a database which could "be used as a reference and analytical tool for identifying good practices, lessons learned, emerging gaps, as well as key elements of a possible Roadmap of UN system organizations on the 2030 Agenda and the SDGs" (UNDESA 2018). Each SDG includes targets which fulfilment is measured through indicators.

With the goal of measuring progress on SDG goals, 231 indicators have been developed and can be consulted at UNDESA statistics division's webpage [11]. These monitoring indicators contribute to understanding how far a country is to achieving a sustainable development. However, SDGs are to be implemented across different territorial scales including subnations, metropolitan, and local governments, which are as integral to SDGs as national governments (Kanuri et al. 2016).

The SDGs come into effect in a moment when more people live in urban areas than in rural ones, and this trend continues (UNDESA 2014). There is a specific SDG which focusses on cities: SDG#11, "Make cities and human settlements inclusive, safe, resilient and sustainable". One of SDG#11 targets considers the influence of cities beyond their boundaries: "11.A: Support positive economic, social and environmental links between urban, per-urban and rural areas by strengthening national and regional development planning".

Furthermore, there is another goal which focusses on including LC perspective in the supply chain: SDG#12, "Ensure sustainable consumption and production patterns". Two of SDG#12 targets report explicitly to life cycle or supply chain: "12.3: By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses"; and "12.4: By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle".

Although, targets 11.A, 12.3, and 12.4 directly refer to Life Cycle thinking or to cities as the system to be considered, there are other SDGs, in addition, the targets of which can

[11] https://unstats.un.org/sdgs/

either include the LC perspective, can be calculated at a city level, or the implementation of which will involve cities. This targets have been extracted from UN SDGs webpage[12] and are presented in Table 1, including the indicators considered for each target. In these targets cities will have something to either evaluate, contribute, implement, or will be affected by its achievement. Performing LCA of cities would contribute to enhance the available information of city managers to report the SDG indicators and targets progress reports.

[12] https://sustainabledevelopment.un.org

Table 1. SDGs targets which can either include the LC perspective, can be calculated at a city level, or the implementation of which will involve cities. Source: UN SDGs webpage

SDG	SDG Targets	Indicator/s
SDG 3: Good Health and Well-being	3.6 By 2020, halve the number of global deaths and injuries from road traffic accidents	3.6.1 Death rate due to road traffic injuries
	3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	3.9.1 Mortality rate attributed to household and ambient air pollution
		3.9.2 Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (exposure to unsafe Water, Sanitation and Hygiene for All (WASH) services)
SDG 6: Clean Water and Sanitation	6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all	6.1.1 Proportion of population using safely managed drinking water services
	6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations	6.2.1 Proportion of population using safely managed sanitation services, including a hand-washing facility with soap and water
	6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	6.3.1 Proportion of wastewater safely treated
	6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	6.4.1 Change in water-use efficiency over time
		6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources
	6.A By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including	6.A.1 Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan

	water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies	
SDG 7: Affordable and Clean Energy	7.2 By 2030, increase substantially the share of renewable energy in the global energy mix	7.2.1 Renewable energy share in the total final energy consumption
	7.3 By 2030, double the global rate of improvement in energy efficiency	7.3.1 Energy intensity measured in terms of primary energy and GDP
SDG 11: Sustainable Cities and Communities	11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums	11.1.1Proportion of urban population living in slums, informal settlements or inadequate housing
	11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons	11.2.1 Proportion of population that has convenient access to public transport, by sex, age and persons with disabilities
	11.3 By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries	11.3.1 Ratio of land consumption rate to population growth rate
		11.3.2 Proportion of cities with a direct participation structure of civil society in urban planning and management that operate regularly and democratically
	11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage	11.4.1 Total expenditure (public and private) per capita spent on the preservation, protection and conservation of all cultural and natural heritage, by type of heritage (cultural, natural, mixed and World Heritage Centre designation), level of government (national, regional and local/municipal), type of expenditure (operating expenditure/investment) and type of private funding (donations in kind, private non-profit sector and sponsorship)
	11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations	11.5.1 Number of deaths, missing persons, and persons affected by disaster per 100,000 people
		11.5.2 Direct disaster economic loss in relation to global GDP, including disaster damage to critical infrastructure and disruption of basic services

	11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	11.6.1 Proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated, by cities
		11.6.2 Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)
	11.7 By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities	11.7.1 Average share of the built-up area of cities that is open space for public use for all, by sex, age and persons with disabilities
	11.A Support positive economic, social and environmental links between urban, per-urban and rural areas by strengthening national and regional development planning	11.A.1 Proportion of population living in cities that implement urban and regional development plans integrating population projections and resource needs, by size of city
	11.B By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels	11.B.1 Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015-2030a
	11.C Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials	11.C.1 Proportion of financial support to the least developed countries that is allocated to the construction and retrofitting of sustainable, resilient and resource-efficient buildings utilizing local materials
SDG 12: Responsible Consumption and Production	12.2 By 2030, achieve the sustainable management and efficient use of natural resources	12.2.1: Material footprint, material footprint per capita, and material footprint per GDP
		12.2.2: domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP
	12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment	12.4.2 Hazardous waste generated per capita and proportion of hazardous waste treated, by type of treatment

	12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse	12.5.1 National recycling rate, tons of material recycled
	12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature	12.8.1 Extent to which (i) global citizenship education and (ii) education for sustainable development (including climate change education) are mainstreamed in (a) national education policies; (b) curricula; (c) teacher education; and (d) student assessment
SDG 13: Climate Action	13.2 Integrate climate change measures into national policies, strategies and planning	13.2.1 Number of countries that have communicated the establishment or operationalization of an integrated policy/strategy/plan which increases their ability to adapt to the adverse impacts of climate change, and foster climate resilience and low greenhouse gas emissions development in a manner that does not threaten food production (including a national adaptation plan, nationally determined contribution, national communication, biennial update report or other)
	13.3 Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning	13.3.1 Number of countries that have integrated mitigation, adaptation, impact reduction and early warning into primary, secondary and tertiary curricula
		13.3.2 Number of countries that have communicated the strengthening of institutional, systemic and individual capacity-building to implement adaptation, mitigation and technology transfer, and development actions
	13.B Promote mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and small island developing States, including focusing on women, youth and local and marginalized communities	13.B.1 Number of least developed countries and small island developing States that are receiving specialized support, and amount of support, including finance, technology and capacity-building, for mechanisms for raising capacities for effective climate change-related planning and management, including focusing on women, youth and local and marginalized communities
SDG 14: Life Below Water	14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution	14.1.1 Index of coastal eutrophication and floating plastic debris density
	14.2 By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action	14.2.1 Proportion of national exclusive economic zones managed using ecosystem-based approaches

	for their restoration in order to achieve healthy and productive oceans	
	14.5 By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information	14.5.1 Coverage of protected areas in relation to marine areas
	14.7 By 2030, increase the economic benefits to Small Island developing States and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism	14.7.1 Sustainable fisheries as a percentage of GDP in small island developing States, least developed countries and all countries
SDG 15: Life on Land	15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements	15.1.1 Forest area as a proportion of total land area
		15.1.2 Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type
	15.9 By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts	15.9.1 Progress towards national targets established in accordance with Aichi Biodiversity Target 2 of the Strategic Plan for Biodiversity 2011-2020
	15.B Mobilize significant resources from all sources and at all levels to finance sustainable forest management and provide adequate incentives to developing countries to advance such management, including for conservation and reforestation	15.B.1 Official development assistance and public expenditure on conservation and sustainable use of biodiversity and ecosystems

1.5. Rationale and research objectives

International environmental governance initiatives, such as the Conference of the Parties, base the accountability of CO_2 emissions focussing on the country where those emissions are produced. However, using a life cycle perspective of environmental impacts is gaining momentum since a specific Sustainable Development Goal (SDG) on responsible consumption and production (SDG#12) was set and reported in 2015 (UN 2016a).

This shift requires methods to allocate the share of impacts which should be assigned to each block of the supply chain, and LCA is one of the bests candidates to be used (Ness et al. 2007). LCA can be used in products and other systems which have impacts at micro, meso, and macro levels (European Commission 2010). However, current LCA ISO standards focus on products or organizations and there is no ISO standard prepared to assess cities, regions, or countries from a life cycle perspective.

The World Resources Institute together with C40 and ICLEI joined efforts to publish the first protocol for community-scale GHG emission inventories (WRI et al. 2014). It is a first step to assess geographically fixed systems including the possibility to consider impacts from a LC perspective (the so called Scope 3). Unfortunately, the results given by the existing standards and methods to assess cities do not bring all the information that could be given and use different definitions of the systems under study (Albertí et al. 2017).

The results obtained from the application of any existing standard do not facilitate comparison (Albertí et al. 2018a). Therefore, if neither the comparison between cities nor the ranking of them is possible, the application of benchmarking solutions becomes more difficult. Comparison of assessment results is not possible because they are provided in absolute terms. If the analyst wants to compare two cities with different number of inhabitants and level of development, the emissions considered with the current frameworks do not consider how much the function of the system (which was not yet been stated) has been fulfilled (Albertí et al. 2017). Hence, the current situation reduces the city actors' capacity of putting results together, extracting conclusions, and applying common strategies.

UN Habitat (2012) states that cities are responsible for more than 60% of carbon dioxide emissions. Therefore, if a tool that could assess carbon dioxide and other environmental impacts at a city level is developed, that tool would be assessing most of the emissions at a global scale causing climate change. The World Bank adds more information by including the effect of city residents and taking into account all greenhouse gases. In that case, the share of emissions attributable to cities raises to 80% (The World Bank 2016). It is a matter of focusing on the major contributor! This thesis is providing solutions on how to quantify the problem in order to facilitate the change and choose the most adequate response. This will be done by including the function of a city in the impact assessment and thus allow analysts to understand which are the impacts that a city is causing to fulfil its function. This argument is supported by Cities Climate Leadership Group (C40) as their premise is that: "better, more transparent measurement leads to better management" (C40, 2018).

Hopefully, this thesis will be a step to city LCAs and, therefore, to benefit present and future urban citizens by allowing city officials to manage their cities with a tool that includes a life cycle perspective, allows comparison and best practices sharing, avoids problem shifting, and includes aspects from the three dimensions of sustainability. It is stated that over 80% of the world's population is expected to live in urban areas by 2050 (The World Bank 2016). Thus, the tools designed today and the decisions of tomorrow based on these tools will affect more than three quarters of the global population.

A similar rationale is argued in a more economy-based statement by the OEDC. OECD focuses on adaptation costs and warns that 80% of the climate change adaptation costs are expected to be borne in urban areas (OECD 2014). This thesis is based on the same rationale than OECD is applying. This is, to focus on the major contributor to the problem, fix and develop ideas to measure it and provide tools to turn the source of the problem into a source of solutions. The reasoning is aligned with the UNEP view to generate opportunities for people by catalysing a global transition to a low-carbon economy (UNEP 2011).

The European Union is also a main actor for fostering research and tools development for effective climate change fighting. It is this way not only because 75% of the population in Europe lives in urban areas, but also because climate change impacts on European cities as hubs of Europe's economic activity, social life and culture, innovation and knowledge-creation on a way that has repercussions far beyond the city borders (European Union 2016). This is aligned with the belief of UNFCCC that cities are part of the solution and that it is necessary to create mechanisms to include sub-National authorities in the international environmental governance, as it is in cities where solution implementation takes place (UNFCCC 2008). This thesis is providing the first steps for life-cycle oriented city sustainability assessment tools to effectively understand the impacts caused by these "hubs" and, on this basis, let decision takers base their solutions on knowledge- and science-based reasoning.

The complexity of sustainability applied to cities and the need to implement urban action through a multi-level approach is stated by the Union for the Mediterranean (UfM) in accordance with the Strasbourg Declaration: "an integrated approach is needed" (UFM 2011); and this thesis aims to contribute to. Furthermore, the way to tackle these city assessments have to be:

a) multidisciplinary, including different fields of expertise such as engineering, environment, biology, mathematics…;
b) multilevel, considering not only city officials but also public servants from the regions and the country where the city is located;

c) with continuous bottom-up and top-down feedback, to take the benefits from both approaches; and
d) iterative.

In relation to point c) above, the thesis follows the Regions of Climate Action (R20) statement which points out that the fight against climate change must include the "bottom up" commitment of all stakeholders (R20 2016). A bottom up approach contributes to determine the areas of improvement of a system while top down approaches trend to fade the accountability of each area of the assessed system. Thus having bottom up considerations is crucial for getting a useful standard which would hopefully be derived from this work.

The work done by the City Protocol Society (City Protocol 2015), the British Standards Institution (PAS 2070 2014), and the World Business Council on Sustainable Development (WRI et al. 2014) has been taken into account. These organizations could contribute to the creation of a standard to define a common method applicable to all cities regardless of size or type, embracing protocols that may help cities deploy solutions throughout the services they provide to their citizens. The consideration of upstream and downstream impacts in city assessment is aligned with the promotion of circular economy which foster the internalization of functions (Sauvé et al. 2016) performed at a distance, outside the perimeter of the city. Assessing the impact added to the city due to the internalization of functions requires that the scope of the impact evaluation includes the entire supply chain and that impacts along that supply chain are shared based on a scientific criterion and not on arbitrary decisions (Azapagic and Cliff 1999).

Keeping in mind all the above mentioned considerations, the **research objectives** of this thesis are:

1. To propose criteria on which conditions city LCA methodology should comply with.
2. To review the existing environmental assessment methods and to analyse their compliance with the criteria set in objective 1.
3. To review the existing city assessment methods and analyse their compliance with the criteria set in objective 1.
4. To propose how to define the goal of a city LCA.
5. To propose how to define the following scope items of a city LCA:
    a. the function,
    b. the functional unit,
    c. the reference flow,
    d. the boundaries of the city system, and
    e. the allocation procedures to be followed.
6. To contribute to the understanding of the validity of LCA along time.
7. To explore the consequences on the choices of system substitution when credits are calculated.

Table 2 indicates the sections where the different research objectives are dealt with. 1-3 are dealt with in section 3.1. The research objectives 4, and 5a, 5b, and 5c are dealt with in section 3.2. The research objectives 5d and 5e are dealt with in section 3.3. Finally, the research objective 6 and 7 are fulfilled through section 3.4 and section 3.5 respectively.

Table 2. Dealing with the objectives of this thesis

Objective	Section
1. To propose criteria on which conditions city LCA methodology should comply with.	Section 3.1
2. To review the existing environmental assessment methods and to analyse their compliance with the criteria set in objective 1.	Section 3.1
3. To review the existing city assessment methods and analyse their compliance with the criteria set in objective 1.	Section 3.1
4. To propose how to define the goal of a city LCA	Section 3.2
5. To propose how to define the following scope items of a city LCA:	
a. the function,	Section 3.2
b. the functional unit,	Section 3.2
c. the reference flow,	Section 3.2
d. the boundaries of the city system, and	Section 3.3
e. the allocation procedures to be followed.	Section 3.3
6. To contribute to the understanding of the validity of LCA along time	Section 3.4
7. To explore the consequences on the choices of system substitution when credits are calculated	Section 3.5

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Chapter 2. Methodology

2.1. Introduction

The research process (Figure 6) starts with the definition of a research question. In order to evaluate if the existing state of the art is able to provide answer to that research question, a systematic literature review is performed (Section 3.1). The review includes inventorying and analysing the state of the art, published until 2017, regarding existing sustainability assessment tools and its suitability to be applied through a LC perspective to systems beyond buildings.

In order to accomplish the overall goal of the review, a number of specific goals are pursued:

a) Reviewing and analysing the existing LC based methods in the construction sector (finding how up in the construction hierarchy is LCA being used (Figure 7) from product and service methods to sector or organisation methods).
b) Reviewing the existing sustainability assessment methods applied to “beyond buildings” systems.
c) Inventorying the existing indexes and compound indexes that may be useful to assess a city from a sustainability perspective.
d) Setting the criteria to be fulfilled by LCAs of cities

Once the criteria are set and the research gaps are identified, research is conducted to fill in each of those gaps. The framework established by ISO 14040:2006 and ISO 14044:2006 for developing an LCA starts by defining the goal and scope of the study. Therefore, another systematic literature review has been performed so as to extract the procedure for defining the goal, function, functional unit, and reference flow of such a complex system as a city. Afterwards, how to solve these LCA scope items is suggested in section 3.2.

The same method is applied to the boundary setting and the allocation procedures for a city LCA. The revised literature lays the foundation to develop and/or propose specific procedures for city LCAs which are presented in section 3.3.4 of this thesis. The study is complemented with a survey to city stakeholders, presented in section 3.3.4.3, which aims to gather their perception and evaluation of the proposed procedures for the definition of boundaries and the allocation of impacts.

Furthermore, applied contributions are seek through case studies. Firstly, being a city a very long lasting system, information on how do LCA results remain valid in time is explored in section 3.4. Secondly, consequences on the choices of system substitution when credits are calculated are provided in section 3.5.

Finally, in Chapter 4 the results as a whole are discussed, and the overall conclusions of this thesis are provided in 0.

2.2. Methodological process

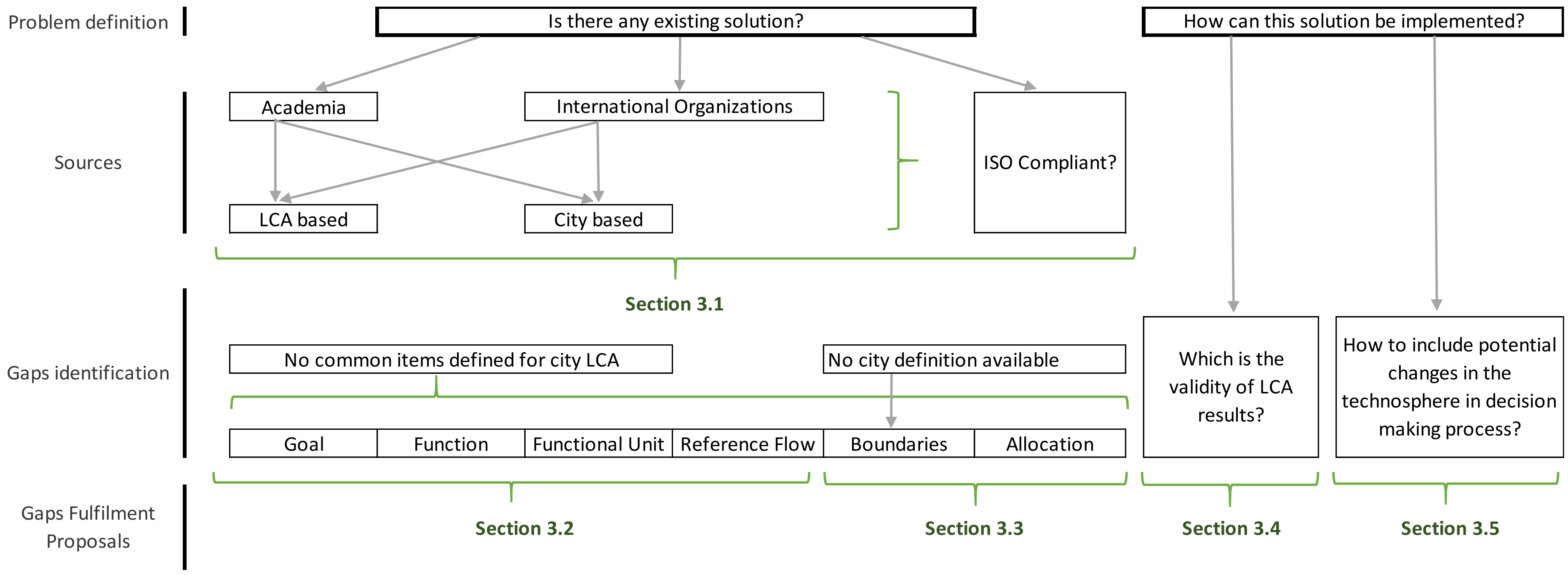
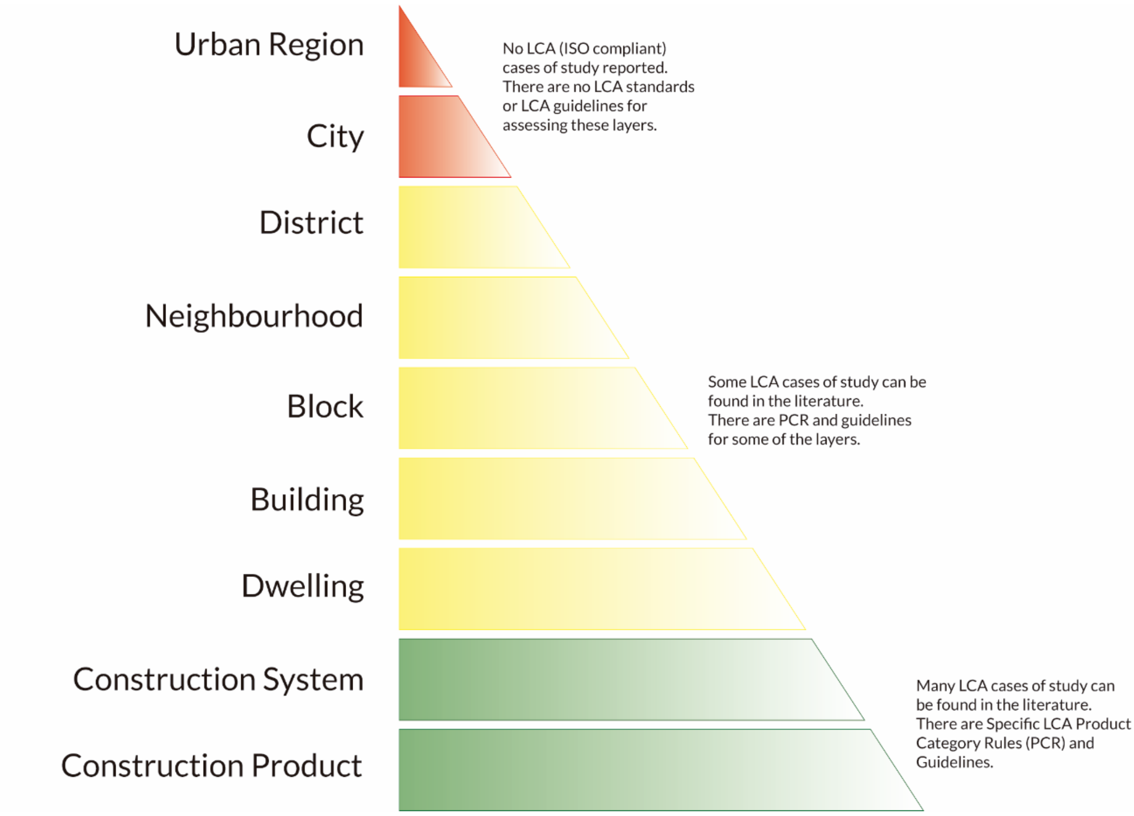


Figure 6. Methodological process of this thesis.

Chapter 3. Results



3.1. Towards life cycle sustainability assessment of cities. A review of background knowledge[13]

[13] The information in this section is extracted from this published article: Albertí, J., Balaguera, A., Brodhag, C., Fullana-i-Palmer, P., (2017). Towards life cycle sustainability assessment of cities. A review of background knowledge. Science of the Total Environment, 609, 1049–1063. https://doi.org/10.1016/j.scitotenv.2017.07.179. Web of Science Impact Factor (2017): 4.610. Quartile – Environmental Sciences Q1 (27/242).

3.1.1. Introduction

3.1.1.1. LCA-based standards and guidelines

Life Cycle Assessment (LCA) has been accepted as a useful tool to assess environmental impacts and to address eco-design and eco-innovation (Ness et al. 2007; Lotteau et al. 2015b). The potential scope of LCA has evolved from taking into account only the environmental aspect to assess the three pillars of sustainability: environment, economy, and social equity. Life cycle costing (LCC) and social-LCA were introduced in the 1980s and in the first decade of the 21st century (Guinée et al. 2011). Moreover, the life cycle (LC) perspective is being introduced in the policy agenda. It is used for decision making and has been standardized as a way to communicate the environmental performance of products (i.e. environmental products declarations or EPD) in order to boost green products demand (Del Borghi 2013). The Sustainable Consumption and production international agenda launched in Johannesburg in 2002, promoted by the Marrakech process and later formalized as one of the 17 sustainable development goals (SDG12) in the 2015-2030 agenda, have pushed LCA application to specific sectors or systems into the international policies on sustainable development (Life Cycle Initiative 2016).

From the early 70s, were LCA was focused on quantifying environmental impacts on products (Consoli et al. 1993; Guinée et al. 2011), there was a significant contribution of the Society of Environmental Toxicology and Chemistry (SETAC) towards the standardization of LCA since 1993 (Consoli et al. 1993) and a release of the first LCA standard by the International Organization for Standardization, ISO 14040 (ISO 1997), which was reviewed in 2006 (ISO 2006b). A stronger involvement of multi-sectorial and transversal agents and stakeholders reached to promote in 2003 the UNEP/SETAC Life Cycle Initiative (LCI), which fosters LC approaches worldwide (Life Cycle Initiative 2016).

During the first decade of the 21st century, part of the ISO 14040 series of standards was compiled in 2006 in the form of the new ISO 14040 and ISO 14044 to apply LCA to products and services (ISO 2006c) and the Institute for Environment and Sustainability within the Joint Research Centre (European Commission 2010) released the ILCD Handbook. In parallel, the principles of LCA were tend to be used specifically for assessing one impact category: the Carbon Footprint (CF) (i.e. in 2001, the first Bilan Carbone methodology was published and later on revised (ADEME 2010)).

After 2010, LCA-based guidelines such as the British standard (PAS 2050: 2011) and the Greenhouse Gas Protocol (drafted in 2009 and consolidated in 2011 (WRI and WBCSD 2011), and amended in 2013 (WRI and WBCSD 2013)) were developed. Also new standards such as ISO 14067 (ISO 2013) to provide guidance for the quantification and reporting of a Product Carbon Footprint (PCF) were released. The European Commission fostered a new generation of LCA-based standards in Product Environmental Footprint ((PEF, 2010), amended in 2012 (European Commission 2012a)) and Organizational Environmental Footprint (OEF) (amended in 2013 (European Commission 2013)), which were included in the Single Market Act (European Commission 2012b, c). The Bilan Carbone Association also developed an organizational carbon assessment method in 2013 (ABC 2013). In 2014, the organizational LCA (OLCA) was internationally standardized with the release of the ISO 14072 (ISO 2014a) while, one year later, the Life Cycle Initiative promoted a guideline (Guidance on organizational LCA) for public use in 2015 (UNEP et al. 2015).

3.1.1.2. Goal and scope of this review

The overall objective of this review section is: inventorying and analysing the current state of the art regarding existing sustainability assessment tools and its suitability to be applied through a LC perspective to systems beyond buildings.

In order to accomplish the overall goal, a number of specific goals are pursued:

e) Reviewing and analysing the existing LC based methods in the construction sector (finding how up in the construction hierarchy is LCA being used (Figure 7) from product and service methods to sector or organisation methods).
f) Reviewing the existing sustainability assessment methods applied to "beyond buildings" systems.
g) Inventorying the existing indices and compound indices that may be useful to assess a city from a sustainable perspective.
h) Setting the criteria to be fulfilled by a LCSA of cities based on the existing methods.

The document types included are scientific papers in indexed journals, standards, guidelines, and regulations. No restriction of time coverage has been applied. The search has been performed in the following databases: ISI Web of knowledge, Scopus and Google Scholar. Keywords used for browsing included: LC perspective; LCA; Sustainability assessments; Urban; City; Sustainability Indices; Indicators; Indexes; Environmental assessment; Urban design.

As a result, this review will help to: (i) Policy makers, decision takers, environmental scientists, managers and administrators looking for an environmental assessment for cities, and who would like to get a fast and precise information panel. (ii) Scientists aiming at concluding if current sustainability assessments are enough to tackle with a specific sustainability dimension issue for cities. (iii) Scientists to use it as a basis for improvement of any current sustainability assessment. (iv) Scientists to use it as a basis to create new city oriented sustainability assessment tools.

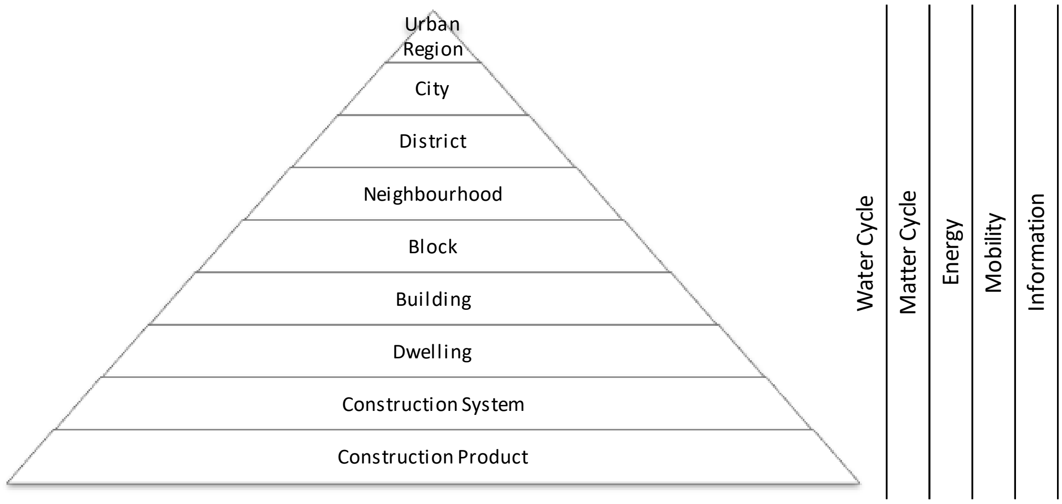


Figure 7. Built environment hierarchy. Inspired by City Protocol 2015

3.1.1.3. The categorization of the sustainability approaches

Since its development as a concept (Brundtland 1987), many assessment approaches to sustainability have been already developed and the scientific community classifies them based on different factors (Table 1).. Back in the late nineties, Moberg already compared different approaches (i.e. environmental impact assessment, LCA, emergy analyses or environmental footprint, among others), depending on their focus on natural resource use or/and environmental impacts, on the usability, and on the integration of the approach (Moberg 1999). With other colleagues, this categorization was further developed (Finnveden et al. 2003), based on the following factors: "degree of site-specificity, degree of time specificity, type of comparison, degree of quantification, system boundaries, types of objects, and types of impacts and effects considered". Furthermore, the same researchers (Finnveden and Moberg 2005) separated the approaches depending on whether they were procedural or analytical, the types of impacts considered, the object of study, and if the approach was descriptive or change-oriented. In 2007, Ness and co-workers categorised them in three main types: indicators/indices, product-related assessments, and integrated assessment tools (Ness et al. 2007)

A different classification was done by answering the following questions: is the relationship with sustainability "implicit or explicit? What is to be sustained? What is to be developed? For how long?" (Kates et al. 2005).

An early and somehow different classification put the focus on the relationships between approaches (consecutive, complementary, competing/incompatible, encompassing or overlapping) instead on the approaches themselves (Baumann and Cowell 1999).

Table 3. Factors for the categorization of sustainability approaches

Key factors to define categories						Classification by
Indicator	Product Related	Integrated assessment tool	-	-	-	(Ness et al. 2007)
Focus on natural resources or Environmental impact	Usability	Integration of the approach	-	-	-	(Moberg 1999)
Degree of site-specificity	Degree of time-specificity	Type of comparison	Degree of quantification	System boundaries	Types of objects, impacts and effects considered	(Finnveden et al. 2003)
Procedural or analytical	Object of study	Descriptive or change oriented	Types of impacts considered	-	-	(Finnveden and Moberg 2005)
Relation with sustainability implicit or explicit?	What is to be developed?	For how long?	-	-	-	(Kates et al. 2005)
Consecutive relation	Complementary relation	Competing /incompatible relation	Encompassing/ overlapping relation			(Baumann and Cowell 1999)

3.1.1.4. The hierarchy of the built environment and its relevance to sustainability

The construction sector influences social, economic, and environmental aspects in most developed countries. It achieves about seven percent of total employment in Europe and contributes to more than six percent in average to the GDP (OECD.Stat 2016a), and employment rate (OECD.Stat 2016b) in the 28 European Union countries. Regarding environmental impacts, the building sector is responsible for over one third of the final energy consumption ("the sum of consumption by the different end-use" (IEA 2013)) worldwide and for emitting approximately one-third of global CO_2 emissions (IEA 2013). This sector includes not only the construction of buildings but also that of infrastructure such as energy generation plants, transportation facilities, roads, railways, airports or water supply facilities, which, in addition, modify the land use of the region. As in any product's LC, in a construction system LC, the impacts do not only occur in one single stage (i.e. the use stage) but in every stage of its LC (Figure 8) and the relative contribution of the different LC stages to the total impact will depend on the construction processes involved and the type of system being built (Figure 8).

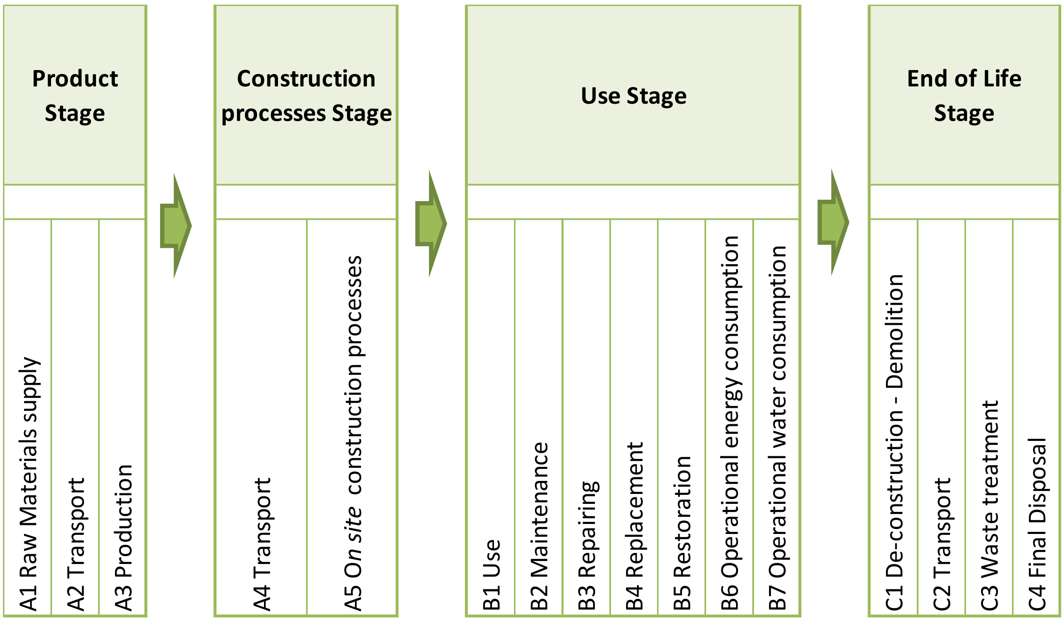


Figure 8. LC stages within construction. Source: EN (2011a) and Wittstock et al. (2012a)

The built environment can be described in the form of a hierarchical pyramid (Figure 7) of increasingly complex elements. The functioning of each stratum of this pyramid requires the existence of five flow types (water, matter, energy, mobility and information) (City Protocol 2015)

3.1.1.5. The importance of cities

In this review section, "city" is understood to include different terms (as nearly synonyms) which may be found in the literature used by different authors, such as: city-region, urban region, urban agglomeration, and urban settlement. In this new century, cities are being more and more on the focus of sustainable development agendas. One key issue is to improve the management of cities so as to foster economic growth with less social instability and environmental depletion" (Rotmans et al. 2000; Devuyst et al. 2001). Furthermore, cities and their development are considered "as one environmental, economic, social, and cultural challenge of the future" (Wiek and Binder 2005). The reason is that cities are and will be the place of living, working, and social interaction for the majority of the World population (Wackernagel and Rees 1996; Ache 2000; Ravetz 2000). The fact of conceiving cities as large emitters of pollutants (Koop and van Leeuwen 2015) and taking into account their social connotations implies the need to use triple bottom line based sustainability assessment tools (Nijkamp and Vreeker 2000).

The importance of cities has been increasingly approached by international, multilateral, and city-focused organizations. The United Nations (UN) Secretary General's Special Envoy, Michael Bloomberg, recently stated that "Now is the time for nations to partner with cities as they create more ambitious climate targets over the next year, both to help the world avoid the worst impacts of climate change and to benefit millions of people" (UN and UN Habitat 2014). There are different programs within the UN which focus on urban settlements. According to UN-HABITAT, 78% of the world's energy consumption takes place in cities and they are responsible for more than 60% of global warming, because of activities such as energy generation, vehicles, industry, and biomass use (UNHABITAT). Another UN Agency, United Nations Department of Economic and Social Affairs (UNDESA), states that about one-fifth of the world's population lives in areas of physical scarcity and near one quarter of the population faces economic water shortage (UNDESA 2015a).

At European level, 75% of the citizens live in cities and the EU warns about how climate change impact to cities, will affect Europe's economic activity hubs, social life, and culture; and how these impact will have repercussions beyond the city borders (i.e. water scarcity threaten and increasing wastewater treatment needs due to increase of population density, increase of temperature due to heat island effect, or concentration of infrastructure sensible to extreme events) (European Union 2016).

Financing will be an important issue regarding cities adaptation to and mitigation of climate change and, therefore, more economically oriented organizations have also focussed on this issue. For instance, the World Bank (WB) states that: "Residents of cities are responsible for as much as 80% of global greenhouse gas emissions while, at the same time, residents in cities are facing significant impacts from climate change. Up to 80 percent of the expected $80 billion to $100 billion per year in climate change adaptation costs are expected to be needed in urban areas" (The World Bank 2016). The Organization for Economic Co-operation and Development (OECD) also considers the important role that cities will play in climate change fighting due to three reasons: the already mentioned concentration of people expected to live in urban areas (70% by 2050) and the expected increase of urbanization; and the vulnerability of cities to storm surges and rising sea levels (specially in Asia) (OECD 2014).

Finally, clear examples of how cities position their leadership is explained by the number of relevant city-focussed organizations created. For instance, the Cities Climate Leadership Group (C40 2016) has the specific objective of addressing climate change in megacities. The Compact of Mayors (CM) tries to get data and standardize solutions through a common platform. The Energy Cities (EC) associates local European authorities to foster an energy transition towards low carbon generation. The Regions of Climate Action (R20 2013) works at a region level to improve its sustainability behaviour through the development of clean energy projects and social and ecologic audits.

The Local Governments for Sustainability (ICLEI) works at local level through the application of tools, strategies, and methodologies with the global goal of making cities more sustainable. The Global Network of Cities, Local and Regional Governments (UCLG) that represents the interests (not only environmental) of the local governments on the international and multilateral organizations. Or the World Cities Network which focuses on the increase of resilience of cities against climate change (WCN 2016). Thus, cities have acknowledged their contribution to the environmental impact and have identified ways towards sustainability (Martos et al. 2016). Sustainability is the word most frequently found in literature (de Jong et al. 2014) and LCA is a tool to help decision making for more sustainable results (Ness et al. 2007).

3.1.2. Definition of a city

Analysing the different city assessment methods, an important issue arises: there is not a unique definition of city. Moreover, there is no consensus on what an urban human settlement is (Table 4). In order to better understand the methods and the results they deliver, research on the definition of “city” and how to define a human agglomeration as “urban” has been performed.

Most literature found focusses on defining either what cities are or on describing what urban means, when referring to human settlements and human agglomerations. The differentiae in both, cities and urban (settlements), are quite similar, which brings to consider that the genera need to be related somehow. In addition, these common differentiae between cities and urban settlements can be understood as a consequence of the fact that, at least, being an urban settlement is a necessary condition to define a human agglomeration as a city. Genera and differentiae (Lyons 1977; Bussler and Fensel 2004) chosen by different authors for the city definition are presented in Table 4.

Table 4. Genera and differentiae chosen for the "city" definition by different authors

Organization	Definition	Genus	Differentia	Citation
Academia	“Boundaries of cities are defined based on population density (i.e., urban settlement area), which do not necessarily match the politically defined city boundaries.”	City	Administrative[14] Geography[15]	(Mori et al. 2015)
BSI	“Boundary usually geopolitical and defined by one or more municipal governments”	City	Administrative Geography	(PAS 2070 2014)
UN	“Built-up or densely populated area including the suburbs and continuously settled commuter areas which may be smaller or larger than a metropolitan area”	City	Population density Geography	(Mori and Christodoulou 2012) (Okpala et al. 2007)
UN HABITAT	UNHABITAT Does not define but determines the factors on which a city can be defined: "a city can be defined in terms of population and land use"	City	Population density Geography	(Mori and Christodoulou 2012) (Okpala et al. 2007)
UNEP	“The single political jurisdiction, which contains the historical city centre”	City	Administrative Centre[16]	(UNEP 2009)
WBCSD	“Geographically discernible subnational entities such as communities, townships, cities, and neighbourhoods. It can also indicate all levels of subnational jurisdiction as well as local government as legal entities of public administration.”	City	Administrative	(WRI et al. 2014)

[14] Administrative boundaries, designation from another administrative level or by law. An area with an existing administrative municipality.
[15] Orography or geographical morphology.
[16] Land Use, historic centres, urban consolidated areas, number of dwellings.

Mori and colleagues confirm the lack of consensus and the variety of definitions and methods for defining the urban concept (Mori et al. 2015). These authors base their definition of urban boundary on the population density data but they assume that other differentiae (Table 4) might influence the definition of any city: administrative boundaries, functional boundaries or morphological boundaries.

Considering the number of cases which define a city (Table 4), obtaining common differentiae would help to establish a consensual definition of "urban" applied to human settlements (Table 5). The chosen differentiae can be different in each country and continent (UN 2005). The Demographic Yearbook (2005 and forward) provides all the definitions, determined by each country, of what is "urban". Differentiae are determined by either the country administration or the city administration itself and, sometimes, more than one group of differentiae (within a country) can be determined (UNDESA 2014; UN Habitat et al. 2016).

Similarly to the analysis done in Table 4, an analysis of which are the differentiae considered in each country in the world to define a human settlement as "urban" is provided in Table 5 which includes the number of times the differentiae is referenced in the urban definition obtained from the Demographic Yearbook yearly published by UNDESA (UNDESA 2015b). Both weak reference (relation not explicitly stated) and strong reference (relation explicitly stated) to a differentia were considered. The resulting Table 5 shows that, out of eight differentiae, seven are enough to distinguish between urban and non-urban settlements. The two most frequently used out of those seven leads to the proposal to define an urban area through its population and administrative area of influence. Its economy distribution, the presence of a city centre, and the population density are also differentiae which contribute to better define it.

Table 5. Differentiae on the urban settlement definition throughout the world

Region of the world considered	Differentiae							
	Population[17]	Population density	Area	Administrative[18]	Geographic[19]	Centre[20]	Services[21]	Economic[22]
World								
Strong (S) influence	67	14	6	58	0	18	13	20
Weak (W) influence	4	1	6	3	1	4	0	4
Africa								
S influence	8	2	0	11	0	2	3	3
W influence	0	0	1	2	0	1	0	0
America, North								
S influence	11	2	0	6	0	5	5	0
W influence	0	0	1	1	0	2	0	0
America, South								
S influence	4	0	0	7	0	4	0	1
W influence	0	0	2	0	0	0	0	0
Asia								
S influence	17	4	3	16	0	3	4	9
W influence	2	1	1	0	0	0	0	3
Europe								
S influence	21	3	3	14	0	4	1	7
W influence	2	0	1	0	1	1	0	1
Oceania								
S influence	6	3	0	4	0	0	0	0
W influence	0	0	0	0	0	0	0	0

[17] Population, people living within the boundaries.
[18] Administrative boundaries, designation from another administrative level or by law. An area with an existing administrative municipality.
[19] Orography or geographical morphology
[20] Land Use, historic centres, urban consolidated areas, number of dwellings.
[21] Services provided.
[22] Economic aspects considered. Economy main sector.

3.1.3. Life Cycle Assessment of the built environment

Several methodologies have been applied to the different elements that compound the built environment hierarchy (Figure 7). LCA-based product-focused guidelines and standards implicitly include construction products. Moreover, a building is considered a product to be assessed through existing LCA standards as well. Even neighbourhoods have been assessed from this perspective. Upwards the hierarchy, the complexity of the element assessed is increasing, while the analyst uses the same standard initially thought for simpler goods (products) and services. A review of the existing indices, standards, guides, and methods for construction-related elements is shown in Table 6 and Table 7, with the intention to discover if any sustainability assessment method for cities exists complying with the following criteria: (i) holistic point of view, (ii) multi-criterial environmental impact assessment, (iii) analysis from a LC perspective, and (iv) adequacy for comparison among different cities or urban regions. Even if there is not such a method per se, the methods which were useful for products, buildings, and neighbourhoods will be analysed to see if they are flexible enough to be applied to the complexity of either a city or an urban agglomeration.

A review from 2008 (Ding 2008) analyzed more than 20 different assessment tools, where only the design stage of projects was assessed while other stages of the LC were not. A recent review of more than thirty case studies focused on the building sector (residential, offices, and schools). The review showed the increasing interest in applying environmental assessments, specially LCA, to the building sector and the increasing alignment of the regulatory framework which requires the development of environmental assessments (Buyle et al. 2013). A more city-focused review by Mori (2012) studied sixteen indicators analysing their strength in approaching to sustainability.

3.1.3.1. LCA of construction products

EN 15804 European standard provides core product category rules (PCR) (EN 2011a), in accordance with ISO 14025 (ISO 2006a), for the so called Type III environmental product declarations (EPD) for any construction product or service (for instance, for tiles(Benveniste et al. 2011)). EPDs have been demonstrated to be a useful tool in reducing environmental impacts of products (Gazulla Santos 2012), including those from the construction sector. Afterwards, a new generation of LCA-based standards for Product Environmental Footprints (PEF, 2010, amended in 2012 (European Commission 2012a)) were included in the Single Market Act (European Commission 2012b) to avoid a miscellaneous of national policies and to simplify legislation. The generation of sector operational guidelines such as the EeBGuide (Wittstock et al. 2012b) for LCA studies of buildings and construction products is a result of this policy towards standardization. The repetitiveness of the assessment and the common concepts established for similar products reinforce the usability of the results, be that use for policy making, eco-design, comparison or benchmarking.

3.1.3.2. LCA for buildings

The European Union has been increasingly fostering the reduction of the environmental footprint of buildings. The energy efficiency directive (European Parliament 2012) intends to reach an energy consumption reduction and to increase renewables share in the EU by 2020. The use of environmental standards in the building sector has continued as current European policies are promoting Nearly Zero-Energy Buildings (NZEB) to focus on the energy consumption at the use stage, which is contributing (for non-efficient buildings) up to 90% of the environmental impacts of all life cycle stages (Buyle et al. 2013). In addition, there is a trend to "incorporate the entire LC of the building products including the energy, carbon emissions, and impacts for raw material extraction, manufacturing, transporting, and disposing of the products" (Blengini and Di Carlo 2010a). In spite of this policy trend, the need for further discussion and research around the buildings environmental assessment through a LC perspective is claimed (Li et al. 2013). This is the case of Kylili and colleagues, who analysed the role of NZEB from a LC perspective, confirming that studies assessing the sustainability of NZEB should be considering LCA as well as social aspects, and that both issues need more research and development (Kylili and Fokaides 2015a). Although LCA for buildings is getting more and more performed, there is not a clear definition on which the function, functional unit (FU) and reference flow (RF) should be at the upper levels of the hierarchy, where the case studies are scarce or inexistent. These definitions are influenced by the goal chosen but, indeed, there should be a common basis, agreed by the scientific community, which would help to make results more comparable (European Commission 2010). The inclusion of social and economic aspects through the definition of an agreed function, FU, and RF could satisfy both needs.

3.1.3.3. LCA beyond buildings

There have been some implementations of LCA at upper levels than buildings (Lotteau et al. 2015c). Lotteau and colleagues reviewed different assessments of neighbourhoods, and focused on 21 case studies finding that there was no common FU although the different objects of study were similar. At the neighbourhood level, no LC standards exist and, therefore, there are not consensus proposals (Lotteau et al. 2015a) about which the function, FU, boundaries, and RF should be. For example, regarding the FU, the most used is related to the area covered by the neighbourhood (km^2 or m^2) with, sometimes, more specificity (i.e. m^2 of living space or floor area). The number of inhabitants or households; or the neighbourhood itself, are also considered in the FU to develop the LCA. Other studies have applied LCA to a specific part of the neighbourhood. This is the case of Trigaux and colleagues, who, in 2016, focused on LCA and LCC of road infrastructures in neighbourhoods (Trigaux et al. 2016a). Despite this lack of standardisation of the key LCA concepts, some scoring tools such as the Sustainable Districts Scheme from the German Sustainable Building Council (DGNB) are starting to take into account LC principles (Trigaux et al. 2016a).

3.1.4. Sustainability approaches for cities, urban regions, and countries.

Several methods has been found in the literature and have been analysed regarding their approach to the different sustainability dimensions and their use of a LC perspective. Information for sustainability indices, for readability, has been separated in two tables: Table 6 and Table 7. Sustainability standards and guidelines are described in Table 8.

3.1.4.1. Sustainability indices

Ad hoc sustainability indices for cities have been developed by several kinds of organizations and from different perspectives. Table 6 describe and classify those indices with information on: (i) if the index considers sustainability (social, economic, and environmental aspects) and if the dimensions are taken explicitly (strong consideration) or implicitly (weak consideration); (ii) the type of organization that has developed the index; (iii) its applicability to cities; (iv) the indication of more than one environmental impact being used; (v) if the index includes the assessment of indirect impacts (Scope 3); and (vi) the use or not of a LC methodology (beyond Scope 3). In addition, Table 7 complements Table 6 with information about the index calculation parameters and some analytical observations.

In some cases, city indices are adapted (re-scaled) from existing country sustainability indices. In other cases, there is not a specific boundary to apply the index to, meaning that the index can be applied to any geographical scope. A sort of indices are applied to local and regional contexts as case studies (Böhringer and Jochem 2007; Singh et al. 2008; Mori and Christodoulou 2012).

Ad hoc city indices have been developed worldwide. This is the case of the city of Seattle, where some sustainability indicators are used to tackle different problems in different areas of the city, and being a differential characteristic that the citizens themselves are those choosing the way of measuring the indicators (Sustainable Seattle). Other examples of city ad hoc sustainability indicators are: the Sustainable Index of Taipei (Lee and Huang 2007); the Maastricht 2030 project (Rotmans et al. 2000); the Compass Index for Sustainability of the Orlando city (Atkisson and Hatcher 2001); or the Toronto and Region conservation program for the living city (TRCA 2016).

Other indices may not be directly developed for one city but for a number of cities within a specific region, with the same cultural and underlying characteristics. This is the case of the Sustainability Cities Index (SCI), developed by Forum for the Future (Forum for the Future 2010). Several indicators were generated in order to analyse the cities of Britain. Those indicators took into account three main topics: the environmental impact of the city; the quality of life of their residents; and what they call the “future proofing”, i.e., how well is the city prepared for a sustainable future.

Similarly, in 2002, a 22 indicators based system was developed to define the urban sustainability index (USI) (Zhang 2002). This was specifically designed for the context of urban China. Singh and colleagues reviewed some other indices developed for wide regions, such as the Ecosistema Urbano performance Index (Singh et al. 2008), a method developed in 1994 for getting indicators and testing the environmental behaviour of 103 Italian municipalities during 10 years.

In parallel to the evolution of the previously mentioned indices, the urban metabolism concept is being rethought as a way to understand the city by using a sort of new indices (City Protocol 2015). The concept of urban metabolism is "a holistic approach to urban planning, indicating that environmental quality improvement in urban areas rests on the careful use and removal of energy and water" (City Protocol 2015). This definition incorporates the need of "exploring the interactions among resource flows, urban transformation processes, waste streams and quality of life" (European Commission 2010). Urban Metabolism describes the flows happening in a city including: energy (in form of energy equivalents, if it is the only flow accounted), water, materials, and nutrients (Kennedy et al. 2011). The creation of the City Protocol Society (CPS) contributed to the definition of the City Protocol Anatomy, which establishes the "definitions and methodologies that identify a minimum set of city data (from available city data catalogues) suitable for measuring city functions according to the structure of the City Anatomy" (City Protocol 2015). The CPS determined the indicators of the City Protocol Anatomy using those from ISO 37120 standard (ISO 2014b) and creating 59 new core indicators.

Table 6. City Indices, sustainability and LC perspective considerations

Name	Sustainability dimension			Developing Organization type	Ever applied to cities or regions?	Multi-impact assessment	Assess indirect impacts?	LC Methodology?	Year	Reference Data
	Economic	Social	Environmental							
Aegean Region Index	S[1][2][3]	S	S	Academia	Yes	Yes	No	No	2010	(Kondyli 2010; Mori and Christodoulou 2012)
Algarve Region Index	S	S	S	Academia	Yes	Yes	No	No	2009	(Mascarenhas et al. 2010; Mori and Christodoulou 2012)
City Development Index			S	International Organization	Yes	Yes	No	No	2002	(UN Habitat 2002; Mori and Christodoulou 2012)
City Prosperity Index	S	S	S	International Organization	Yes	Yes	No	No	2012	(Moreno and Murguía 2015)
City Protocol	S	S	S	International NGO	Yes	Yes	No	No	2015	(City Protocol 2015)
City Sustainability Index	S	S	S	Academia	Yes	Yes	Yes	No	2012	(Mori and Christodoulou 2012)
Compass Index for Sustainability	S	S	S	Academia	Yes	Yes	No	No	2001	(Atkisson and Hatcher 2001; Singh et al. 2008)
Dashboard of Sustainability	S	S	S	International Institute	No. Country	Yes	No	No	2001	(Scipioni et al. 2009)

[1] S: Strong consideration of the sustainability dimension
W: Weak consideration of the sustainability dimension

Name	Sustainability dimension			Developing Organization type	Ever applied to cities or regions?	Multi-impact assessment	Assess indirect impacts?	LC Methodology?	Year	Reference Data
	Economic	Social	Environmental							
Ecological Footprint			S	International Network	Yes	Yes	Yes	No	1990	(Wackernagel and Rees 1996; Global Footprint Network 2016; SPUR 2016)
Ecosistema Urbano			S	Project Based	Yes	Yes	No	No	1994	(Singh et al. 2008)
Ecosystem Well-Being Index			S	Academia	No. Country	Yes	No	No	2001	(Prescott-Allen 2001; Böhringer and Jochem 2007; Mori and Christodoulou 2012)
Emergy/Exergy			S	Academia	Yes	Yes	Yes	No	1996	(Odum 2000; Mori and Christodoulou 2012)
Environmental Adjusted net product or Green GDP	S		S	Academia	No. Country	Yes	No	No	1972-1990	(Hartwick 1977; Böhringer and Jochem 2007; Dietz and Neumayer 2007; Mori and Christodoulou 2012)
Environmental Performance index	S	S	S	Academia	No. Country	Yes	No	No	2002	(Esty et al. 2005, 2006; Böhringer and Jochem 2007)
Environmental Sustainability Index		S	S	Government organization and Academia	No. Country	Yes	No	No	2016	(Esty et al. 2005; ESI 2016)
Environmental Vulnerability Index			S	International NGO	No. Country	Yes	No	No	1999	(SOPAC 2005)
Genuine progress Indicator	S	W	W	Academia	No. Country	Yes	No	No	1995	(Cobb et al. 1999; Lawn 2003)

Name	Sustainability dimension			Developing Organization type	Ever applied to cities or regions?	Multi-impact assessment	Assess indirect impacts?	LC Methodology?	Year	Reference Data
	Economic	Social	Environmental							
Genuine Savings	S		S	Academia International Organization	No. Country	Yes	No	No	1993	(Dietz and Neumayer 2007; Hanley et al. 2015)
Green Net National Product (Equivalent to EPD)	S		W	International Organization	No. Country	Yes	No	No	2003	(UN 2003)
Human Development Index (HDI)	S	S		International Organization	No. Country	Yes	No	No	1990	(UNDP 2010, 2015)
Human Well-Being Index	W	S		Academia	No. Country	Yes	No	No	2001	(Prescott-Allen 2001; Böhringer and Jochem 2007; Mori and Christodoulou 2012)
Index of Sustainable Economic Welfare	S	W	W	Academia	No. Country	Yes	No	No	1989	(Aly and Cobb Jr. 1989)
Inequality adjusted HDI	S	S		International Organization	No. Country	Yes	No	No	2010	(UNDP, 2010, 2015)
Living Planet Index			S	International NGO	No. Country	No	No	No	2008	(WWF 2016)
Maastricht 2030	S	S	S	City council	Yes	Yes	No	No	1999	(Rotmans et al. 2000)
Reggio Emilia Index	S	S	S	Academia	Yes	Yes	No	No	2001	(Ferrarini et al. 2001; Mori and Christodoulou 2012)
Satellite-based-Sustainability			S	Academia	No. Country	No	Yes	No	2011	(Sutton 2003; Mori and Christodoulou 2012)

Name	Sustainability dimension			Developing Organization type	Ever applied to cities or regions?	Multi-impact assessment	Assess indirect impacts?	LC Methodology?	Year	Reference Data
	Economic	Social	Environmental							
Sustainable Cities Index	W	S	S	International NGO	Yes	No	No	No	2007-2010	(Forum for the Future 2010)
Sustainable Development Indicators	W	W	W	Academia	Yes	Yes	No	No	2014	(Ding et al. 2014)
Sustainable Index of Taipei	S	S	S	Academia	Yes	Yes	No	No	2007	(Lee and Huang 2007; Singh et al. 2008; Mori and Christodoulou 2012)
Sustainable Net Benefit Index	S	W	W	Academia	No. Country	Yes	No	No	1999	(Lawn and Sanders 1999)
Sustainable Seattle	S	S	S	City council	Yes	Yes	No	No	1998	(Sustainable Seattle; Lee and Huang 2007; Singh et al. 2008; World Bank Institute 2013)
SW Victoria Index	S	S	S	Academia	Yes	Yes	No	No	2009	(Graymore et al. 2009; Mori and Christodoulou 2012)
Toronto and Region conservation program for the living city			S	Public Authority	Yes	Yes	No	No	2010	(TRCA 2016)
Urban Sustainability Index			S	Academia	Yes	Yes	No	No	2002	(Singh et al. 2008)
Water Footprint		W	S	International Institute	yes	No	yes	No	2002	(Hoekstra et al. 2009)

Name	Sustainability dimension			Developing Organization type	Ever applied to cities or regions?	Multi-impact assessment	Assess indirect impacts?	LC Methodology?	Year	Reference Data
	Economic	Social	Environmental							
Well-Being Index	S	S	S	Academia	No. Country	Yes	No	No	2001	(Prescott-Allen 2001; Böhringer and Jochem 2007; Mori and Christodoulou 2012)

Table 7. Indices, calculation parameters and other relevant considerations

Index Name	Calculation parameters	Relevant considerations	Reference Data
Aegean Region Index	Compound by three composite sub-indicators: Economic: "size of an economy, Productive structure of an economy, Degree of specialisation". Social: "population size, Population structure, degree of cohesion of a society". Environmental: "quantity and quality of environmental resources".	Composite sustainability indicators generated specifically for the islands of the north Aegean region in Greece. The indicators cover economic, social and environmental factors from a policy generation perspective.	(Kondyli 2010; Mori and Christodoulou 2012)
Algarve region Index	20 local indicators for both local and regional scale (population evolution, unemployment, public green space, water consumption, etc).	Local sustainability indicators are assessed "in a regional context by use of a participative approach that can consider local stakeholders' interests".	(Mascarenhas et al. 2010; Mori and Christodoulou 2012)

Index Name	Calculation parameters	Relevant considerations	Reference Data
City Development Index (CDI)	To be applied to cities, regions, and countries. It consists of five sub-indices considered in two blocks: facilities supply and waste. Calculated by five sub-indices such as city product, infrastructure, waste, health and education.	Single measure of the level of development in cities. Each sub-index is a compound index where normalization has been applied so as to obtain values between 0 and 1.	(UN Habitat 2002; Mori and Christodoulou 2012)
City Prosperity Index (CPI)	Extension of the CDI. Five dimensions of prosperity: productivity, quality of life, infrastructure, equity and environmental sustainability.	Broader approach to development than CDI including more dimensions. In 2015 "equity" was changed to "equity and social inclusion" and the "governance and legislation" dimension was added to the previous five dimensions resulting on a six dimensions index.	(Moreno and Murguía 2015)
City Protocol	ISO 37120 plus 59 core indicators.	Measures the city functions structuring them through the city anatomy.	(City Protocol 2015)
City Sustainability Index		Fulfils four requirements: (i) triple bottom line; (ii) capture leakage effects; (iii) created to assess cities sustainability; and (iv) able to assess all cities in the world.	(Mori and Christodoulou 2012)
Compass Index for Sustainability	Nature, economy, society and well-being parameters	The index transforms indicators into a set of four indices of performance in each parameter.	(Atkisson and Hatcher 2001; Singh et al. 2008)
Dashboard of Sustainability (DS)	Free software to simulate the complex relationships between economic, social and environmental issues.	Integrates sustainability by creating concise evaluations through mathematics and graphics integrating sustainability in the decision-making process.	(Scipioni et al. 2009)
Ecological Footprint (EF)	Land and water use. Energy, food, water and all the resources are converted into global hectares.	Assesses the land and water requirements for a country or region needed to maintain the living standard of their inhabitants.	(Wackernagel and Rees 1996; Global

Index Name	Calculation parameters	Relevant considerations	Reference Data
			Footprint Network 2016; SPUR 2016)
Ecosistema Urbano	20 Indicators	Defined to assess 103 Italian municipality for more than 10 years.	(Singh et al. 2008)
Ecosystem Well-Being Index (EWI)	EWI is the result on averaging 51 indicators of: "land, water, air, species and genes, and resource use, or average of indices of land, water, air, and species and genes".	Ecosystem wellbeing implies that "the ecosystem, maintains its diversity and quality, its capacity to support people and the rest of life, its potential to adapt to change and endure".	(Prescott-Allen 2001; Böhringer and Jochem 2007; Mori and Christodoulou 2012)
Emergy/Exergy	Provides information about the quality and the quantity of energy. Emergy: equivalent energy embodied to produce designated goods and services. Exergy is defined as the sum of available energies of all kinds.	Odum created in 1996 a methodology for Regional Emergy Analysis where "all resources and goods are expressed in solar emjoules" which reflects the measure of the "solar energy that was needed for producing them". This index can be used for "assessing energy scarcity or availability and energy efficiency in the extraction of natural resources".	(Odum 2000; Mori and Christodoulou 2012)
Environmental Adjusted net product (EDP) or Green GDP	"EPD = GDP – (depreciation of produced capital) – (amount of resource depletion and environmental degradation)".	Environmental accounting aggregate. EDP I: accounts for natural resource depletion only. EDP II: accounts for both depletion and environmental degradation.	(Hartwick 1977; Böhringer and Jochem 2007; Dietz and Neumayer 2007; Mori and Christodoulou 2012)
Environmental Performance Index (EPI)	Composed by 25 indicators focused on "measures relevant to two core objectives: (i) reduction environmental stresses to human health (the Environmental Health objective)	Complementary to the ESI but more environmentally focused. Fosters the measurement of "policy performance in reducing environmental stresses on human health and in promoting ecosystem vitality". EPI focuses "on a	(Esty et al. 2005, 2006; Böhringer and Jochem 2007)

Index Name	Calculation parameters	Relevant considerations	Reference Data
	(ii) protection of ecosystems and natural resources (the Ecosystem Vitality objective)”.	set of environmental issues based on six policy categories which governments can legislate on”.	
Environmental Sustainability Index (ESI)	5 components: Environmental systems, reducing environmental stresses, reducing human vulnerability, social and institutional capacity and global stewardship. 21 indicators and 76 variables	Quantifies how likely a country will be to preserve its valuable environmental resources effectively over the time. It was the basis for developing the EPI.	(Esty et al. 2005; ESI 2016)
Environmental Vulnerability Index (EVI)	Composed by 50 indicators: -32 indicators of hazards, -8 indicators of resistance, -10 damage measuring indicators.	Assesses the “vulnerability of physical environment” per country. Characterises vulnerability in an identifying issues to be addressed within each of the three pillars of sustainability of a country's development”.	(SOPAC 2005)
Genuine progress Indicator	Modified GDP measure taking into account environmental and social factors.	Relabelling of ISEW.	(Cobb et al. 1999; Lawn 2003)
Genuine Savings	GS = (investment in some kinds of capital)-(total disinvestment in other types of capital). GS is derived of EDP – (consumption).	Based on the Hartwick's rule: “amount of investment in produced capital (buildings, roads, knowledge stocks, etc.)) = (to exactly offset declining stocks of non-renewable resources)”.	(Dietz and Neumayer 2007; Hanley et al. 2015)
Green Net National Product (GNNP)	“(i) EDPI = GDP - (depreciations of natural resources caused by their extraction from the net national income (NNI)), (ii) EDPII = (NNI) – (the costs necessary to reach the same state of the environment at the end of the period as existed at the beginning of the period)	Aggregation, equivalent to the EDP, which is calculated by adding up monetarized values.	(UN 2003)

Index Name	Calculation parameters	Relevant considerations	Reference Data
	(iii) EDPIII =EDPII-(costs of environmental pressure and destruction (calculated by willingness-to-pay methods))".		
Human Development Index (HDI)	Life expectancy index, Education index, Income Index.	Emphasizes people and their capabilities as the ultimate criteria for assessing the development of a country, instead of economic growth alone.	(UNDP 2010, 2015)
Human Well-Being Index (HWI)	Health and Population, Welfare, Knowledge, Culture and Society, as well as an Equity Index. Based on 36 indicators.	Human wellbeing: "all members of society should be able to determine and meet their needs and have a large range of choices and opportunities to fulfil their potential".	(Prescott-Allen 2001; Böhringer and Jochem 2007; Mori and Christodoulou 2012)
Index of Sustainable Economic Welfare (ISEW)	"ISEW = personal consumption + public non-defensive expenditures - private defensive expenditures + capital formation + services from domestic labour - costs of environmental degradation - depreciation of natural capital (i) Distribution of income. (ii) Economic activities not counted in the conventional Gross National Income. (iii) time adjustments. (iv) damage caused by economic activities. (v) the consideration of net capital endowment of foreign investors".	Integration of "environmental and social externalities in national welfare accounting". The GDP calculated through ISEW "is more appropriate for measuring social welfare". This is again, a modified GDP measure taking into account environmental and social factors.	(Aly and Cobb Jr. 1989)
Inequality adjusted HDI	Life expectancy index, Education index, Income Index and Level of inequality.	Adjusted HDI where each dimension's value is reduced depending on its level of inequality.	(UNDP, 2010, 2015)

Index Name	Calculation parameters	Relevant considerations	Reference Data
Living Planet Index (LPI)	Measure of populations of 1686 vertebrate species across all regions of the world.	“Assesses the impacts of human activities on ecosystems in themselves or/and ecosystem functions, referring to indicators of biodiversity”.	(WWF 2016)
Maastricht 2030	Economic, social and environmental flows in the city.	To provide a long-term planning of a city in terms of threats and opportunities.	(Rotmans et al. 2000)
Reggio Emmilia Index	25 indicators (Quantifying: Nitrates, Chlorides, Discharges in atmosphere, waste water treatment, green areas, traffic and farming among others)	Assessment of 45 municipalities within the province of Reggio Emilia in Italy from a sustainability perspective.	(Ferrarini et al. 2001; Mori and Christodoulou 2012)
Satellite-based-Sustainability	“(Light energy emitted) / (ecosystem services measured by a land-cover dataset and ecosystem service values)”.	An empirical environmental sustainability index which confronts night-time satellite imagery and ecosystem service valuation.	(Sutton 2003; Mori and Christodoulou 2012)
Sustainable Cities Index	13 indicators to measure: Environmental impacts, Quality of life and future-proofing so as to enhance local authorities capacity to plan a more sustainable city	Analyses 20 cities in Britain. Also applied in Australia (Australian Conservation Foundation).	(Forum for the Future 2010)
Sustainable Development Indicators	Spatial Logical and time dimensions.	Calculation through the Trinity of Cities Sustainability (TCSSLTD)	(Ding et al. 2014)
Sustainable index of Taipei	51 sustainability indicators which are divided into four categories: environment, economy, society and institutions.	Case study of Taipei city in Taiwan. Analyse the trend of the 51 indicators from where a composite sustainability index is generated integrating the four categories.	(Lee and Huang 2007; Singh et al. 2008; Mori and Christodoulou 2012)
Sustainable Net Benefit Index (SNBI)	Relabelling of ISEW and GPI. SNBI has a different “explanation of the rationale for an alternative index and the presentation of the items used in its calculation”.	Modified GDP measure taking into account environmental and social factors.	(Lawn and Sanders 1999)

Index Name	Calculation parameters	Relevant considerations	Reference Data
	- Private consumption expenditure - the cost of noise pollution, - the cost of commuting, - the cost of crime, - the cost of underemployment, - in some cases, the cost of unemployment, - the cost of lost leisure time.		
Sustainable Seattle	Citizens choose the indicators	Indicators chosen to tackle different problems in different areas of the city.	(Sustainable Seattle; Lee and Huang 2007; Singh et al. 2008; World Bank Institute 2013)
SW Victoria Index	Social: "age structure, population growth rate, and people completed year 12". Environmental: land use, remnant vegetation, dry land salinity, wind erosion, water erosion, soil structure decline) Economic: Household income, employment diversity, unemployment rate.	Assessment of the South West region of Victoria in Australia. It is done "at the regional to sub-catchment scale". Economic, environmental, social and institutional elements are considered.	(Graymore et al. 2009; Mori and Christodoulou 2012)
Toronto and Region conservation program for the living city	Aquatic and terrestrial habitat and Species; Surface and groundwater quality; climate; hydrology.	Specifically focused on the watersheds of the Toronto region and its Lake Ontario waterfront.	(TRCA 2016)
Urban Sustainability Index	22 weighted Indicators considering three parameters: urban potential, urban status and urban coordination.	Chinese cities focused.	(Singh et al. 2008)
Water Footprint (WF)	- Blue water - Green water - Grey water.	Provides the total consumption by "an individual or a community in volume of freshwater used to produce the goods and services".	(Hoekstra et al. 2009)

Index Name	Calculation parameters	Relevant considerations	Reference Data
Well-Being Index (WBI)	“The arithmetic mean of a Human Well-being Index (HWI) and an Ecosystem Well-Being Index (EWI)”.	Assumes the linkage between healthy environment and healthy humans. Takes the arithmetic mean normalized by "proximity-to-target" approach.	(Prescott-Allen 2001; Böhringer and Jochem 2007; Mori and Christodoulou 2012)

3.1.4.2. Sustainability standards and guidelines

During the last two decades, more city-focused environmental tools are being developed and refined (Table 8).

A first achievement in sustainability assessments guidance is the result from the work of several organizations, listed in chapter 1.5, including the World Resources Institute (WRI), ICLEI (ICLEI), and C40 (C40 2016), which contributed to the creation and reviewing of the Global Protocol for Community-Scale Green House Gas Emission Inventories (GPC) (WRI et al. 2014). In this protocol, two methods for inventory compilation were proposed. The first one was the City-induced Framework, which is a consumption based accounting method, where the emissions from both production and consumption activities taking place within the city boundary are considered. There are some emissions released outside the city boundary taken into account as well. The second method is the Scopes Framework, and categorizes all emissions into scopes, depending on where they physically occur: scope 1 (within the city boundary), scope 2 (grid-supplied electricity, steam, heating, and cooling), scope 3 (outside the city boundary) (WRI et al. 2014).

The British Standards Institution reinterpreted the GPC, developing the PAS 2070. The aim was to provide “a robust and transparent method for consistent, comparable and relevant quantification, attribution and reporting of city-scale Green House Gas Emissions (GHG) (direct and indirect) emissions” (PAS 2070 2014). Being “comparable” may be argued against, as normalization of the impacts through a common FU is a necessary step to comparative assessments (ISO 2006c; European Commission 2010).

Lotz and Brent (2014) divided what they called “carbon projects” into four specific types: carbon footprinting (CF), carbon disclosure projects (CDP); carbon neutrality endeavours, and profit-driven emission reduction incentive projects (Lotz and Brent 2014). These authors also compiled during 2014 a practical guideline focused in CFP of organizations and companies. A framework for sustainable development assessment to be applied to cities, the “Trinity of Cities Sustainability from Spatial, Logical and Time Dimensions”, was drafted with the aim at being a tool for guiding the process of selection of sustainable development indicators (SDI), and providing a conceptual framework for the holistic assessment of the city growth sustainability(Ding et al. 2014).

Mori & Christodoulou initially proposed a City Sustainability Index in 2012 (Mori and Christodoulou 2012). In 2015, they proposed a new method based on constraint and maximization indicators (Mori et al. 2015). While constraint indicators focus on “the necessary minimum conditions for city sustainability, maximization indicators measure the benefits that a city generates in socio-economic” terms. The authors recommended using their method for policy-making processes and advised to make the “choice of constraint indicators using a top-down approach”. In addition, they advised to use a “bottom-up approach for defining maximization indicators”, as this technique involves multiple stakeholders.

In 2016, Martos and colleagues focused on analysing the design of sustainable cities in order to improve their environmental performance by focusing on: building energy consumption, urban transport, green areas planning, water supply, and waste management; on a city-wide scale (Martos et al. 2016).

From a different perspective, sustainability assessments are applied neither to a city nor to a region but to a urban-region (Ravetz 2000). In the following cases, the assessment is done through an ad hoc tool designed for the area to be assessed.

In the UK, the Integrated Sustainable Cities Assessment Method (Ravetz 2000) was applied to a urban region, the Greater Manchester (UK) to look for policy gaps according to a set of indicators.

In the United States of America, a “hybrid Life Cycle trans-boundary greenhouse gas emissions footprint” was applied to 8 cities (Denver, Boulder, Arvada, Ft. Collins, Portland, Seattle, Minneapolis, and Austin) (Hillman and Ramaswami 2010). In this case, only some flows were assessed through a LC perspective: food, water, fuels, and cement.

In Australia, a sustainability assessment was applied to Sidney (Newman 2006), using a previously defined method by Pope (Pope et al. 2004), which balances the assessment of environmental, social and economic aspects. This study highlights the population as a key factor in environmental impacts and suggests that only from a triple bottom line perspective unexpected social impacts can be avoided.

In Finland, the cities of Helsinki and Porvoo were analysed through carbon footprinting from a consumption perspective (basing the study on the carbon emissions of two average citizens). As a result, a warning was sent about the service-intensive economies, as they may be outsourcing not only the manufacturing of products but also their related impacts (Heinonen and Junnila 2011).

Table 8. Standards and guidelines by sustainability dimension and LC perspective

Standard/Guideline			Dimension									
Type	Acronym	Method	Economic	Social	Environmental	Developing organization	Ever applied to cities or regions?	Multi-impact assessment	Assess indirect impacts?	Life-cycle Methodology?	Year	Reference Data
Guide	BC	Bilan Carbone			X	ADEME	Yes	No. Only CO_2-eq	Yes	No	2001	(ADEME 2010), (ABC 2013), (Eggermont 2013)
Guide	GPC	Community Scale GHG			X	WBCSD	Yes	No. Only CO_2-eq	Yes	No	2014	(WRI et al. 2014)
Guide	EF	Ecological Footprint			X	GFPN	Yes	Yes	Yes	No	2016	(Global Footprint Network 2016)
Guide	EEB	EeBGuide			X	EC	No	Yes	Yes	Yes	2012	(Wittstock et al. 2012a)
Standard	PCR	EN 15804 - Product Category Rules (PCR)			X	EAN	No	Yes	Yes	Yes	2011	(EN 2011a)
Standard		EN 15978:2011			X	EAN	No	Yes	Yes	Yes	2011	(EN 2011b)
Directive	EIA	Environmental Impact Assessment (EIA)			X	EU	No	Yes	not clear	No	1985	(Pope et al. 2004; European Parliament and Council of the European Union 2014)
Guide	GHG	Greenhouse Gas Protocol			X	WBCSD	No	No. Only CO_2-eq	Yes	No	2013	(WRI and WBCSD 2013)
Guide	OLCA	Guidance on OLCA			X	UNEP-LCI	No	Yes	Yes	Yes	2015	(UNEP et al. 2015)
Standard	ISO	ISO 14025:2006			X	ISO	No	Yes	Yes	Yes	2006	(ISO 2006a)
Standard	ISO	ISO 14040:2006			X	ISO	No	Yes	Yes	Yes	2006	(ISO 2006b)
Standard	ISO	ISO 14044:2006			X	ISO	No	Yes	Yes	Yes	2006	(ISO 2006c)

Standard/Guideline			Dimension			Developing organization	Ever applied to cities or regions?	Multi-impact assessment	Assess indirect impacts?	Life-cycle Methodology?	Year	Reference Data
Type	Acronym	Method	Economic	Social	Environmental							
Standard	ISO	ISO 14067:2013			X	ISO	No	No. Only CO_2-eq	Yes	Yes	2013	(ISO 2013)
Standard	OLCA	ISO 14072 - OLCA Standard			X	ISO	No	Yes	Yes	Yes	2014	(ISO 2014a)
Guide	LCA	Life Cycle Assessment (LCA)			X	SETAC	No	Yes	Yes	Yes	1993	(Consoli et al. 1993)
Guide	OEF	Organizational Environmental Footprint (OEF)			X	EC	No	Yes	Yes	Yes	2013	(European Commission 2013)
Guide	OAM	Organizational Assessment Method			X	ABC	No	No. Only CO_2-eq	Yes	No	2013	(ABC 2013)
Standard	PAS	PAS 2050			X	BSI	No	No. Only CO_2-eq	Yes	No	2011	(PAS 2050: 2011)
Standard	PAS	PAS 2070			X	BSI	Yes	No. Only CO_2-eq	Yes	No	2014	(PAS 2070 2014)
Assessment	A4S	Assessment for Sustainability	X	X	X	Academia	Yes	Yes	No	No	2004	(Pope et al. 2004; Newman 2006)
Assessment	CF	Carbon footprint – Consumption based			X	Academia	Yes	No	No	No	2008	(Heinonen and Junnila 2011)
Case Study	Hybrid LCA	Hybrid life cycle-based trans-boundary GHG emission footprint			X	Academia	Yes	No	Partially	No	2009	(Hillman and Ramaswami 2010)

Standard/Guideline			Dimension									
Type	Acronym	Method	Economic	Social	Environmental	Developing organization	Ever applied to cities or regions?	Multi-impact assessment	Assess indirect impacts?	Life-cycle Methodology?	Year	Reference Data
Method	ISCAM	Integrated Sustainable Cities Assessment Method			X	Academia	Yes	Yes	No	No	2000	(Ravetz 2000)
Guide	PEF	Product Environmental Footprint (PEF)			X	EC	No	Yes	Yes	Yes	2012	(European Commission 2012a)
Directive	SEA	Strategic Environmental Assessment			X	EU	No	Yes	not clear	No	2001	(Pope et al. 2004) (European Parliament 2001)
Guide	WBA	Well-Being Assessment	X	X	X	Academia	No	Yes	No	No	2001	(Prescott-Allen 2001)

3.1.5. Conclusions

Different methods, indices and standards have been used to measure the sustainability of the behaviour of a specific city, a city-region, an urban agglomeration, a group of cities, or an urban-region. In most types of assessments, the Life Cycle perspective of the object of study is not taken into account although, in few cases, the affectations outside the boundaries are considered.

The three pillars of sustainability (economic, social, and environmental) are seldom considered together, being the environmental one the most addressed. Several environmental impact categories can be taken into account (like those included in EN 15804:2012 (CEN 2012)) but it is not often the case. If only one category is considered (following the "good enough is best" principle (Bala et al. 2010a)), it is usually related to climate change whether it is called carbon footprint, CO_2 equivalent emissions or global warming potential. Complementarily, there are sustainability indices and assessments which include only one environmental impact but, at the same time, assess other non-environmental areas such as social and economic aspects (Table 6 and Table 8).

The LC perspective has been applied up to a neighbourhood scale in the construction hierarchy. No consensus has been found about how to define the Functional Unit to neither the neighbourhood scale nor the urban scale, where few references can be found in the literature. Not all the existing methods take into account external impacts of the city over other areas beyond the city boundaries (Mori and Christodoulou 2012).

According to ISO 14044 (ISO 2006c), as there is not a common Functional Unit defined, the reviewed existing methods are not prepared to perform comparative assertions among cities or regions; however, they may allow self-comparison over time.

Nevertheless, some cities have been already studied using different methods to approach sustainability, environmental impacts or a life cycle perspective. For instance, the Greenhouse Gases Protocol methodology has been applied to more than 100 cities. However, not a single methodology or standard has been found to include all the following aspects: (i) holistic point of view, (ii) multi-criterial environmental impact assessment, (iii) analysis from a LC perspective, and (iv) the adequacy for comparison among different cities or urban regions.

All in all, it seems that research effort must be delivered in order to develop and use life cycle sustainability assessments to cities on an ISO-like compliant way. In the meantime, and in a period when cities are gaining relevance to combat environmental impacts as climate change, decision makers currently lack the information given by LCA to shape the configuration of cities and urban regions. The first anticipated step for the methodological development of LCA to be applied to cities should be giving guidance for the definition of the city function, the functional unit to allow comparability of cities and full sustainability assessment, and the reference flow to quantify impacts.

3.1.6. References

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3.2. First steps in life cycle assessments of cities with a sustainability perspective: a proposal for goal, function, functional unit, and reference flow[24]

[24] The information in this section is extracted from this published article: Albertí, J., Brodhag, C., Fullana-i-Palmer, P., (2018). First steps in life cycle assessments of cities with a sustainability perspective: A proposal for goal, function, functional unit, and reference flow. Science of the Total Environment, 646, 1516–1527. https://doi.org/10.1016/j.scitotenv.2018.07.377. Web of Science Impact Factor (2017): 4.610 – Quartile – Environmental Sciences Q1 (27/242).

3.2.1. Introduction

3.2.1.1. Background of the study

Cities and urban regions (cities hereafter) play a significant role in sustainable development due to the magnitude (Koop and van Leeuwen 2015) and the geographical scope of their impacts. Furthermore, there is a clear trend of the world population migrating from countryside to cities (Machel 2004; Ding et al. 2014), which means that the activities that take place in cities and, as a consequence, their related environmental impacts are expected to rise.

However, the assessment of environmental impacts of cities cannot be limited to local ones (e.g., photochemical ozone creation potential). Cities are not only generating impacts due to the activities developed within their boundaries. Seen from a Life Cycle (LC) perspective, cities are also indirectly generating distant impacts because of the upstream processes that take place outside the city boundaries (e.g. the production of electricity needed to run the city). Thus, those should be considered.

An example that justifies the need of remote impacts consideration can be found in the construction sector. A building is one of the constituent elements of the city and accounts for nearly 20% of global greenhouse gases (GHG) emissions (ABC 2016). The Global Carbon Agenda for 2050 by the Global Alliance for Buildings and Construction includes an estimation that 28% of the effort to reduce GHG emissions in the construction sector could come from building materials (Table 9), which are usually not obtained within the boundaries of a city.

Table 9. Building's global policy priorities for GHG reduction to comply with the Global Carbon Agenda 2050. Source ABC (2016)

Near / net-zero energy building	24%
Deep renovation	16%
Low GHC energy supply	32%
Low GHG material	28%

Another example is the case of food production, distribution and consumption infrastructure. Self-sustained cities regarding food production are rare and, even though suburban agriculture is progressing, cities import foodstuffs to fulfil the lack of production. As the impacts on biodiversity loss due to food production are upstream (Wolff et al. 2017), cities should be responsible for impacts beyond their boundaries.

High density human concentrations are commonly seen as more efficient than disperse urbanisation models (European Commission and UN Habitat 2016; UN Habitat et al. 2016). However, density may imply the generation of infrastructures which would not be needed in the case of low density human concentration. This is because the increase of density may imply the overcoming of the carrying capacity of the services provided by local ecosystems. For instance, in the case of not so dense human concentrations, large water supply infrastructures to extract water from far sources might not be required. Not always intensification is environmentally friendlier (Fullana-i-Palmer et al. 2009) and, in the case of cities, the increase of the population density has specific environmental connotations from a LC point of view which should be considered.

On the other hand, cities have the opportunity to influence impacts reduction worldwide (both resources and emissions), as cities' day to day development into a more sustainable way could be quantitatively significant so as to get reflected in global indicators (IEA 2016).

The importance of cities in fighting climate change is recognised by both multilateral bodies (European Commission and UN Habitat 2016; European Union 2016; IEA 2016; The World Bank 2016) and the scientific community (Wright et al. 2011; IPCC 2016; Martos et al. 2016; Petit-Boix et al. 2017). In 2008, at the 14th Conference of the Parties (COP14, Poznan, Poland), the Network of Regional Governments for Sustainable Development (nrg4sd), through a proposal by the Catalan Delegation (the so-called "Catalan Amendment"), asked the United Nations Framework Convention on Climate Change (UNFCCC) to recognise the role of the sub-nations in the climate change fight. The official recognition came in COP16, which took place in Cancun in 2010. From that moment on, sub-nations have been contributing more and more to the COPs. An example happened during COP20 (Lima, 2014) when the Lima Paris Action Agenda (LPAA) was launched so as to establish a non-state actor zone for climate action online platform (NAZCA), where cities and sub-national regions (among others) could register their climate change commitments.

Even more, since COP21, where the Paris Agreement (PA) was achieved, cities are expected to play a significant role in CO_2-eq emissions reduction (UN and UN Habitat 2014; UNFCCC 2015). Sub-nations are recognised as "non-Party Stakeholders" and, therefore, the effort for setting voluntary goals is recognised and the UNFCCC calls for enhancing these voluntary goals and cooperation. Furthermore, since the PA, fora are expected to be created in order to listen to and give a platform for experts at the sub-nation level in the fight against Climate Change. Regional and local leaders already participated in COP22, that took place in Marrakech in 2016, summiting a roadmap for action with the aim of launching a Global Campaign and implementing a Framework for localizing Climate Finance (Local and Regional leaders of 114 countries 2016). Examples of these fora are: the Habitat III conference, which resulted in the New Urban Agenda (UN 2016b; UN Habitat 2016a); the Cities and Climate Change Science Conference (IPCC 2018); or the recently hold high level political forum on sustainable development 2018 which included a specific topic on the Sustainable Development Goal #11 (SDG#11) (UN DESA 2018).

On the one hand, a relevant actor (cities) in the battle of reducing environmental impacts worldwide is recognised. On the other hand, an assessment tool, Life Cycle Assessment (LCA), which has been demonstrated to be a good instrument for the diagnosis of the environmental potential problems is also recognised. Knowing these two realities, a question arises: why have not there been any developments in the LCA methodology in order to adapt it to contribute to the assessment and improvement of the environmental behaviour of cities and help decision makers to take action at a city level?

Probably, the complexities of both the assessment method and the system under study have been an obstacle for carrying out city LCAs. This section tries to pave the way to future city LCA application by defining the needed concepts to develop any LCA as described in ISO 14044 (2006) or ISO 14072 (2014). It is assumed that the ISO family 14040 and 14044 are product oriented, however, the procedure set in these ISO standards can be useful to handle the development of LCA of complex systems.

3.2.1.2. Sustainability assessment methods for cities

Quantitative assessment methodologies are being more and more used for establishing criteria to reduce environmental impacts and to implement eco-design or eco-innovation to different types of systems. Regarding the impacts, the focus is specially placed on CO_2 equivalent emissions (CO_2-eq) (Heinonen and Junnila 2011; PAS 2070 2014; WRI et al. 2014; CDP (Carbon Disclosure Project) 2016; Albertí et al. 2017; Mirabella and Allacker 2017; Uchiyama and Mori 2017; Cellura et al. 2018), which have relevance at a global level, and on water use (Rygaard et al. 2014; Lane et al. 2015; Marques et al. 2015; Spiller 2016; Godskesen et al. 2018). Nevertheless, other impacts, such as acidification, eutrophication, abiotic depletion, human toxicity, etc. may have an important regional or local relevance, as indicated by different initiatives or standards (EN 2011a; European Commission 2012a; ISO 2017). LCA and Life Cycle Sustainability Assessment (LCSA) are effective tools that assess different sectors and geographical coverages through a holistic perspective avoiding environmental impact shifting (Ness et al. 2007). Generation of new methods from a LC perspective for assessing new systems with a significant impact contribution (e.g. cities) would enhance the role of LCA in sustainability assessments (Bare 2014; Petit-Boix et al. 2017) and in sustainable development (Rebitzer et al. 2004). LCA is mainly focused on the environmental aspect of sustainability while the social and economic aspects are seldom addressed specially because of the early development stage of Social Life Cycle Assessment (S-LCA) (Hellweg et al. 2014).

LCA is a holistic tool that measures and assesses, through a step-wise procedure, different environmental impacts of the system under study. LCA is accepted as useful in sustainability assessments (Bare 2014) and, specifically, as an exhaustive method for the environmental assessment of buildings (Cabeza et al. 2014) and neighbourhoods (Lotteau et al. 2015a). It is important to take into account that LCA is useful not only in building systems but also in the construction sector in general (including civil engineering) (Cabeza et al. 2014). Unfortunately, the process of assessing upper levels within the built environment (from construction products to urban areas) is complex and, in the case of urban assessments, the literature is still scarce (Soust-Verdaguer et al. 2016b; Albertí et al. 2017; Mirabella and Allacker 2017; Petit-Boix et al. 2017; Mirabella et al. 2018).

They do exist some guidelines and standards for city assessments but they focus on a single environmental impact (usually global warming potential (GWP)). This is the case of the works done by the British Standards Institution (BSI) and the World Resource Institute (WRI) (PAS 2070 2014; WRI et al. 2014). However, there are no LCA-based standards, i.e. assessing through a multi-impact approach and a LC perspective, and which have made the effort to define the function, the functional unit (FU) and the reference flow (RF) for a city LCA.

In addition, a lot of city-based indicators exist as well (Albertí et al. 2017). Again, they are normally mono-criterial, as they only include one of the impact categories or one of the aspects of sustainability. Indicators have been widely used for assessing sustainability, but more than one indicator (or a composite indicator) is needed to achieve a holistic perspective (Torres-Delgado and Palomeque 2014). Moreover, some of them are designed for assessing a specific city with its own characteristics, such as the cases of: Taipei region (Lee and Huang 2007), Algarve (Mascarenhas et al. 2010), Reggio Emmilia (Ferrarini et al. 2001), the Aegean region (Kondyli 2010) or South West Victoria (Graymore et al. 2009). These ad hoc tools are only operational for the city for which the indicator was created or for cities which have very similar characteristics.

The development of new impact assessment methodologies contributes to achieve a better understanding of the systems under study; however, as stated by Bare (2014), these methodologies should: "(1) be as scientifically defensible as practical; (2) be as reproducible and transparent as possible; (3) represent the severity or potency of the individual contributors (or stressors); (4) take into consideration the appropriate level of spatial scale; (5) take into consideration the appropriate level of temporal scale; (6) be inclusive of all impacts; (7) be suited to evaluate all stressors; (8) be applicable to the entire world; (9) be practical".

3.2.1.3. The need for developing Life Cycle Sustainability Assessment methodology for cities

There have been a number of developments of Product Category Rules (PCR), which have led to a growing use of LCA-based product declarations such as Environmental Product Declarations (EPD), Product Carbon Footprints (PCF), and Product Environmental Footprints (PEF). During the last decade, many LC standards and guidelines have been published, and it is understood that for each product category there is a need of, somehow, a form of a PCR in order to be effectively useful for product comparison (Ingwersen and Subramanian 2013). It is important to note that the construction sector may be the one with more PCRs and EPDs developed. Standardisation of methods is a key issue in order to develop an environmental product declaration (Cerutti et al. 2016) and, following this reasoning, an LCA based method for cities is a needed step for a future Environmental City Declaration (ECD) or a City

Environmental Footprint (CEF) definition. A systematic literature review on the sustainability or environmental assessments of cities has been previously performed by Albertí et al. (2017), and section 3.2 goes beyond the state of the art by proposing methodology on the goal and part of the scope of a city LCA, and by connecting the other sustainability dimensions through the use of the City Prosperity Index (CPI) as technical performance within the FU.

City LCA is essential to tackle the big numbers of environmental impacts, as, for instance, cities account for 80% of global greenhouse gas emissions (The World Bank 2016). However, the current situation for city sustainability assessments is that there is a lack, at least, of one of the following aspects: "(1) holistic point of view, (2) multi-criterial assessment, (3) LCA perspective and (4) the possibility to compare results among different cities Worldwide" (Albertí et al. 2017).

3.2.2. Methods

A systematic literature review has been performed so as to extract the procedure for defining the goal, function, functional unit, and reference flow of a complex system. The framework established by ISO 14040:2006 (ISO 2006b) for developing an LCA starts by defining the goal and scope of the study. Section 3.2 focuses on determining the goal, and the function, FU and RF of the system under study among the many issues to be defined in the scope. Despite the process of LCA development is specified in ISO standards (ISO 2006b, c) and other guidelines (European Commission 2010), a complete and systematic procedure for defining FUs and RFs adequate for very complex systems has not been found. Nevertheless, some literature (such as EN, 2011; European Commission, 2012; Finkbeiner et al., 2010; Guinée, 2002; UNEP, 2011; UNEP et al., 2015, among others) has been found regarding the method for FU definition. However, this literature is mostly product-focused and do not cope the multi-functionality of a city and other important differences, such as: (i) different and evolving number of inhabitants and their quality of life; (ii) income; (iii) level of literacy; (iii) access to services; or (iv) current and aimed level of development, among others. An interesting contribution (Reap et al. 2008a) which provides potential sources of error when defining the function, FU and RFs of a system has been summarized and adapted to cities in Figure 9.

In order to avoid problem shifting between different aspects of sustainability, the authors seek to include social and economic considerations in the city LCA. The complexity of LCSA as an addition of an LCA + S-LCA + Life Cycle costing (LCC) makes city LCSA quite unrealistic nowadays. As generally proposed by Baitz et al. (2013), in order to feasibly include the economic and social dimensions in the city LCA, the authors propose to introduce the use of the CPI as technical performance within the functional unit . An exemplification of the variation of the results after the application of different normalization factors is described. The basic ideas, issues/criteria (general and city specific), and some proposals to consider when dealing with these LCA items for city LCAs are presented in chapter 3. An academic (not real) example on Electricity Mix in Region X will be used as an example of a sector largely experienced in LCA to introduce some methodological issues. The complexity of a city goes far beyond that of an electricity facility subsystem, which is part of it. The idea behind starting from a relatively simple system, such as the electricity mix, is to be able to extract the essence of the procedure for LCA items definition, and to find parallelisms to be applied to a complex system: the city as a whole.

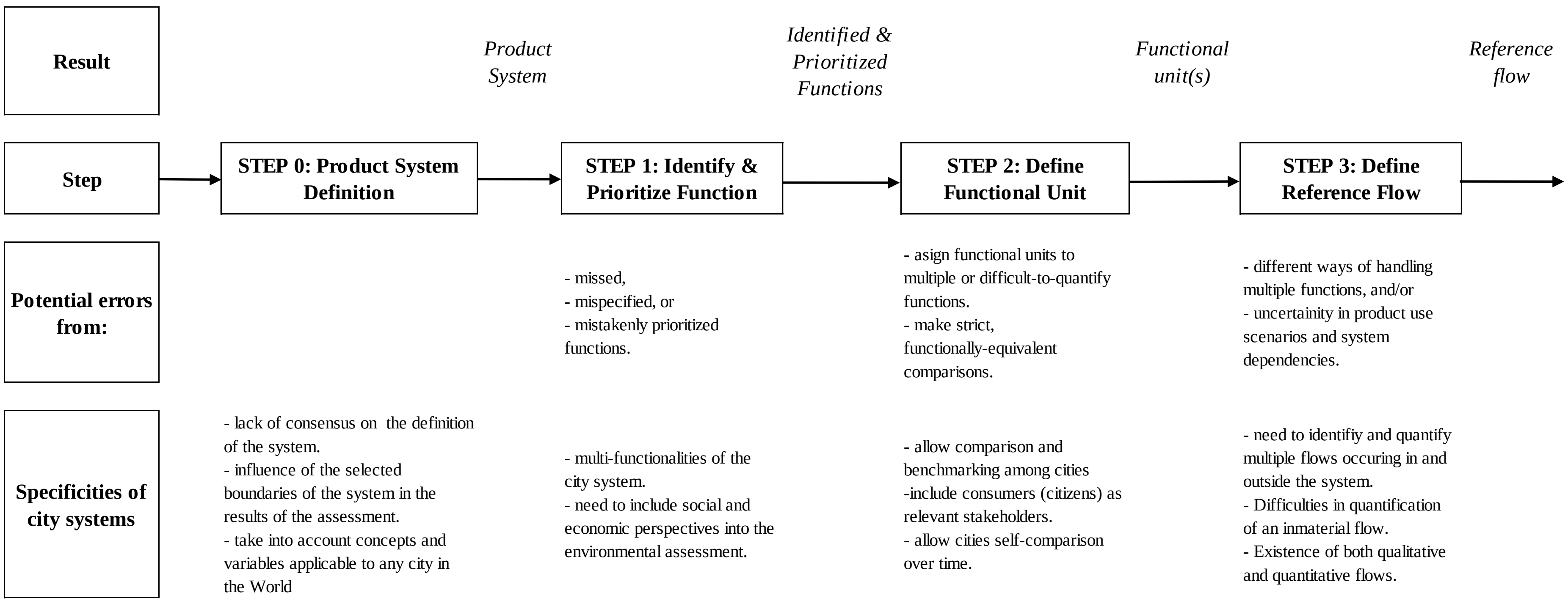

Figure 9. First steps for LCA, common errors and applicability to the city systems. Adapted from Reap et al. 2008a

3.2.3. Results and discussion

3.2.3.1. How to define the goal of a city LCA

According to ISO 14040 (ISO 2006b), the goal of an LCA shall state: "the intended application; the reasons for carrying out the study; the intended audience, and whether the results are expected to be used in comparative assertions intended to be disclosed to the public". More extensively, the International reference Life Cycle Data System (ILCD) Handbook (European Commission 2010) referring to the ISO 14044 (ISO 2006c) establishes six aspects that should be described during the definition of the goal: "(1) intended application(s) of the deliverables / results; (2) limitations due to the method, assumptions, and impact coverage; (3) reasons for carrying out the study and decision-context; (4) target audience of the deliverables / results; (5) comparative studies to be disclosed to the public; (6) Commissioner of the study and other influential actors". In the following lines we are applying these six aspects into the case of a city.

(1) Intended application of the deliverables/results (What?)

<u>Electricity Mix example</u>. The aim of the study is to compare the environmental impacts due to electric power generation by different competing technologies, when applied to the needs of consumption of region X.

<u>Proposals for a City</u>.

- To determine the environmental impact hot spots of city Z, taking into account economic and social aspects.
- To benchmark the environmental impact of city Z among different cities in the World.
- To find out the influence of prosperity in the city environmental impact.
- To assess the environmental impact of a citizen in relation to her human development.
- To determine the amount of environmental impact produced by a citizen to achieve a unit of prosperity.

(2) Limitations due to the method, assumptions and impact coverage

<u>Electricity Mix example</u>. "Wind power plants have visual impacts which are not dealt with in LCA".

<u>Proposals for a City</u>. The high complexity of the object of study will make analysts to take assumptions to obtain preliminary results. This is in line with ISO 14044, when in chapter 4.2.1 it states: "Due to the iterative nature of LCA, the scope may have to be refined during the study". This will be a must for the first attempts to build a LC inventory but, with the evolution of metering devices, the internet of things, and the development of big data procedures; the information and flows in a city would be easier to quantify.

Different types of environmental impacts should be taken into account so as to avoid problem shifting because, in the case of city LCA, local impacts have special relevance.

- Limitations due to the method. LCA was developed for products and services, not for cities, whose nature is different. Furthermore, LCA rules require the definition of the system, the city. However, there is no consensus on this definition. LCA is site-unspecific while cities have geographical boundaries and their impacts have local relevance. During the inventory phase, the environmental impacts of all the constituent components of a city should be considered. Another limitation of LCA is that this assessment method is not considering the three sustainability dimensions. The intention to shift from LCA to LCSA through normalizing the FU does not address the complexity of sustainability as well as performing an LCA+LCC+SLC. The goal of the normalization method is to get in between theory and practicality (Bala et al. 2010a; Baitz et al. 2013a). Thus, while social and economic impact categories are not included, the sustainability perspective will be addressed through the use of aggregated indexes, that incorporate social and economic information, as technical performance within the FU.

- Limitations due to the assumptions. The LCA may vary depending on what a city is. In addition, if a normalizing factor is used, it will influence the results of the city LCA. Furthermore, in the case that the normalizing factor was the CPI, the analysts would assume that the CPI of the city is that of its inhabitants, while it is only a mean value.

- Limitations due to the impact coverage. Due to the existence of the geographical boundaries of cities, the relevance of the local impacts is increased. Thus, apart from the global impacts, special considerations on the local burdens should be included in the assessment. A balance between site specific and site unspecific assessment should be found so as to assign the impacts to the corresponding city. Geographic boundaries will need to be set and impacts among the supply chain shall be allocated.

(3) Reasons for carrying out the study and decision-context (Why?)

<u>Electricity Mix example</u>. Region X is highly dependent on primary energy import, so finding more independent environmentally friendly and economically affordable alternative technologies is in the Government's policy agenda.

<u>Proposals for a City</u>. City managers and decision makers need a more detailed and scientific-based information in order to benchmark the cities they are managing. They need to focus their efforts to implement the improvements where better returns of the investment can be achieved from social, environmental, and economic points of view. The following reasons on why carrying out a city LCA could be considered:

a) To help policy makers to have a deeper knowledge of the city alignment with sustainability.

b) To improve the environmental performance of City Z addressing the relevant issues, in order to fulfil the Environmental Action Plan 2020 more efficiently, and facilitate an improvement strategy.
c) To facilitate sharing best practices among the cities within City Z's network.
d) To position City Z in the top list towards sustainability in order to attract sustainable tourism.

(4) Target audience of the deliverables

Electricity Mix example. The results will be shown to government officials and members of the Parliament.

Proposals for a City. Each intended application and reason for carrying the study of the above list (a) to (d) may lead to different target audiences.

a) would be intended to target an internal non-technical audience (e.g. the Major).
b) would be intended to target an internal technical audience (e.g. a city public servant).
c) would be intended to target an external both technical and non-technical audience (e.g. city networks).
d) would be intended to target an external non-technical audience (e.g. tourism fair participants).

(5) Comparisons intended to be disclosed to the public

Electricity Mix example. This study is a comparative assertion which may only be disclosed to the public if the Region X Government decides to do so.

Proposals for a City. Unless the aim of the study is internal, cities would want to benchmark their performance against other cities'. Therefore, most probably, a comparative assertion may happen and, in addition, if the city is well positioned, information may be disclosed for marketing purposes.

- This study is a comparative assertion which will be disclosed to the public to position City Z as more sustainable than other cities.
- No comparative assertion is intended.

(6) Commissioner of the study and other influential actors

Electricity Mix example. The commissioner of the study is the Region X Government, and the energy companies A and B are co-financing it.

Proposals for a City. Normally, the study will be financed by the City Council. However, other funding institutions may participate, such as national or international funding agencies. Other influential actors may be environmental NGOs, public servants, municipal and regional agencies and neighbourhood organizations among others.

As a summary, the goal of a city LCA may include:

The determination of the amount of environmental impacts produced by a citizen to achieve a unit of prosperity, from a more site-specific point of view and assuming that the CPI is that of its inhabitants, with the aim of helping policy makers to have a deeper knowledge of the city alignment with sustainability, in order to target both technical and non-technical audiences and to position the City as more/less sustainable than other cities.

3.2.3.2. Determining the function of the system

The function describes the performance characteristics of the system under study (ISO 2006d) and the service which the system is delivering. Furthermore, the functional unit is a quantification of this performance for use as a reference unit, which allows the practitioners to set a common baseline of performance on which they can compare different systems that fulfill the same function in different ways. The characteristics considered in the functional unit are included in the reference flow, defined as a quantity on which all inputs and output flows of the system quantitatively relate.

Sometimes, a system is providing more than one service and multi-functionality has to be taken into account. The analyst may chose a primary function but it is necessary to take into account the sub-functions of the system (Reap et al. 2008b). Apart from these function related considerations, according to Günther and Langowski (1997) and the European Commission (2010), time considerations and consumer habits play a significant role in the behaviour of the system and its performance in achieving its function. For example, the life span chosen varies the distribution of impacts along the product or service life cycle. Also, during the use stage, depending on the consumer behavior, the life span of the product can get reduced or increased.

<u>Electricity Mix example.</u> The function may be: the generation of electric power and supply to the grid over a specific time span with a specific quality. In this case, a sub function, if any, could be the generation of steam or hot water for satisfying industrial or domestic needs.

<u>Proposals for a City</u>. To have a fair comparison, it is essential that the functions of the systems to be compared are the same (Smith Cooper 2003; ISO 2006c). Therefore, there is a need to establish and agree upon what the function of a city is. Moreover, Lagerstedt et al. (2003) state that a more realistic evaluation is achieved if the main function is complemented by a group of core criteria. Some guidance about how to define the function of a city and which core criteria should be taken into account could be inferred from generic (no city based) guidelines. The function definition should take into account concepts and variables applicable to any city in the World.

In the case of cities, consumers/citizens are an inherent part of the system. Cities are not comparable to products being manufactured by a production system and later used by a costumer. The costumers become citizens and they are part of the system under study, and they have a role in its environmental behaviour. Furthermore, cities aim to increase the happiness and security of its citizens and, at the same time, it is the search of that happiness and security by the citizens that makes a city a city (Aristotle 1st century BC, cited in Clayton 2017).

The World Commission on Environment and Development defined sustainable development as the one which ‘‘meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: (i) the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and (ii) the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.” (Brundtland 1987).

There is an increase of population living in urban areas (from 30% in 1950 to 54% in 2014) and the prospective is that the trend will continue (up to 66% in 2050) (UNDESA 2014). This fact may emerge as a result that people feel they can better meet their needs (like poverty alleviation) in cities than in the countryside (Machel 2004; Ewers et al. 2018). But which are the *needs* of the population? The Maslow’s pyramid (Maslow 1943) could be a fairly good tool for establishing the needs of citizens. However, analysing how much and how well are each of those needs covered may be quite complex. In this study, we aim at basing the covering of the populations needs on, at least, these three dimensions: (1) long and healthy life; (2) knowledge; and (3) a decent standard of living. This may be achieved by using the Inequality adjusted Human Development Index (IHDI).

The Human Development Index (HDI) was created to set the background criterion for assessing the development of a country. As cities play a significant role in the development of a country (Hoselitz 1953), the function of a city could be aligned to achieving the goal of Human Development (HD). The relation between HD and cities gets reinforced since cities are included in the *Goal 11* of the recently established SDGs (UN Habitat et al. 2016).

Apart from using a single index to define the function of a city, another practical advantage of considering the HDI within the function of a city is that the economic and social aspects can be somehow incorporated to the environmental assessment (see Figure 10).

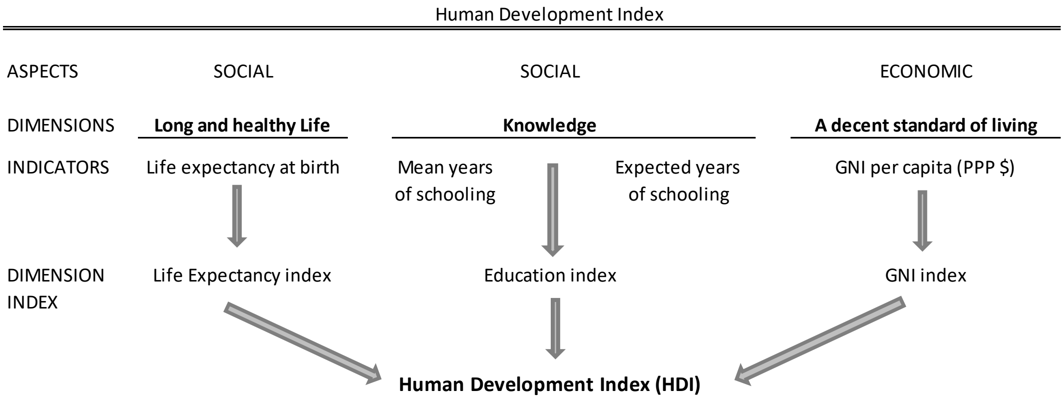

Figure 10. Human Development Index (HDI)[25]. Source: UN Development Programme (2016)

However, the HDI, described in Figure 10, lacks of information about inequalities, poverty, human security or empowerment, among others (UNDP 2010, 2015; Klugman and Rodríguez 2011). To increase the representativeness of these aspects within the index, the UN enhanced the HDI, defining the Inequality adjusted HDI, IHDI (Figure 11), which reduces each dimension’s value depending on its level of inequality. The HDI can be understood as an index of “potential human development” (UNDP 2010, 2015). HDI would be the maximum level of the IHDI that a country could get, if inequality did not exist.

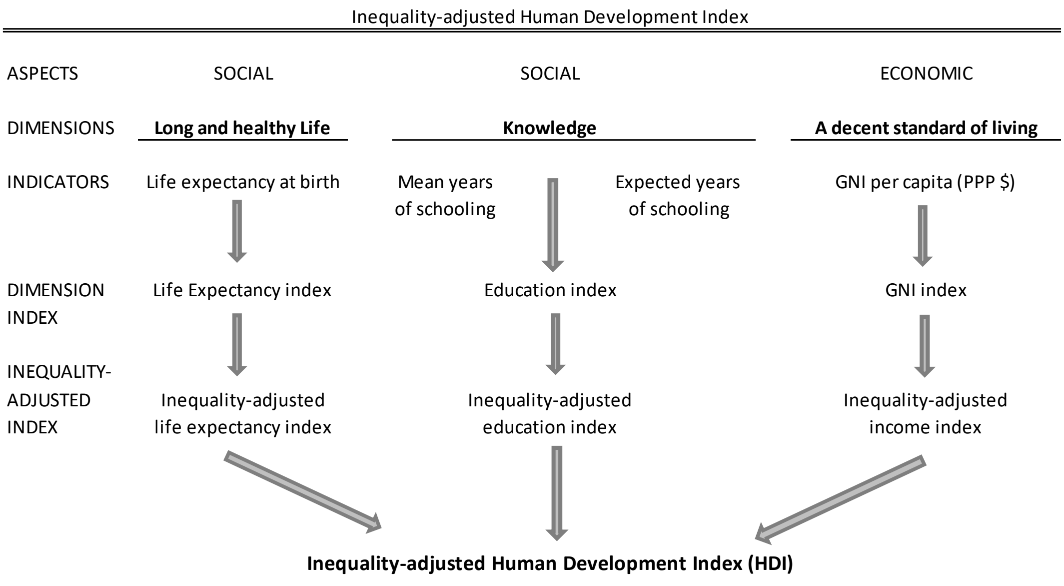

Figure 11. Inequality adjusted Human Development Index (IHDI). Source: UN Development Programme (2016)

[25] GNI: Gross National Income; PPP: Purchasing Power Parity in US Dollars.

Although there would still be some lack of information regarding human security, empowerment or gender inequalities (UNDP 2010, 2015; Klugman and Rodríguez 2011), which can be analysed through different specific indexes, the UN considers the IHDI as a representative for the "actual level of human development" (UNDP 2010, 2015). Apart from the mentioned limitation above, both the HDI and the IHDI were originally developed for country assessment. Fortunately, there exists a specific index, inspired by the HDI rationale, which is focused on cities and which, at the same time, is considering all the dimensions of the IHDI plus other ones. This multidimensional index is the City Prosperity Index (CPI), developed by UNHABITAT (Moreno and Murguía 2015). This global index considers different aspects and dimensions through the aggregation of indicators (Table 10). There are two characteristics that reinforce the choice of the CPI: the data used for its calculation, which include environmental, social and economic aspects, and the object of study of the CPI's calculations: a city. In addition, the CPI is an internationally accepted index which already has been applied to over 400 cities across the world. For a practical purpose, the authors suggest the use of CPI_1=CPI/100 which seeks to transform the magnitude of CPI on a per unit basis. Thus, when the full prosperity is achieved, the emissions coincide with the real ones while, with a lower CPI, the emissions virtually increase. CPI_1 is used hereafter. Albertí et al (2017) published a more extended review of assessment methods and indicators for cities.

Table 10**.** Dimensions of the CPI. Source: UN Habitat (2016)

DIMENSIONS	**DIMENSION INDEX**	**SUB-INDEXES**	
1. Productivity (Economic)	City Productivity Index (P)	Economic Strength (ES) Economic Agglomeration (EA) Employment Sub Index (E)	City Prosperity Index (CPI)
2. Infrastructure (Social)	City Infrastructure Index (ID)	Housing Infrastructure Sub Index (HI) Social Infrastructure (SI) Information and Communication Technology Sub Index (ICT) Urban Mobility Sub Index (UM) Urban Form Sub Index (UF)	
3. Quality of Life (Social)	City Quality of Life Index (QOL)	Health Sub Index (H) Education Sub Index (E) Safety and Security Sub Index (SS) Public Space (PS)	
4. Equity and Social Inclusion (Social)	City Equity and Social Inclusion Index (ESI)	Economic Equity Sub Index (EE) Social Inclusion Sub Index (SI) Gender Inclusion Sub Index (GI) Urban Diversity Sub Index (UD)	
5. Environmental Sustainability (Environmental)	City Environmental Sustainability Index (ES)	Air Quality Sub Index (AQ) Waste Management Sub Index (WM) Sustainable Energy Sub Index (SE)	
		Participation Sub Index (P)	

6. Governance and Legislation (Social)	City Governance and Legislation Index (UGL)	Municipal Finance and Institutional Capacity (MFIC) Governance of Urbanization (GU)	

We understand the benefits of using a globally recognised index that includes, as much as possible, economic and social aspects. In our case, the normalization of the FU with an index with strong social and economic influence will somehow complement the environmental LCA for cities.

Normalization will make sense when the aim is comparing two cities, as they may probably have different level of development, different number of inhabitants, and different amount of environmental impact. If that is the case, normalization will contribute to understand that it can be possible for a city to have higher impact (or higher impact per inhabitant) while better performing its function (prosperity), from a holistic perspective, than another with lower impact, and, therefore, the comparison should not be made on environmental impact alone.

Having said this, the function of a city may be defined as: Providing a proper environment to human beings, allowing them to live with a certain level of prosperity.

3.2.3.3. Determining the functional unit

The definition of the FU is a key factor for allowing different systems to be comparable (Goldstein et al. 2013). According to ISO 14040 (ISO 2006b), the FU is a "quantified performance of a product system for use as a reference unit". From a more practical way, the ILCD Handbook (European Commission 2010), referring to the ISO 14044 (ISO 2006c), states that the FU shall "name and quantify the qualitative and quantitative aspects of the function(s) along the questions "what", "how much", "how well", and for "how long"".

The FU includes the magnitude and duration of the service during the life span of the system (Smith Cooper 2003). This author also sets a requirement in determining the FU for comparative LCAs, which is the inclusion of three characteristics: (1) the magnitude, (2) the duration and (3) the expected level of quality.

The FU definition can vary from a single magnitude (mass, energy, volume…) to a qualitative and quantitative description of the specific system under study (some examples in construction sector activities are included in Table 11). In order to ensure a fair comparison, comparative LCAs influence even more the way the FU is defined. The more descriptive the better the FU; however, allowing other systems to have the same FU so as to grant a coherent comparison must be kept in mind. The lack of consensus in defining similar FUs for similar products or services is a barrier for LCA application.

Table 11**.** Examples of functional units in different areas

Area	**Systems assessed**	**Functional Unit**	**Citation**
Renewable energy for electricity generation systems	10 wind turbines, 9 Photovoltaic , 3 Solar thermal, 5 biomass and 3 hydro systems	Unit of Energy (usually kWh)	(Varun et al. 2009)
Renewable energy for electricity generation systems	100 different case studies including: wind power, Solar (Photovoltaic and Solar thermal), geothermal and hydropower	Unit of Energy (usually kWh)	(Asdrubali et al. 2015)
Construction	Buildings (167 case studies)	The whole system under study (Building)	(Buyle et al. 2013)
Construction	20 Single-family houses	The whole system under study (i.e. Building), a ratio of performance of the function (i.e. m^2 of useful or heated area), or a part of the system under study (i.e. envelope, shading…)	(Soust-Verdaguer et al. 2016b)
Construction	Neighbourhoods (21 case studies)	The whole system under study (i.e. Neighbourhood, household), a ratio of performance of the function (i.e. inhabitant, m^2 of living space/inhabitant, m^2 energy reference area, floor area).	(Lotteau et al. 2015c)
Construction	Road infrastructure in residential neighbourhoods (from the road, and from the neighbourhood perspectives)	The whole system under study (i.e. Roads) or a ratio of performance of the function (i.e. vehicles per day).	(Trigaux et al. 2016b)
Construction	Buildings and building related industry and sector (review of 61 original articles studying different systems)	The whole system under study (i.e. Building, family house,…), a ratio of performance of the function (i.e. m^2 of useful or heated area, number of lives in a house (per capita basis), “energy/surface” ratio (usable, heated, total, …)), or a part of the system under study (i.e. envelope, a tone of a specific type of brick, 1 m^2 of laid wood floor, commercial offices, a room, the envelope …)	(Cabeza et al. 2014)

Area	Systems assessed	Functional Unit	Citation
Water supply systems	A case study (including three scenarios) of an urban water cycle in the city of Tarragona	Volume of water	(Amores et al. 2013)
Tourism	Holiday Farms	The building where the activity happens (i.e. the whole hotel or farm); the revenue of the activity (i.e. units of financial value); the time while the service is provided or a ratio of time (i.e. One hotel night, Bed/night or guest·night); specific services (i.e. A meal).	(Cerutti et al. 2014)

Electricity Mix example. The FU for a Power Plant or supply mix may be: (1) the amount of electricity (MWh) consumed by City Z (2) during 50 years (3) according to the grid quality requirements.

Proposals for a City. In order to avoid lifespan variations, a “per year” consideration is taken into account in the FU definition. The number of inhabitants taken as a reference is one million instead of one habitant because this reference is closer to the order of magnitude of inhabitants that cities have. The specific answers for a city could be the following: What? The level of CPI. How much and How well? Full CPI per million of inhabitants. How long? Per year. Therefore, the Functional Unit of a City could be formulated as**:** One million of inhabitants living with full City Prosperity Index in a given year.

3.2.3.4. Determining the system reference flow

According to ISO 14040 (ISO 2006b), the RF is “the measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit”. The ILCD Handbook (European Commission 2010)) referring to the ISO 14044 (ISO 2006c) defines the RF as “the flow(s) to which all other input and output flows quantitatively relate”. When comparing systems, the function(s) and the FU must be the same for all systems compared; however, they could have different reference flows.

Smith Cooper (2003) divides the RFs in two parts: the identification and the quantification of flows. Regarding the identification of flows, this author advises to identify the RF through looking at the “interface issues” (materials and energy flows) including those happening between sub-functions of the system.

Electricity Mix example. The RFs of each Power Plant being compared would be a concrete quantity of MWh produced, e.g.: 103 MWh produced at the wind power plant; 98 MWh produced at the coal power plant; etc. Depending, for example, on the distance the power plant is located from Barcelona and therefore the energy loss in transport, the fraction of useful MWh will be different; therefore, different production energy is needed to fulfil the same consumption service (or FU).

Proposals for a City. A city is a complex system composed by complex subsystems, from a brick to a district. The city protocol urban anatomy defines distinctive cycles in any city (Figure 12): water, matter, energy, mobility and information (City Protocol 2015). Moreover, land use changes should be taken into account in the impact assessment stage (Reap et al. 2008a).

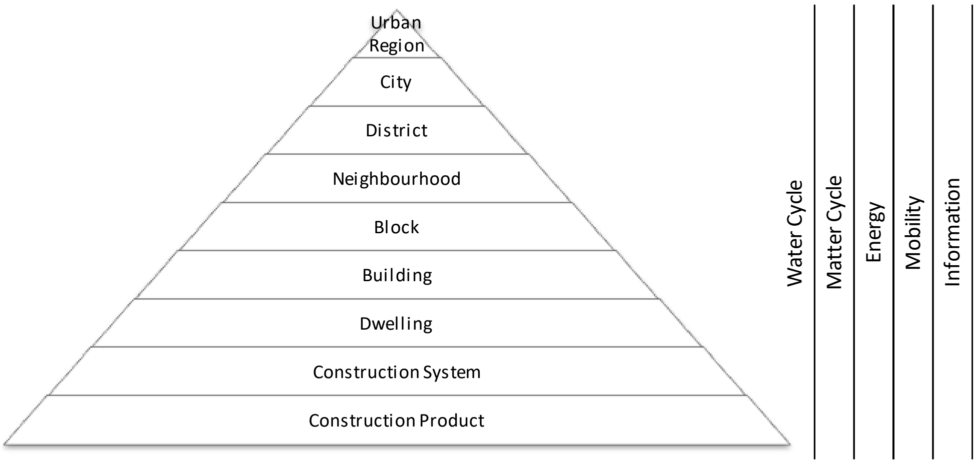

Figure 12. Hierarchy of the built environment and its common cycles. Source: Albertí et al. (2017)

All flows happening in a city are contributing to achieve the function of the city. Another issue will be how to define the boundary of the city (administrative, geographic, functional, etc.) but solving this is not an aim of section 3.2 and needs further research. Direct measurement would be the most useful way for flow quantification although this should be proved in a pilot study, and its adequacy would rely on which is the level of metering already existing in the city under study.

For instance, if an analyst is willing to perform an LCA of a yogurt packaging, the FU (i.e. protecting and carrying 1 kg of yogurt keeping its organoleptic properties during 15 days) would be transferred into a RF which would be different depending on the package's size (8 packs of 125g, 4 packs of 250g, 1 pack of 1kg, etc.). These numbers may even change depending on how often the different types of packaging are broken. Thus, it is through the RF that the analyst can make the system accomplish with the same service no matter which is the object under study.

Reference Flow of a city: the number of cities which is equivalent to a city of one million inhabitants living with full prosperity in a given year.

In the case of cities, the RF (1) implies that all results would be weighted according to the number of inhabitants and the prosperity of the studied city. For instance, the city of Zurich (ZRH) has a $CPI_{1\ ZRH}$ of 0.765 and 4.05E+05 inhabitants (P_{ZHR} = 0.405 million inhabitants). Barcelona (BCN) has a $CPI_{1\ BCN}$ of 0.729 and 1.82E+06 inhabitants (P_{BCN} = 1.615 million inhabitants).

$$RF = \frac{1}{P} \times \frac{1}{CPI_1} \quad (1)$$

Thus, to compare the impacts (I) between BCN and ZRH the following weighting is proposed:

$$I'_{BCN} = \frac{I_{BCN}}{P_{BCN} \times CPI_{1\ BCN}} \quad (2)$$

$$I'_{ZRH} = \frac{I_{ZRH}}{P_{ZHR} \times CPI_{1\,ZHR}} \quad (3)$$

If (2) and (3) are applied to the GWP (in t CO_2-eq) of Barcelona (I_{BCN}=4.053E+6 t CO_2-eq) and Zurich (I_{ZHR}=1.822E+6 t CO_2-eq) respectively, the weighted emissions (in t CO_2-eq/10^6 inhabitants) evolve to I'_{BCN}=3.44E+06 in the case of Barcelona and I'_{ZHR}=5.89E+06 in the case of Zurich. These two values are now more comparable and, therefore, the analyst, given the data used, is able to state that, for the same level of performance, Barcelona emits less CO_2-eq than Zurich.

3.2.3.5. CPI as a way to include a sustainability perspective in the LCA of cities

Even though the goal may be established for assessing cities from an environmental perspective, economic and social aspects should be included somehow. On the one side, it is important that recommendations from LCA results consider potential trade-offs between social, economic and environmental areas as it is stated by Finkbeiner et al. (2010), as well as by the UNEP (2011). However, on the other side, integration of S-LCA and LCC considerations into environmental LCA imply a number of difficulties (Reap et al. 2008b; Hellweg et al. 2014). The LCSA is an addition of three complex methods which difficult its wide practice. Moreover, a city is a complex system which has seldom been assessed from a LC perspective.

These two challenging facts and the need to assess cities through a life cycle perspective and including social and economic aspects lead to the search of a more simple method to start with. Thus, we suggest including LC perspective in the assessment of the environmental impacts. Once the function of a city has been stated, the CPI and the number of inhabitants will be used as a performance measurement of this function. This level of performance applied to a set of environmental impacts, that include LC perspective in the inventory, is a way to set the environmental performance evaluation, not of an organization as stated in ISO (2003) but of a city. We assume that, by not including economic and social life cycle inventory data, we are not performing a city LCSA.

Nevertheless, the use of the CPI as technical performance within the FU to include social and economic aspects keeps metering the fulfilment of the service while it influences the most important part of an LCA: the FU. As the FU is influencing the entire LCA inventory, it can be considered that by normalizing the FU by the CPI, with social and economic aspects, we are providing a sustainability performance indicator, with environmental, social and economic information.

The second characteristic intends to increase the usefulness of the LCA for cities. Comparisons allow benchmarking and benchmarking opens the door to exchanging both best practices and solutions. The method suggested by Frischknecht (1997) is to take into account “comparable functions in terms on what is accepted as comparable in the market place" (Smith Cooper 2003). It is following this rationale that special care has been taken in the function and FU definitions, aiming at facilitating the comparison and benchmarking of results between cities regardless of their cultural, demographic or economic contexts. This is a key issue for boosting LCA as a proper tool not only for a specific region or cultural group of cities but for any urban region around the World.

The normalization of the FU may be useful to different purposes such as integrating the carrying capacity in the LCA (Bjørn and Hauschlid 2015), to be able to compare results among different complex systems, and to incorporate social and economic performance aspects to the LCA achieving a feasible (i.e.: simplified) LCSA.

By using the CPI, it could be considered that some double counting exists, because the CPI includes environmental information (Table 10). However, we think the risk of double counting is low. Firstly, the CPI only assesses environmental impacts in one out of the six assessed dimensions (having 22 sub-dimensions, and 64 indicators), the Environmental Sustainability dimension, which is assessed by three sub-dimensions (and 7 indicators): air quality (3), waste management (3), and suitable energy (1). Only one out of the 3 environmental sub-dimensions (and only two out of the 64 indicators) deals with emissions, assessing CO_2 emissions (and only from burning fossil fuels) and fine particles (UN Habitat 2016b). Therefore, the influence in CPI by environmental impacts as known in LCA is very low.

3.2.3.6. Analysis of eighteen cities' CO_2-eq emissions and the influence of the normalization factor in the indicator results

The calculated environmental behaviour of a city may change depending on how the FU definition is formulated. This fact is exemplified below. First of all, CPI values based on six dimensions for 18 cities are taken from UN Habitat reports (Moreno and Murguía 2015) and presented in Table 12. Secondly, data regarding the emissions of 17 of those cities on a given year and their population are extracted from the Carbon Disclosure Project database (CDP, 2016). For the case of Barcelona, the city council has provided the data (Barcelona City Council 2011). Even though a LC perspective has not necessarily been taken into account for data collection of CO_2-eq emissions, and although the emissions' year and the population's year do not always coincide, the goal in this chapter is to see if the results are sensible to changes in the normalization factor (P and/or CPI; where P = the number of millions of inhabitants in a city). This sensibility is reflected in how different cities change their position in the ranking (Figure 13).

Table 12. CPI, Population and GWP per city

City	CPI_1	P [M Inhabitants]	GWP [t CO_2-eq]
Addis Ababa	0.3672	3.38	3.71E+06
Athens	0.7079	0.66	4.71E+06
Barcelona	0.7288	1.62	4.05E+06
Guayaquil	0.6117	2.35	6.79E+06
Hong Kong	0.7335	7.31	4.27E+07
Jakarta	0.5723	10.08	2.78E+07
Lagos	0.3745	21.00	2.94E+07
Lima	0.6782	8.76	1.54E+07
Lisbon	0.761	0.55	1.93E+06
London	0.7706	8.60	4.02E+07
Madrid	0.7478	3.16	1.03E+07
Mexico	0.6807	8.87	2.37E+07
Montreal	0.7988	1.89	1.37E+07
New York	0.7443	8.49	4.94E+07
Quito	0.555	2.24	5.23E+06
Tokyo	0.7782	13.51	7.01E+07
Toronto	0.798	2.75	1.83E+07
Zurich	0.765	0.40	1.82E+06

The emission values in Table 12 are normalised in Table 13 in order to let the results be comparable among cities. Absolute numbers of emissions do not provide information to allow comparison, as a more populated city is expected to have higher emissions. The impact values in each impact category (only one in this exercise: GWP) shall be weighted by a factor depending on which characteristics are included in the FU definition: the RF. While calculating emissions per inhabitant provides better information than absolute emissions, not considering how those inhabitants live and achieve a certain level of development and prosperity makes the results still incomplete for comparison. Table 13 summarizes the GWP of 18 cities and the evolution of the GWP impact category depending on the normalization factor.

Table 13. GWP (t CO_2-eq) for 18 cities depending on the normalization factor

City	GWP	GWP / P	GWP / CPI_1	GWP / ($P \cdot CPI_1$)
Addis Ababa	3.71E+06	1.10E+06	1.01E+07	2.98E+06
Athens	4.71E+06	7.10E+06	6.66E+06	1.00E+07
Barcelona	4.05E+06	2.51E+06	5.56E+06	3.44E+06
Guayaquil	6.79E+06	2.89E+06	1.11E+07	4.72E+06
Hong Kong	4.27E+07	5.84E+06	5.82E+07	7.97E+06
Jakarta	2.78E+07	2.76E+06	4.85E+07	4.82E+06
Lagos	2.94E+07	1.40E+06	7.86E+07	3.74E+06
Lima	1.54E+07	1.76E+06	2.28E+07	2.60E+06
Lisbon	1.93E+06	3.53E+06	2.54E+06	4.64E+06
London	4.02E+07	4.67E+06	5.22E+07	6.06E+06
Madrid	1.03E+07	3.25E+06	1.37E+07	4.35E+06
Mexico	2.37E+07	2.67E+06	3.48E+07	3.92E+06
Montreal	1.37E+07	7.27E+06	1.72E+07	9.11E+06
New York	4.94E+07	5.82E+06	6.64E+07	7.81E+06
Quito	5.23E+06	2.34E+06	9.43E+06	4.21E+06
Tokyo	7.01E+07	5.19E+06	9.01E+07	6.67E+06
Toronto	1.83E+07	6.65E+06	2.30E+07	8.34E+06
Zurich	1.82E+06	4.50E+06	2.38E+06	5.89E+06

If both the population and the CPI are considered (Table 13), the resulting value for a given city is more comparable to any other city in the World (i.e. Figure 13) and to the city itself in different moments in time.

The ratio of "environmental impact per inhabitant" provides information about how inhabitants contribute to environmental impacts. The problem is that the inhabitants in the World neither live the same way nor are able to get the same level of development. Here the CPI appears to be useful.

The ratio of "environmental impact per CPI unit" provides information about how the achievement of each unit of prosperity contributes to impacting the environment. The problem here is that not all cities have the same number of inhabitants. Hence, the normalization through a combination of both, the number of inhabitants and the CPI, allows a better comparison among all cities in the World taking into account how, both their inhabitants and their standard of life, contribute to impacting the environment. Figure 13 compares the position of eighteen cities depending on which ratio is considered.

Position		GWP	GWP / P	GWP / CPI_1	GWP / (P ·CPI_1)
1	*Lowest*	Zurich	Addis Ababa	Zurich	Lima
2	*Emissions*	Lisbon	Lagos	Lisbon	Addis Ababa
3	*Ratio*	Addis Ababa	Lima	Barcelona	Barcelona
4		Barcelona	Quito	Athens	Lagos
5		Athens	Barcelona	Quito	Mexico
6		Quito	Mexico	Addis Ababa	Quito
7		Guayaquil	Jakarta	Guayaquil	Madrid
8		Madrid	Guayaquil	Madrid	Lisbon
9		Montreal	Madrid	Montreal	Guayaquil
10		Lima	Lisbon	Lima	Jakarta
11		Toronto	Zurich	Toronto	Zurich
12		Mexico	London	Mexico	London
13		Jakarta	Tokyo	Jakarta	Tokyo
14		Lagos	New York	London	New York
15		London	Hong Kong	Hong Kong	Hong Kong
16	*Highest*	Hong Kong	Toronto	New York	Toronto
17	*Emissions*	New York	Athens	Lagos	Montreal
18	*Ratio*	Tokyo	Montreal	Tokyo	Athens

Figure 13. Variations of position ranking of cities considering different factors

In some cities (i.e. Barcelona or Hong Kong), the use of a normalization factor or another implies little change (one position movement). Instead, there are other cities (such as Athens for CPI and Lisbon for number of inhabitants) whose position is more affected by the normalization factor chosen. For instance, being Addis Abbaba in the second position means that it is the second city with fewer GWP taking into account the prosperity of its inhabitants. As both the CPI and the GWP are low, it could be stated that although the ration GWP/(P·CPI) of Addis Abbaba is a good one, its government should put efforts on increasing Addis Abbaba's CPI, and therefore, the prosperity of its inhabitants.

3.2.4. Conclusions

Cities are relevant actors both in the generation of impacts and the potential for reducing environmental externalities. LCA, as a widely accepted tool for assessing environmental aspects of sustainability, is a good candidate for evaluating environmental impacts of cities. However, if comparison is considered a must, some common definitions in the goal and scope of the assessments need to be set. Thus, some items of a City LCA have been proposed: goal, function, FU and RF.

Even though LCA lacks of social and economic information, the use of the CPI, as technical performance within the FU of the city LCA, can be a solution for including the social and economic dimensions of sustainability and, by this means, a way to set an indicator of the environmental performance of a city in providing prosperity to its inhabitants. The advantage of this approach is the avoidance of the creation of social and economic impact categories while the sustainability assessment perspective is kept in the LCA. Therefore, this normalization may provide a practical solution for assessing systems by means of LCA but with the holistic perspective of a LCSA.

The impact of 18 cities has been analysed showing how the use of different normalization factors changes the rank of each city in the list. The per million inhabitants consideration of the environmental impacts contribute to allow comparison. However, it is still needed to consider how these inhabitants do live. The use of CPI is a good way to include this characteristic in the results making them comparable.

Within the list of eighteen cities, while the consideration of the number of inhabitants moves a city up to ten positions in the list, the consideration of social and economic aspects can move it up to three. Thus, the sustainability reputation of some cities can be increased or decreased not only depending on their number of inhabitants, but also on how cities perform in social and economic terms. This is exemplified in the comparison of Barcelona and Zurich's GWP, which shows that, even though Barcelona has a higher GWP [t CO_2-eq] than Zurich, if population and prosperity are considered as normalization factors, the modified GWP of Barcelona is lower than that of Zurich.

The information in section 3.2 is a first step to the performance of city LCAs with sustainability perspective which could, in the long run, result in the standardisation of Environmental City Declarations (ECD). System boundary definition and allocation procedures, for instance, should be also stated in future research so as to set the basis for performing a comparative pilot city LCA.

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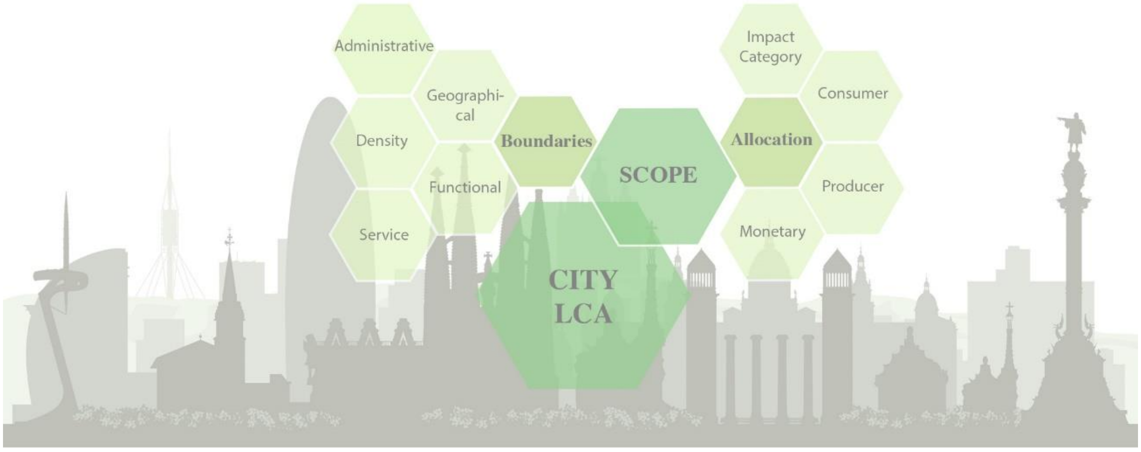


3.3. Allocation and boundaries in life cycle assessments of cities[26]

[26] The information in this section is extracted from this published article: Albertí, J., Roca, M., Brodhag, C., Fullana-i-Palmer, P., (2019) Allocation and system boundary in life cycle assessments of cities. Habitat International, 83, 14-54. https://doi.org/10.1016/j.habitatint.2018.11.003. Web of Science Impact Factor (2017): 3.000 – Quartile – Environmental Studies Q2 (28/109); Planning and Development Q1 (10/57); Urban Studies Q1 (4/40).

3.3.1. Introduction

Cities have become a hotspot during the second decade of the 21st century. The decisions that will be taken to manage cities will have midterm economic, social and environmental consequences (Rotmans et al. 2000; Devuyst et al. 2001). The majority of the population lives, works, or develops social activities in city regions (Wiek and Binder 2005). Furthermore, after the Paris Agreement, cities are expected to play a significant role in CO_2-eq emissions reduction, as sub-nations are recognised as “non-Party Stakeholders” (UN and UN Habitat 2014; UNFCCC 2015). Thus, the existence of evaluation methods and tools to drive cities towards sustainable development will have a widespread effect. For this reason, many international, multilateral and city-focused organisations have been created so as to generate knowledge and to face the challenges surrounding cities and their environmental behaviour (Albertí et al. 2017). These include organizations that aim to develop or to adapt an adequate assessment tool for sustainable development. Life Cycle Assessment (LCA) seems to be a good candidate for this purpose.

LCA has proved to be a proper tool to induce a reduction of environmental impacts of products, services and organizations (Ness et al. 2007). Albertí, Brodhag, & Fullana-i-Palmer, (2018) made a first proposal of a common function, functional unit (FU), and reference flow (RF) for developing city LCAs. We use the term “city LCA” to indistinctively refer to the life cycle assessment of any form of urban area geographically defined as stated in chapter 4.1.2. We use the term urban referring to the definitions set by UN, (2005).The definition of LCA items is a further step within the definition of the goal and scope of a city LCA, which should consider (Albertí et al. 2017): “(i) holistic point of view, (ii) multi-criterial assessment, (iii) LCA perspective, and (iv) the possibility to compare results among different cities or urban regions”.

LCA development often has specific rules for each type of system under study, as the ISO standards are just giving a framework to all type of systems. Environmental Product Declarations Programmes (ISO 2006a) and the Single Market for Green Products Initiative by the European Commission (European Commission 2012c) set Product Category Rules (PCR) for each economic sector. Being cities a fairly different type of system, a specific PCR should be expected (without the intention to consider a city as a product, although it may be seen as a service to humans’ development). However, very few contributions to city LCA may be found in the literature, being Albertí et al., (2017); Mirabella and Allacker, (2017); Petit-Boix et al., (2017); and Soust-Verdaguer et al., (2016) the only really specific references.

The definition of the system boundary determines which processes are included and which left out of an LCA study. This implies that the inventory data that needs to be gathered and the allocation of impacts may change depending on the definition of such boundaries ISO 14044 (2006c). Therefore, defining boundaries is a key step in LCA (European Commission 2010). Furthermore, properly defining boundaries using the same criteria for all systems under analysis is a precondition to perform comparative LCAs (ISO 2006c; Gössling 2013).

LCA may require determining how to allocate environmental burdens among different processes and systems (Nicholson et al. 2009). Moreover, ISO 14044 (2006b) specifies that, for comparative LCA studies, the same allocation procedures need to be used for all systems. If allocation principles and scale-specific constraints of the system are different, the comparison becomes impracticable (Gössling 2013; Dalin and Rodríguez-Iturbe 2016). Furthermore, the choice of the allocation procedure adopted has a significant impact on the results of the LCA (Cashion et al. 2016).

In LCA studies, especial attention must be devoted to allocation procedures in order to avoid double counting of impacts. ISO 14040 (2006c) states that "the sum of the allocated inputs and outputs of a unit process shall be equal to the inputs and outputs of the unit process before allocation". This is particularly important in the field of city LCAs, as these assessments are considering flows happening in and outside their boundaries, as well as flows happening both in international waters and airspace. This is, for instance, the case of shipping or tourism. Both cases imply that there is a need to allocate impacts, so that they are distributed amongst cities. The result of this allocation will have to follow the requirements of ISO 14044 (2006c), ensuring that the totality of the relevant emissions are considered and properly distributed.

The present study explores procedures to define the city-boundaries and environmental impact allocation procedures to further develop an LCA methodology that is specific for cities.

3.3.2. Methods

In order to analyse the applicability of existing definitions of system boundaries and allocation approaches to city LCAs, a revision of procedures in use has been conducted and presented in section 3.3.3. We have identified the existing LCA methods (European Commission, 2010; ISO, 14040 (2006b), 14044 (2006c), 14025 (2006a), 14067 (2013), 14072 (2014a); UNEP, 2011; UNEP et al., 2015) defining the boundaries of the systems under study and the allocation of burdens, and we have found that they are product, service or organization focused. However, the specificities of a complex system, of which cities are an example, are seldom taken into account.

Additionally, existing methods for city assessment do not have a full LC perspective and do not abide by the principles established in the ISO LCA standards (Albertí et al. 2017). Internationally accepted protocols and guidelines (ISO 2014b; PAS 2070 2014; WRI et al. 2014) provide a basis on which city assessments have already been performed. Furthermore, in different economic sectors, the reviewed scientific literature includes methodological and case study articles which provide information: a) on the methods to establish systems boundaries (UN 2005, 2016b; Reap et al. 2008b; OECD 2013; WRI et al. 2014; PAS 2070 2014; Lotteau et al. 2015a; Dijkstra 2016; European Commission and UN Habitat 2016; Sibiude et al. 2016; Uchiyama and Mori 2017); and/or b) on the allocation procedures (ISO 2006b, c, a, 2014a; Kahn Ribeiro et al. 2007; UNEP 2011; European Commission 2012a; Manfredi and Vignali 2014; de Jong et al. 2014; Cerutti et al. 2016; Schrijvers et al. 2016; Cristóbal et al. 2016; Baldini et al. 2017).

The revised literature lays the foundation to develop and/or suggest specific procedures for city LCAs which are presented in section 3.3.4. The study is complemented with a survey to city stakeholders, presented in section 3.3.4.3, which aims to gather their perception and evaluation of the proposed procedures for the definition of boundaries and the allocation of impacts. The involvement of stakeholders in establishing the appropriate methods and the inclusion of participatory approaches is an alternative procedure for dealing with allocation and system's limits definition (Mendoza Beltran et al. 2016).

In summary, the present study has been based on a thorough review of existing guidelines and standards as well as academic works linked to system boundaries and allocation procedures. This systematic literature review has grounded the development of specific procedures for city LCAs which have been validated via a survey.

3.3.3. Revision of existing procedures

3.3.3.1. Procedures to define the system boundaries

The ISO 14044 (2006b) defines system boundaries as the “set of criteria specifying which unit processes are part of a product system”. It establishes that, when delimiting system boundaries, it is essential to consider: (i) the need of alignment between the system boundary and the goal of the study, and (ii) the determination of which processes are included or not within the LCA study. The criteria to define the boundaries of the system which are set in the ILCD Handbook are aligned with those in the ISO 14044 definition (European Commission 2010). The accurate definition of boundaries contributes to the replicability of the LCA, and avoids, at least partially, burden shifting among the life cycle (LC) stages, by keeping the impacts inside the system boundaries (Baldini et al. 2017). A method to include burdens inside the system boundaries is the system expansion. This broadens the boundaries of the system including shared activities and its related impacts. While system expansion is useful for comparative purposes, in non-comparative LCAs it implies the inclusion of burdens that may not be related to the main function of the system. The impacts of these secondary functions, after the system expansion, should be subtracted so as to keep the goal and scope of the assessment.

Boundaries of a city LCA can be understood from two different perspectives: geographical and functional. The geographical boundaries are typical of entities such as cities, are easy to understand by the relevant stakeholders. Thus, the definition of the geographical boundaries of a city will be useful for determining which impacts are local, and which impacts are not. The functional boundaries set which activities are relevant or not for the assessment, no matter the place where the activity takes place, following the usual LCA criteria. Procedures on how to define boundaries of a city LCA are explored in chapter 4.1. The difference between the LCA of a city and that of other systems is that the former is geographically established. This will make city LCA need a definition of the geographical boundaries apart from the usual definition, in any LCA, of the functional ones.

Figure 14 exemplifies the variability of the size of the system under study depending on different geographical boundaries chosen. As an example, it depicts three delimitations of Barcelona that the European Commission has set in its Urban Data Platform (OECD 2013; European Commission et al. 2016), which have increasing levels of coverage, respectively called (OECD 2013): the *city area*, the urban administrative area that goes beyond the local administrative boundaries; the *functional urban area*, which comprises the city area plus the commuting zone; and the *metro area,* which considers the Classification of Territorial Units for Statistics level 3, NUTS-3 (from French: Nomenclature des Unités Territoriales Statistiques), which includes all urban agglomerations of more than 250.000 inhabitants.

The administrative boundaries, which were not taken into account by the Urban Data Platform, have been considered (white perimeter in Figure 14) for informative purpose.

The inner dark-grey shaded area corresponds to the so-called city area and represents the smallest coverage considered, which includes the city of Barcelona and multiple municipalities attached to it. Therefore, it overtakes the administrative boundaries of the Barcelona city council by including those towns and suburbs that are directly connected and have a similar level of population density. The second mid-grey shaded area widens the area coverage by using the functional urban area. This shaded area in the map includes not only towns and suburbs but also rural areas that are somehow affected by the activity of the city. Finally, the "metro area", represented in the light-grey shaded area, includes most of the province of Barcelona and almost reaches the metro area of Perpignan.

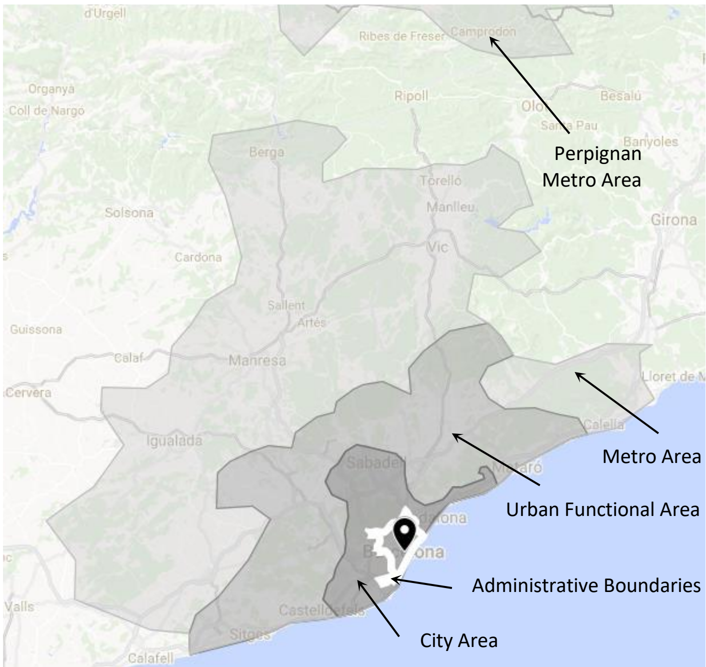
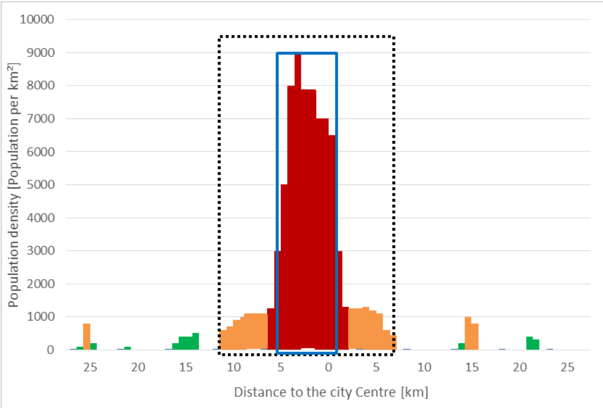


Figure 14. Boundaries of Barcelona based on the Urban Data Platform of the European Commission. Adapted from the European Commission et al. (2016); Map: ©2018 Google

The variation of the boundaries that could set the limits of a city relates to a missing global definition of what a city is. Still, although there is no globally accepted definition, most of the existing ones are based on a set of common variables (see for a review, Albertí et al., 2017).

The work done by the OECD and the European Commission (EUROSTAT and OECD 2011) sets an alternative harmonised method to define the *city*, the *greater city* and the *functional urban area* based on the degree of urbanization in a particular zone. Figure 15 is an example of such a method (extracted from (European Commission and UN Habitat 2016)), which depicts the enhancement of the city boundaries to adjacent towns and suburbs according to their harmonised definition. In this figure, the very-high density area (distances between around 0-5km to the city centre) represents the population included in a narrow town urban configuration (blue line rectangle). If adjacent towns and suburbs are included into the narrow town, the area covers what the European Commission and UN Habitat call a harmonised definition of a city (dash line rectangle).



	Broadville	Narrowtown	Harmonised Definition
Population	600.000	150.000	350.000
Density	Low	High	Medium
Air pollution	Low	High	Moderate
Acces to transport	Poor	Excellent	Fair
Green space	High	Low	Moderate
Population change	Growth	Decline	Stable
Land use growth	Rapid	No growth	Slow growth

Figure 15. Classification of the degree of urbanization. Source: Dijkstra (2016)

This *population density-based* methodology sets another three-way classification of the degree of urbanisation (Dijkstra and Poelman 2014): (i) *cities*, densely populated areas where at least 50% of the population lives in urban centres; (ii) *towns and suburbs,* intermediate density areas where at least 50% of the population lives in urban clusters and less than 50% of the population lives in urban centres; and (iii) *rural areas,* thinly populated areas where at least 50% of the population lives in rural grid cells.

3.3.3.2. Procedures to define the allocation of environmental impacts

Allocation principles determine the method used to distribute responsibility and accountability for the environmental impacts generated by a certain activity. For example, PAS 2070 (2014) provides two methodologies to assess city greenhouse gasses (GHG) emissions based on recognizing cities as consumers as well as producers of goods and services. The first of the proposed methods is the so-called Direct Plus Supply Chain (DPSC) methodology. It includes both territorial GHG emissions and those associated with the larger supply chains serving cities, being this consistent with the GPC (WRI et al. 2014). The second method is the Consumption-Based (CB) approach which uses “input-output modelling to estimate direct and life cycle (LC) GHG emissions for all goods and services consumed by residents of a city” (WRI et al. 2014).

The DPSC methodology provides useful information for city infrastructure planners (WRI et al. 2014), including both direct and indirect impacts from upstream activities. The CB methodology assesses those impacts that are caused by the consumption and production of products and services consumed by the residents of a city. Thus, under the CB, environmental impacts are allocated to the final costumers whereby the production of goods and services exported or served to external visitors (which can be relevant as city population can double due to tourism in some cases and seasons) are excluded from the inventory. For example, following the rationale of this methodology, one would allocate the emissions from electricity generation to consumers (PAS 2070

2014). This would in turn foster a more responsible consumption but could influence trade regulation. The broaden use of the CB methodology could imply a shift in the way the national GHG inventories are calculated. These are currently elaborated following the guides of IPCC (IPCC 2006) from which the governments calculate their national emissions inventory that report in each Conference of the Parties (COP).

The existing guidelines for environmental assessment of cities do not take an LCA ISO compliant perspective. These guidelines include three types of allocation procedures for the case of transportation, which could be extrapolated for other sectors: a) the city-induced activity method; b) the geographic territorial method; and c) the resident activity method (PAS 2070 2014; WRI et al. 2014).

The city-induced framework includes two levels of coverage. The *basic* level assesses the GHG emissions that are generated by activities within the boundaries of the city and energy use (scope 1 and scope 2), while the *basic+* level includes the assessment of transboundary activities, such as transport (scope 3), where, whenever there is a trip between cities, each of these cities is accounted 50% of the resulting impacts. Other sectors considered in Scope 3 by the *basic+* level (WRI et al. 2014) are: energy transmission and distribution losses, industrial processes and product use (IPPU), agriculture, forestry, and other land use (AFOLU).

The geographic territorial method assesses the emissions from activities that occur within the city boundaries (WRI et al. 2014). The resident activity is a variation from the geographical territorial method which assesses the emissions from activities developed by city residents only. This method considers the cause of the impacts dependant of the residence of the consumer, as the aspect that identifies the processes that must be included and excluded from the assessment. For example, if a car (driven or not by a resident) is used to enter the city under study, following the territorial method, only the trip done inside the boundaries would account for the city, while, under the resident method, all trips done by a resident would be accounted no matter whether they happen in or out the city boundaries.

Allocating impacts should be avoided when possible (UNEP et al. 2015). However, according to Baumann and Tillman (2004), there are three common scenarios where allocation procedures are to be used: 1) a multi-output scenario, where one process results in several products (i.e. refinery process); 2) a multi-input scenario, where one process has inputs from several sources (i.e. landfill, incineration or wastewater treatment); and 3) an open loop recycling scenario, where a material of a product is recycled and used into a different product which may not require the same quality criteria (i.e. plastic bottles recycled into clothes).

Following the recommendations by UNEP et al. (2015), allocation through partitioning should focus on physical relationships whenever it is not possible to apply system subdivision. In those cases, allocation through partitioning can be an alternative to determine how to share the responsibility of environmental impacts between cities. The problem of such a solution is related to the determination of the criteria by which to share impacts. These criteria may emerge from arbitrariness rather than a causality based rationale. Moreover, system expansion, which is discouraged by UNEP et al., (2015), might imply an excessive enlargement of the system under study. A consequence of an excessive enlargement of the system, which in the case of cities is large and complex enough, may be a too high number of data to search and, therefore, the deepness of the study may decrease to balance the resources available. In addition, in order to ensure the balance of matter and energy, cities would need to collaborate in order to together perform the LCAs. This would slow down the process of assessment. The abovementioned disadvantages of system expansion were already considered in EN (2011), a standard focussed on construction products. In this standard, given the complexity of the systems assessed and for the sake of simplicity, allocation is prioritized over system expansion.

Only if physical relationships are not properly found, one could base allocation of impacts on economic or other relationships (UNEP et al. 2015). However, (Baldini et al. 2017) compare allocation methods from 39 original articles performing LCA of milk production and find that most of these studies choose economic values as the base parameter for allocation. This fact confirms previous work by de (Vries and Boer 2010), who also found that most analysts tend to choose economic parameters to base allocation in. These authors, in line with (FAO 2010), warn that basing allocation on an economic criterion has the disadvantage that the "economic value depends on place and time and makes the comparison difficult across regions".

3.3.4. Proposed city focussed LCA procedures

Whilst city LCAs have not previously been conducted, their goal would include policy making, planning purposes, and strategy improvement (Albertí et al. 2018a). This surpasses the scope of decision-context usually applied to products, which is used for micro-level decision support: Situation A of the ILCD handbook (European Commission 2010). On the contrary, city LCAs should follow the criteria defined for the meso/macro-level decisions (Situation B), as it has large-scale consequences. When the purpose of the study is related to policy making, a finer set of calculations and especial attention to interactions among different subsystems are required (Gössling 2013). This framework has guided the proposed procedures for defining the boundaries of a city and for allocating its environmental impacts when conducting a city LCA, which are hereby presented.

3.3.4.1. Procedures for defining the system boundary of a city LCA

The geographical boundaries of a city determine the limits of the urban area under study. Meanwhile, the functional boundaries of a city determine the set of activities and its environmental impacts that will be accounted for in the city LCA. Both determine what we define as *boundaries of a city LCA*.

The activities that take place in a city and their impacts can occur beyond its administrative boundaries. Accounting for all these activities can result in an overly complex system definition. Thus, when conducting a city LCA, one should establish procedures for defining the boundaries of a city that are parsimonious in nature, by simplifying the system and only including the relevant activities induced by the city. However, there are several factors that hinder the delimitation of city boundaries.

The first difficulty lies in the variability of the urban form, which is a result of the evolving shape of cities throughout history as well as the existence of different models to define it. The form of a single city can be described by three main models: (i) concentric-zones; (ii) sectorial; and (iii) multiple-nuclei. In addition, systems of cities or metropolitan areas can be defined by a polycentric model (World Bank Institute 2013). The resulting variability of the city shape needs to be taken into account when setting the procedures for defining the geographical boundaries of a city.

A second difficulty in determining the boundaries of a city LCA derives from the fact that the geographical boundaries are not always coincident with the functional boundaries. Geographical boundaries are usually set based on administrative or political criterion, while functional boundaries are based on the provision of services regardless of their geographical location. In addition, inhabitants do not generally perceive the administrative limits of the city in their day to day activity and seldom realize the functional limits of a city. Any agreed boundary definition for city LCA could contribute to clarify to those inhabitants how their consumption pattern is inducing burdens beyond the boundaries they intuitively have in mind. For instance, if an airport, which is outside from the administrative boundaries of the city, is included in the city's functional boundaries, it would make citizens understand that their activity is inducing the impacts derived from the airport infrastructures.

Should the procedure to establish the boundaries of a city be based on the provision of services, a third limitation could arise due to the variability of the types of services provided in different cities and their extent. This variability makes it extremely difficult to choose the one service that could be used to delimit a city. For example, setting the urban transport network as the parameter to set the boundaries of the city may have sense in some cases but cannot be generalized. This would be the case of a city without a transport network and with some sanitation infrastructure. In that city, the simple access to sewage system is enough to consider an area inside the city boundaries.

Three procedures to set the boundaries of a city are proposed below, taking into account the identified challenges.

3.3.4.1.1. Administrative-based boundaries

Administrative-based boundaries attribute the responsibility of environmental impacts to the city only if these occur in the area delineated for the purpose of local administration. *Administrative-based* boundaries are the most frequently used procedure to define cities' geographical boundaries. On the one hand, they facilitate data collection which is usually measured and recorded by administrative bodies. Furthermore, the use of *administrative-based* boundaries facilitates the implementation of changes in policies and urban ordinances, which can derive from the city LCA, since regulatory bodies have competences within such boundaries. Finally, administrative boundaries can be considered steadier, as the change in local administration scope seldom occurs.

Despite these positive traits, administrative boundaries are not naturally perceived by citizens. Cities have merged due to urban development so that no differences can be found when transiting from one to the other. Moreover, from a boundary perspective based on functionality, several services placed outside the city administrative boundaries can be used by both, citizens residing within these boundaries as well as non-residents, i.e. hospitals, airports or industrial zones. Thus, by choosing administrative boundaries, the assessment of the city would fail to include activities that are induced by the city but occur outside its administrative boundaries.

3.3.4.1.2. Density-based boundaries

Density-based boundaries of a city include the areas where environmental impacts occur, based on the population density of these areas rather than the administrative boundaries of the city. The area considered includes towns and suburbs that are adjacent to the city and have continuity in the level of population density. *Density-based* boundaries are increasingly used from a geographical point of view. For instance, the Organization for Economic Cooperation and Development (OECD), the European commission (EC) and the United Nations Habitat Program (UN Habitat) have adopted a harmonised *density-based* definition (OECD 2013). The UN Habitat and the EC have committed to work on "a global people-based definition of cities and human settlements" in the Habitat III conference (Dijkstra 2016; UN 2016b). From a functional point of view, *density-based* boundaries are aligned with most of the services that cities provide their inhabitants with. Still, some facilities, such as airports, are usually not connected to the city through a constant density of population. In such instances, a *density-based* boundary would fail to include in the assessment some activities that might be mainly induced by the city. This issue is considered and tackled in the *services-based* boundaries explained in section 3.3.4.1.3.

Another instance where *density-based* boundaries might misrepresent functional reality occurs when there are terrain singularities (such as water bodies or orographic breaks) between two cities, as depicted in Figure 16. Such singularity creates a discontinuity in the population density that might not be representative of the existing link (or lack of it) between the cities. Tools such as night-time satellite imaging are useful to show the presence of human activities (Nel·lo et al. 2016) and understand if, despite the singularity of cities, these may be considered as a unique urban region. Furthermore, in the inter-city space there may be specific resources used by the city, ecosystem services in particular. Again, services based boundaries can contribute to have all this into consideration.

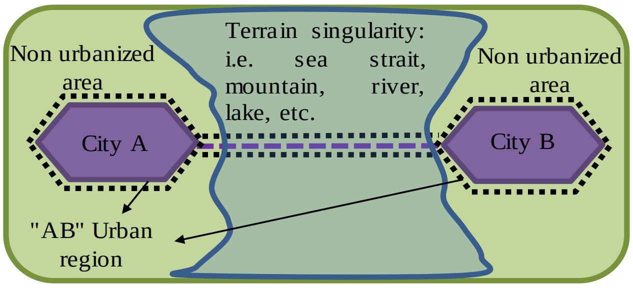


Figure 16. Determination of urban areas. Inspired by OECD (2013)

3.3.4.1.3. Service-based boundaries

In the *service-based* boundaries, impacts are attributed to the city when they are related to activities that provide a service to individuals within the administrative boundaries of the city (whether or not activities occur within its administrative boundaries). As described in 4.1.2, *density-based* functional boundaries cannot always avoid the exclusion of relevant subsystems which are geographically close and have a strong relation of causality with the main system under study (i.e. an airport or an industrial park). *Service-based* boundaries includes and enhances the *density-based* boundaries. Therefore, the problem of the inclusion in the system of activities developed in different areas (as "airport" in Figure 17) that may not be included in the *density-based* boundaries is solved by the *service-based* boundaries. Figure 17 illustrates a situation where an industrial park and an airport are outside three cities' *density-based* boundaries (hexagons A, B and C). Both the airport and the industrial park activities are used by inhabitants from two cities (B and C) that are not under study and, thus, a distribution of the impacts due to these activities should be included in all city LCAs (A and B use the industrial park, and A and C use the airport).

The main advantage of *service-based* boundaries is that the activities that are included within the boundaries of the city are those local plus those that the city induces (being their main recipient, user, or beneficiary). This rationale aims to increase the lifelikeness of city boundaries in terms of social, economic and environmental influence. However, an associated risk to such definition is that boundaries may include areas that are geographically far from the administrative boundaries of the city which may in turn excessively broaden its limits and complexity. This expansion could imply a never ending addition of new processes in the assessment, as it may happen within any LCA, in which the deletion of life cycle processes is only allowed if the overall conclusions of the study are not affected (ISO 2006c). Additionally, the expansion may require a determination of the share of responsibility of each city over the environmental impacts, so as to avoid double counting (see a simplified representation in Figure 17, where the dash line represents the *service-based* boundary of city A and the share of the activities induced by other cities (B and C) is represented with different colours). Ecological or ecosystem service units should be treated as other services used by the city under study.

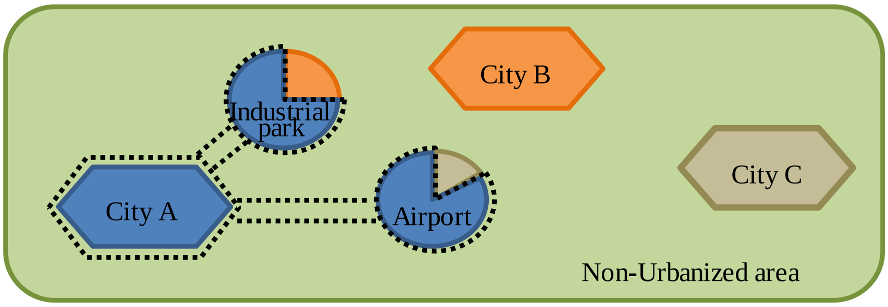


Figure 17. Service-based boundaries based on nodular activities

3.3.4.2. Procedures for defining the allocation principles for a city LCA

Allocation principles determine the method used to distribute responsibility and accountability for the environmental impacts generated by a certain activity. As seen above, this activity could be a multi-input, a multi-output or an open loop process. Existing LCA-based allocation principles (revised in section 3.3.3.2) are neither geographically based nor geographically delimited and are rather focussed on the impacts of particular products or services. A city is a geographically fixed open system, which exchanges matter and energy, including products and services with embedded matter and energy among other cities around the world. Thus, the assignment of impacts due to activities induced by cities should be done to those cities, not to the products, services or other goods that result from those cities' activity. As existing LCA-based allocation principles were not thought to be applied in a city LCA we propose five procedures to do so.

ISO 14044 (2006c) fosters the identification of processes that are shared amongst products to determine the procedures for the allocation of environmental impacts. The realization of a city LCA that considers the location of needs and their impacts is aligned with this precept. Table 14 represents the possible combinations of locations of the needs covered against the impacts associated to the fulfilling of these needs depending on whether any of them are in or out of the city boundaries. Columns identify whether the needs fulfilled by the system are induced from within ($A_{i,1}$), outside ($A_{i,2}$), or both ($A_{i,3}$) the city boundaries. Rows identify the place where the impacts associated to the coverage of needs occur within ($A_{1,j}$) or outside ($A_{2,j}$) , or that impact both in and out ($A_{3,j}$) the city boundaries.

Table 14. Allocation cases by causality

Allocation		NEED		
		IN	OUT	BOTH
IMPACT	IN	$A_{1,1}$ (e.g. buildings , roads, underground …)	$A_{1,2}$ (e.g. tourism)	$A_{1,3}$ (e.g. buildings , roads, underground…)
	OUT	$A_{2,1}$ (e.g. landfill disposal)	$A_{2,2}$ (not assessed)	$A_{2,3}$ (e.g. airports, ports, waste water treatment plant…)
	BOTH	$A_{3,1}$ (e.g. imports)	$A_{3,2}$ (e.g. work commuting, exports…)	$A_{3,3}$ (e.g. water supply infrastructure, electricity grid…)
Where: i: 1, 2, 3; j: 1, 2, 3; and 3 = (1 U 2).				

The existence of scenarios where the impacts are not unambiguously attributable to the city under study demands well-defined allocation procedures. Imagine, for example, an airport for which the analyst would have to decide how to allocate, on the one hand, the impacts of the airport infrastructure, and, on the other hand, the impacts due to the flights which have departures and arrivals from/to the airport under study. The share of the impacts of the airport infrastructure firstly depends on whether the boundaries selected are administrative, density or services based, which will in turn determine whether an allocation procedure is needed. The allocation of the impacts of the flights depends on the allocation approach chosen. The present section proposes several procedures for the allocation of environmental impacts to cities and discusses their implications.

3.3.4.2.1. Monetary-based allocation

Based on the close relationship between economic activities and environmental impacts, the *monetary-based* allocation distributes a share of the environmental impacts assessed to each stage of the supply chain depending on the added value generated at each of these stages in the LC of products or services (Cerutti et al. 2016; Cristóbal et al. 2016). Social benefits or losses are not considered in this approach. . Thus, when applying this allocation procedure, an “environmental intensity” ratio is used (i.e. the intensity of a GWP generating activity can be measured by CO_2-eq/€). To some authors, the *monetary-based* approach increases “the realism and consistency of the LCA method” (Schrijvers et al. 2016). The disadvantage of the *monetary-based* allocation is that it is strongly influenced by economic variations. Thus, results from one year to another may be volatile and difficult to compare over time (Cerutti et al. 2016). Additionally, variability in prices is a challenge to apply the *monetary-based* allocation, due to both currency change and inflation. The use of a Parity Purchasing Power Currency could foster its wider application.

Existing standards accept the allocation of environmental impacts through a *monetary-based* allocation (UNEP et al. 2015), which is currently used by LCA analysts. However, this is seldom the primary or most recommended mechanism, since allocation approaches linked to physical characteristics associated to the provision of goods or services are generally favoured. The sophistication of the economic statistical apparatus provides a lot of data, but today massive data offers new opportunities for measuring physical data.

The use of top-down process is controversial as data should be acquired at the level where it justifies decisions. For instances, the greenhouse gas emission indicators of the regions were calculated in France trough top-down process. National emissions were allocated to the activities of the economic sectors whilst the carbon content of the turnover of each sector is calculated at the national level. The economic statistics of each region allow then to allocate their share of emission. However, in this top-down method, a region making efforts on decarbonisation would not see its emission indicators decrease.

3.3.4.2.2. Producer-based allocation

The *producer-based* allocation assigns environmental impacts to the location where the activities that produce such impacts take place. This is based on the rationale that the activity which is considered to be the main cause for impact generation in the LC of products (or services) is their manufacturing (or provision) which fosters their consumption. In the case of transport, impacts are to be assigned to the place where the producer is.

Many environmental impacts happening in the production site have local affectations. In some sectors, such as agriculture, the production phase involves more than 80% of the impacts (Weber and Matthews 2008). Under a *producer-based* allocation, these impacts are attributed to the production site. This facilitates the practice of LCA (Baldini et al. 2017). However, the model fosters that cities that are heavy importers are not accounted responsible for the way imported products and services are produced or transported, since they are not attributed the environmental impact of products or services they consume or buy (Table 14).

The international shipping of products is an element of the supply chain which is seldom considered in the assessment of national GHG emissions (IPCC 2006). However, the globalization of the economy has raised the relevance of logistics (Sims et al. 2014). While international transport is responsible for 33% of world's trade emissions (Cristea et al. 2013), existing guidelines do not allocate impacts of transport that occur in international waters or airspace neither to the exporter nor the importer (Yamin and Depledge 2004). According to Kahn Ribeiro et al., (2007), changing this rule by assigning impacts to where the producer is located, would increase the focus on reducing international transport emissions.

The *producer-based* allocation could solve this particular problem when evaluating international transport by assigning the impacts happening in international waters and airspace to the producer. However, current guidelines do not consider the allocation of impacts that occur in international airspace or in international waters. PAS 2070 provides some criteria on impacts' allocation happening partly within the geographical boundaries, stating that "the allocation of GHG emissions associated with air transport and shipping to the city may be carried out by allocating a proportion of fuel used or distances travelled to the city based on the proportion of total surface transport to and from these airports and ports serving the city". However, PAS 2070 does not provide guidance on how to determine such "proportion" and does not account for downstream international shipping, such as exports, which happens outside the boundaries of the assessed city.

3.3.4.2.3. Consumer-based allocation

The *consumer-based* allocation assigns the environmental impacts associated with the provision of products and services to the final user/consumer, in this case the city where consumption takes place. This approach is adopted to give incentives towards more sustainable practices and behavioural changes in consumption patterns. It is based on the rationale that the activity which is considered to be the main cause for the production and, thus, the generation of impacts, is the demand and further use/consumption of products or services. Therefore, the impacts originated during the LC of the product should be allocated to the main inducer of the impact generation: the consumer. There are two existing methodologies that attribute environmental impacts to the place where the product or service is consumed: the Direct Plus Supply Chain (DPSC) and the CB.

The CB, also called market-based or destination-based, is used by the GPC so as to allocate Scope 2 emissions based on "contractual instruments" (WRI et al. 2014). It uses an "environmentally extended input-output" modelling (EEIO) based on financial flows to estimate direct and LC GHG emissions for all goods and services consumed by residents of a city". The environmental impact is attributed to the user and, thus, this approach is contributing to give incentives to attain more sustainable practices and behavioural changes on the consumers' side. Furthermore, this methodology contributes to the analysis of the international supply chains and the impacts beyond the administrative boundaries of the city under study. Under such an approach, GHG Emissions will be allocated to activities that do not depend on the location where products and services are produced but rather on where these are consumed (PAS 2070 2014).

A disadvantage of the *consumer-based* allocation is that impacts with local relevance in the production site would be accounted in the consumption city. For instance, water consumption in the production stage could be a relevant environmental indicator for the local government of a city where there is water scarcity (e.g., Abu Dhabi (Gassert et al. 2013)). If water was indeed mostly consumed in Abu Dhabi but a *consumer-based* approach was applied, the impact would be allocated to another city (Reykjavík) where water scarcity may not be relevant (Gassert et al. 2013). Therefore, no political action may be derived from the assessment results.

3.3.4.2.4. Category-based allocation

The way impacts are assigned to one or another system has consequences for all systems of the set (Chancel and Piketty 2015). However, the literature on allocation principles does not consider the possibility to base the allocation of impacts depending on whether the environmental effects under study have a local or global affectation. This approach, which one could call *category-based*, is hereby proposed as an intermediate method between the *producer-* and *consumer-based* allocation. Under the *category-based* allocation, global impacts (i.e. global warming potential (GWP), ozone depletion potential (ODP), etc.) are assigned wherever consumption takes place, while local impacts (i.e. noise, water use (WU), acidification potential (AP), eutrophication potential (EP), etc.) are allocated where the impacts occur. For example, WU should remain allocated in the city where water is extracted since the damaged ecosystems are generally those near the water extraction (that is local by nature). Contrarily, GWP caused by the consumption of products or services should be allocated to the place where the product or service is consumed given that such impact is global.

Figure 18 provides information on the certainty, consensus and geographical affectations of different impact categories. We include GWP, Fossil Fuel Use, and ODP in the definition of *Global*: the harm caused by the impact is dispersed and may have global affectations. We consider the rest of impact categories in Figure 18 as *Local*: the harm caused by the impact has affectations in a localized area.

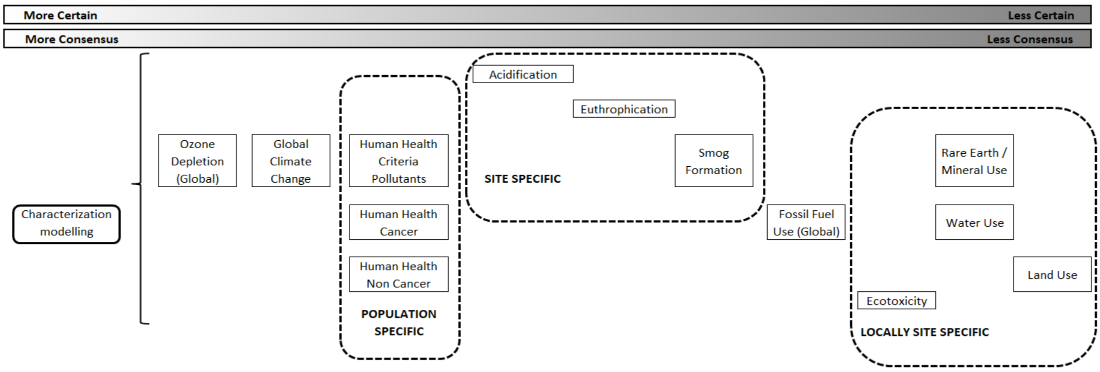


Figure 18. Local and global impact categories. Adapted from Bare (2014)

The rationale behind the *category-based* allocation is to foster action from public bodies so as to reduce the impact where it is caused. This approach is not applied by any current standard since an extra effort is needed to separate global and local impacts (Figure 18).

For instance, accounting the GWP to the cities where consumption takes place would make the developed countries National GHG inventory increase. This should cause a reaction from the State's Government trying to diminish cities' contribution to national GHG inventories by requiring cities to purchase with higher GHG efficiency or to consume less.

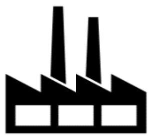
An exemplary impact for the *Local* consideration may be the already mentioned case of WU. Local governments where products are manufactured need to know local WU data so as to be able to relate them to the water bodies' carrying capacity in order to get information on how far they are from sustainably using local resources. This way, assigning the impacts to the producer increases the sustainability of the supply chain, as they are assigned to the actor that should improve the current situation.

It is important that the responsibility is shared between the producer and the consumer. Some authors consider that it is possible to integrate at the local level the global ecological limits, in a top-down approach (Rockström et al. 2009; Wolff et al. 2017). However, we consider that the *category-based* allocation is a good way to foster sustainable consumption behaviour while maintaining part of the responsibility in the producer's side. Contrarily, in the *monetary-*, the *producer-,* and the *consumer-based* approaches, the impacts get arbitrarily assigned to the producer or the consumer; or get dispersed along the supply chain in the case of the *monetary-based* approach. Here is where the *category-based* approach may contribute to assign impacts to those actors that have responsibility on its generation (the consumers) and to those that experience its consequences (the producers' communities and ecosystems).

3.3.4.2.5. Exemplification of the different procedures for assigning impacts to cities

Table 15 presents an hypothetical simplified example describing a life cycle of tomato sauce based on the case study performed by Manfredi and Vignali, (2014) (Table 16). It depicts three stages of the life cycle: tomato production, tomato sauce production, and tomato sauce packaging and final distribution (where we also include the hypothetical consumption and final disposal). Each of the stages occurs in different cities where they produce a certain profit, and generate different environmental impacts. These are described in Table 15.

Table 15. Effect of the allocation method in the LCA results

			
LC Stage	Tomato production	Tomato sauce production	Tomato sauce packaging and distribution
Location	**Girona**	**Messina**	**Ravensburg**
Selling price	0.73€/kg tomato	1.2€/kg tomato sauce	5.23€/kg tomato sauce
Source of the price	(Mercabarna 2017)	(Tapia Cruz 2013)	(Veritas)
Added Value	0.73 €	0.47 €	4.03 €
Producer-based allocation	WU_1 GWP_1 ODP_1 EP_1 AP_1	WU_2 GWP_2 ODP_2 EP_2 AP_2	- GWP_3 ODP_3 EP_3 AP_3
Consumer-based allocation	- - - - -	- - - - -	$WU_t=\Sigma WU_i$ $GWP_t=\Sigma GWP_i$ $ODP_t=\Sigma ODP_i$ $EP_t=\Sigma EP_i$ $AP_t=\Sigma AP_i$
Impact category - based allocation	WU_1 - - EP_1 AP_1	WU_2 - - EP_2 AP_2	- GWP_t ODP_t EP_3 AP_3
	$0,14\times WU_t$	$0,09\times WU_t$	$0,77\times WU_t$

Monetary-based allocation	0,14×GWP_t 0,14×ODP_t 0,14×EP_t 0,14×AP_t	0,09×GWP_t 0,09×ODP_t 0,09×EP_t 0,09×AP_t	0,77×GWP_t 0,77×ODP_t 0,77×EP_t 0,77×AP_t

Table 16. LCA results of tomato production. Source: Manfredi and Vignali (2014)

Category	Unit	ΣCategory$_i$	Tomato production i=1	Tomato Sauce Production i=2	Tomato Sauce packaging and distribution i=3
GWP_i	kg CO_2-eq	0.674	0.181	0.108	0.385
ODP_i	kg CFC-11-eq	7.12E-08	1.05E-08	1.14E-08	4.9E-08
AP_i	kg SO2-eq	0.0031	0.000348	0.000189	0.00246
EP_i	kg PO4-eq	0.00193	0.00138	4.29E-05	0.00051
WU_i	Litres	104.9	103.6	1.3	0

Results from two impact categories, GWP as a global impact and EP as a local one, from Table 16 are used according to the procedures set in Table 15 to understand the consequences of applying one allocation procedure or another. Results are depicted in Figure 19 which shows how the different approaches shift the cities' responsibility of global and local impacts. The *category-based* allocation behaves as a *consumer-based* allocation when allocating global impacts while it behaves as a *producer-based* allocation when allocating local impacts. When this procedure is applied, there is no advantage for the consumer or for the producer, because cities are always assigned with local and/or global impacts. The *producer-based* allocation seems to be the one that mostly distributes the impacts along the cities in the supply chain, while the *monetary-based* allocation does not distinguish between impact categories when distributing the impacts.

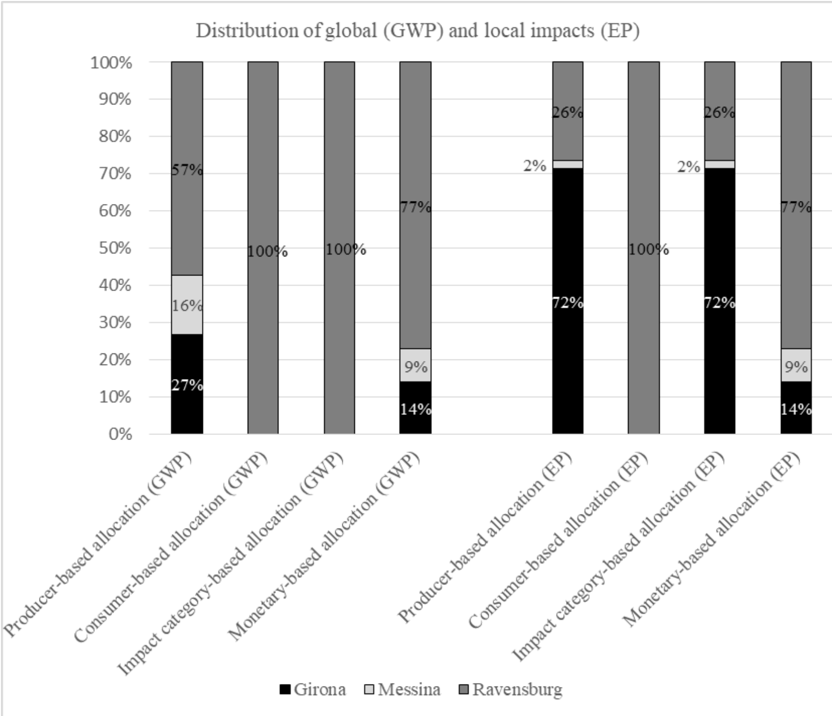


Figure 19. Exemplification on how global and local impacts are allocated depending on the allocation approach chosen

Some facts that may also affect the choice of one allocation procedure or another are: (i) existing economic statistics, (ii) data accessibility by new means such as massive data, or (iii) ecosystem services considerations. This choice may also depend on the usefulness of information for which decision-making is taken, for instance: (i) for infrastructure planning, such as impact studies to compare solutions; (ii) for monitoring global commitments, such as policies and program development; (iii) for the management of key resources, such as ecosystem services, in and out of the boundary of the city; or (iv) for changes in production and consumption patterns.

3.3.4.3. International experts' feedback about the proposed city focussed LCA procedures

The lack of previous literature on how to set a common goal and scope framework for conducting city LCA threatens the solutions proposed above. We have considered consulting an expert panel of stakeholders. Thus, a survey has been prepared so as to gather their opinion about how to set the boundaries of a city under study and how to allocate the impacts of activities that take place in different geographic locations but that are induced by the city under study.

3.3.4.3.1. Survey methodology

The questionnaire was initially distributed via Google Forms to 11 members of the UNESCO Chair in Life Cycle and Climate Change (ESCI-UPF) to test the appropriateness of its layout. Comments on this first pilot survey were collected to adjust the questionnaire, improving its comprehensibility and usability. After this pre-test, the questionnaire was sent to the network of experts of the UNESCO Chair in Life Cycle and Climate Change (ESCI-UPF) including over 1500 professionals of 72 internationally recognised institutions of 29 countries around the world. The questionnaire was sent out during the second half of Jannuary 2018 and was left open till the end of February. Three email reminders were sent to maximize response rate. A total of 83 international experts completed the questionnaire in organisations such as: The Union for the Mediterranean, World Business Council for Sustainable Development, Sustainable Solutions Development Network, UN Habitat, UNI Institute for Environment and Human Security among others, and private companies, universities, and research centers around the world. The survey obtained a response rate close to 5%, an acceptable amount considering it was distributed online. Table 17 presents the main characteristics of the sample obtained. Note that, even though the panel of experts that responded is composed of reputed professionals of well-established institutions, given that sampling was based on voluntary responses, results need to be interpreted as exploratory.

Table 17. Sample Characteristics

Gender	
Male	63%
Female	37%
Origin	
Europe (Spain excluded)	33%
Spain	31%
South America	17%
North America	11%
Africa	4%
Asia	2%
Middle East	1%
Oceania	1%
Education	
PhD	36%

Master	55%
Bachelor	6%
Secondary school	2%
Position	
Top Manager	34%
Middle Manager	22%
Technician / Researcher	41%
Administrative/Intern	2%
Institution	
Consultancy	25%
Public Sector	16%
Research/Academia	46%
Urban Agent	13%

The questionnaire was distributed by email and questions were divided in two sections. Each section depicted a simplified hypothetical scenario where respondents were asked to provide their views on (i) how the responsibility of environmental impacts should be allocated and (ii) how the boundaries of a city should be defined (see additional information for the full questionnaire). The order in which the two sections were presented was randomized to control for order effects.

A first section was devoted to the evaluation of methods for defining the system boundaries of a city. It presented respondents with a hypothetical allocation of the impacts associated with the activities of an airport. Next follows the description of the scenario.

Imagine that the airport where a tourist is arriving is NOT within the administrative boundaries of your city. Nevertheless, you know that most air traffic (>80%) on that airport is due to passengers that visit your city. There are two impacts of the airport that could be included in the boundaries of the city: those related with the infrastructure (i.e.: airport building, the runway, parking lots...) and those related with the flight (such as the fuel consumed by the plane).

Respondents were asked to evaluate alternative methods to set the boundaries to allocate the impacts of the airport infrastructure as well as the allocation of the impacts related with the flights themselves. In particular, they were asked whether the impacts should totally, partially or not be included within the boundaries of the city. Wherever respondents indicated that only a percentage of impacts should be included, a criterion for setting the share was to be indicated.

Finally, respondents were asked to evaluate the following three possible types of boundaries:

1. *Administrative-based boundaries*: the impacts that are attributed to the city are those related to activities occurring in the area delineated for the purpose of local administration.

2. *Density-based boundaries*: the impacts that are attributed to the city are those related to activities occurring in an area that goes beyond the administrative boundaries of the city which includes adjacent towns and suburbs with a continuous level of population density.

3. *Service-based boundaries*: the impacts that are attributed to the city are those related to activities that provide a service to individuals within the administrative boundaries of the city (whether or not activities occur within its administrative boundaries)

In particular, they were asked to rate these methods in terms of their lifelikeness, simplicity and accuracy.

A second section, evaluating allocation procedures, asked respondents to consider a scenario related the manufacturing of a particular product (tomato sauce), as described next:

Imagine that tomatoes are produced in Tomato FRUIT City and these are exported to a Company in SAUCE City, which is buying the tomatoes and preparing tomato sauce to sell it to CONSUMER City, located in a third country where the tomato sauce is consumed. Figure 20 summarises the idea.

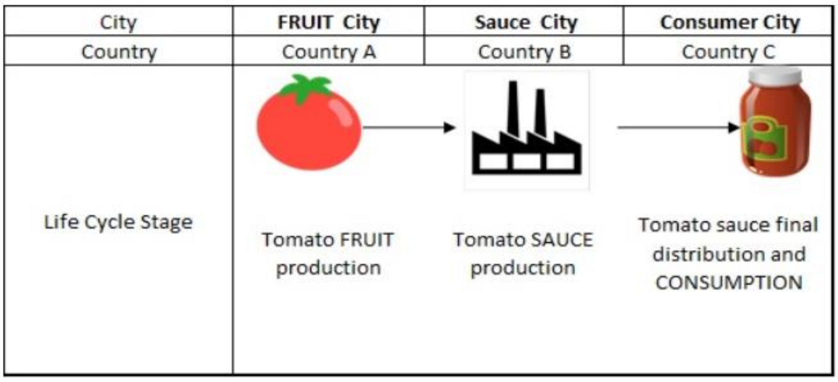


Figure 20. Diagram presented to the survey respondents for allocation considerations

Respondents had to analyse where the environmental impacts of the different stages of production were to be allocated. If they indicated that these had to be distributed amongst several cities, they in turn had to indicate the distribution criteria.

Next, respondents were asked to evaluate the following four allocation procedures:

1. *Producer-based allocation*: assigns the impacts where the activities generating the externality occur. Given that the activities that generally cause the main impacts are those associated with the manufacture of products or services (rather than consumption), places of production will be attributed most impacts.

2. *Consumer-based allocation*: assigns the impacts associated with the production of products and services to the final user. This approach is adopted to give

incentives towards more sustainable practices and behavioural changes in consumption and is based on the rationale that the impacts of production occur because there is demand for the products and services offered.

3. *Category-based allocation*: assigns the impacts depending on whether they have a global or local affectation. Global impacts (i.e. global warming) are placed where consumption takes place, whilst local impacts (i.e. noise, water use, etc.) would be allocated where the impacts occur.

4. *Monetary-based allocation*: After the sum of all impacts in the life Cycle is performed, this approach distributes a share of the impacts to each stage of the supply chain depending on the added value generated at each of these stages.

In particular, they were asked to rate these methods in terms of their lifelikeness, simplicity, accuracy, influence and informativeness.

Finally, the survey respondents were asked to rate the relevance of each of the characteristics used to qualify the boundaries and allocation procedures proposed: lifelikeness, simplicity, accuracy, influence and informativeness.

3.3.4.3.2. Survey results

This section presents the results of the survey. First, we analyse the relevance that respondents associated different dimensions that can be considered when performing an LCA. Next, we analyse the evaluation that respondents made of the methods proposed to define the system boundaries and allocation procedures both when considering a hypothetical scenario and when globally evaluating their characteristics.

3.3.4.3.2.1. Evaluation of characteristics to be considered when performing an LCA

The later part of the survey asked respondents to rate the importance of different characteristics in the realization of an LCA. The considered characteristics were lifelikeness, simplicity, accuracy, influence and informativeness. Table 18 presents the mean evaluation that the importance of each of these dimensions obtained in a scale from 1 to 7 (and corresponding standard deviations). Results show that respondents indicated that the most important characteristic to take into account when deciding the procedure is informativeness (mean= 5.6; sdev=1.4).

Table 18. Mean evaluation (standard deviation) of the relevance of the assessed characteristics to be considered in the boundaries and allocation definition

	Lifelikeness	**Simplicity**	**Accuracy**	**Influence**	**Informativeness**
Mean (Sdev)	5.1 (1.8)	4.7 (1.6)	5.4 (1.6)	5.5 (1.6)	5.6 (1.4)

3.3.4.3.2.2. Evaluation of the procedures to define system boundaries

Results, shown in Table 18, indicate that most experts considered that the effects of the airport infrastructure needed be included in the city boundaries (55.4% of the respondents) whilst 33.7% considered that the impacts of flights also had to be included in the city boundaries. The majority of respondents considered that the effects of flights were rather to be distributed amongst cities (54.2% of the responses). Amongst those, the distribution criteria that was favoured was that based on usage (26.5% of total respondents) followed by the impact category (21.7%).

Table 19. Responses to whether the airport environmental effects should be included in the city boundaries (n=83)

	Airport infrastructure		**Flights**	
Answer	**n**	**% respondents**	**n**	**% respondents**
Yes	46	**55.4**	28	33.7
No	7	8.4	10	12.0
A percentage	30	36.1	45	**54.2**
Benefit	6	7.2	4	4.8
Use	14	16.9	22	**26.5**
Impact category	8	9.6	18	21.7
Others	2	2.4	1	1.2

Respondents rated (in a scale from 1 to 7) the possible methods for the definition of system boundaries (*administrative-, density-* or *services-based*) in terms of their lifelikeness, simplicity and accuracy. Informativeness and influence were only considered in the evaluation of the allocation procedures. Table 20 presents the mean ratings and corresponding standard deviations. Results show that the *density-based* method is considered the most lifelike approach (mean=4.9, sdev=1.6). The *administrative-based* method is rated as the simplest to implement (mean=5.0, sdev=2.0). Finally, the *service-based* method is the one that is considered the most accurate to determine city boundaries (mean=5.1, sdev=1.6).

Table 20. Mean evaluation (standard deviation) of three types of boundaries – Administrative, density and services based - in a scale from 1 to 7 in terms of their lifelikeness, simplicity and accuracy (n=83)

	Administrative-based		**Density-based**		**Service-based**	
	Mean	**(Sdev)**	**Mean**	**(Sdev)**	**Mean**	**(Sdev)**
Lifelikeness	4.1	(1.9)	**4.9**	(1.6)	4.8	(1.7)
Simplicity	**5.0**	(2.0)	4.2	(1.7)	4.0	(1.7)
Accuracy	3.8	(2.0)	4.8	(1.6)	**5.1**	(1.6)

3.3.4.3.2.3. Evaluation of the alternative procedures to allocate environmental impacts

Table 21 presents the proportion of respondents that opted for each of the different alternatives for the allocation of environmental impacts of the tomato sauce chain. Results indicate that most respondents preferred that, for all stages of the supply chain, impacts had to be shared amongst cities and that the distribution had to be based on the impact category. These results are aligned with the procedure proposed in the present work.

Table 21. Choice of allocation of impacts to cities for each of the phases of production/consumption of tomato sauce (n=83)

	Tomato Fruit Production		**Tomato sauce production**		**Distribution and consumption**	
	n	**% respondents**	**n**	**% respondents**	**n**	**% respondents**
Fruit city	15	18.1	4	4.8	7	8.4
Sauce city	6	7.2	26	31.3	9	10.8
Consumer city	8	9.6	9	10.8	24	28.9
Shared	54	**65.1**	44	**53.0**	43	**51.8**
Monetary	*9*	*10.8*	*8*	*9.6*	*8*	*9.6*
Impact category	*40*	***48.2***	*31*	***37.3***	*30*	***36.1***
Others	*5*	*6.0*	*5*	*6.0*	*5*	*6.0*

Respondents were also asked to rate alternative allocation procedures: *produced-based*, *consumer-based*, *category-based* or *monetary-based* in terms of their lifelikeness, simplicity, accuracy, influence and informativeness (in a scale from 1 to 7). Table 22 presents mean results and corresponding standard deviations. Results show that a *category-based* approach is considered to be the most lifelike (mean=4.7, sdev=1.8), accurate (mean= 4.7, sdev=1.7) and informative (mean=4.9, sdev= 1.6) method. The *producer-based* approach is rated as the simplest approach (mean=5.1, sdev=1.6). Finally, the *consumer-based* approach is considered the most influential of the approaches.

Table 22. Mean evaluation (standard deviation) of four types of allocation procedures – producer, consumer, category and monetary-based - in a scale from 1 to 7 in terms of their lifelikeness, simplicity, accuracy, influence and informativeness (n=83)

		Lifelikeness	**Simplicity**	**Accuracy**	**Influence**	**Informativeness**
Producer-based	Mean (Sdev)	4.6 (1.6)	**5.1** (1.6)	4.2 (1.6)	3.8 (2.0)	4.3 (1.7)
Consumer-based	Mean (Sdev)	4.3 (1.4)	4.4 (1.5)	4.3 (1.5)	**5.4** (1.6)	4.8 (1.5)
Category-based	Mean (Sdev)	**4.7** (1.8)	4.0 (1.7)	**4.7** (1.7)	4.7 (1.6)	**4.9** (1.6)
Monetary-based	Mean (Sdev)	3.9 (1.7)	4.3 (1.7)	4.1 (1.6)	4.2 (1.7)	4.3 (1.7)

3.3.4.4. Survey discussion

Among *administrative-*, *density-* and, *service-based* boundaries, the *density-* and the *service-based* ones are the preferred by the panel of experts surveyed (Table 17). Density-based boundaries, being the most life like ones, can be useful for setting the geographic boundaries of a city. In addition, *service-based* boundaries, the most accurate ones, can be the useful for defining the functional boundaries of a city (Table 18, Table 20, and Table 23).

Table 23. Characteristics of different boundaries proposed

	Lifelikeness (second most important)	**Simplicity (less important)**	**Accuracy (most important)**
Administrative-based boundaries	Lowest (4.1)	**Highest** (5.0)	Lowest (3.8)
Density-based boundaries	**Highest** (4.9)	Medium (4.2)	High (4.8)
Service-based boundaries	High (4.8)	Lowest (4.0)	**Highest** (5.1)

Although *monetary-based* is the most commonly used allocation procedure nowadays, it is the less preferred both by literature and by our panel of experts (Table 24). Although *producer-based* allocation is the most used procedure for allocating CO_2 emissions, and even though there is a trend to shift to a *consumer-based* procedure, the *category-based* one is the most accepted by the survey respondents.

When assessing the characteristics fulfilled by the different allocation principles proposed, there are three statements to be set: (i) *Monetary-based* allocation is not being considered as the best option in any of the characteristics proposed; (ii) *Category-based* allocation is the principle that best performs in most (3 over 5) of the characteristics proposed (Table 18); and (iii) *Category-based* allocation is performing best in two over the three most relevant characteristics, and highly performing in the fourth most relevant one (Table 18, Table 20, and Table 24).

Table 24. Characteristics of different allocation procedures proposed

	Lifelikeness (fourth most important)	**Simplicity (less important)**	**Accuracy (third most important)**	**Influence (second most important)**	**Informativeness (most important)**
Producer-based	High (4.6)	**Highest** (5.1)	High (4.2)	Lowest (3.8)	Lowest (4.3)
Consumer-based	High (4.3)	High (4.4)	High (4.3)	**Highest** (5.4)	High (4.8)
Category-based	**Highest** (4.7)	Lowest (4.0)	**Highest** (4.7)	High (4.7)	**Highest** (4.9)
Monetary-based	Lowest (3.9)	High (4.3)	Lowest (4.1)	High (4.2)	Lowest (4.3)

Although the survey is not a definitive validation of the proposed procedures, it is useful to understand the perception by different stakeholders. Thus, we consider the abovementioned results as another support to the statements set in the conclusions.

3.3.5. Conclusions

Boundary setting and allocation procedures have been studied and compared. Two type of boundaries need to be set in a city LCA, as a city is a geographically fixed open system. The geographical boundaries of a city determine the limits of the urban area under study and are useful for determining which impacts are local, and which impacts are not. Meanwhile, the functional boundaries of a city determine the set of activities, and its environmental impacts that are relevant or not for the assessment, no matter the place where the activity takes place. Both determine what we define as *boundaries of a city LCA*.

It has been found that current city assessment tools use a vague definition of “city” and, therefore, no consensus is achieved for geographical boundary setting. This fact makes the current city assessments results barely comparable among cities.

In section 3.3, LCA procedures are taken into account to propose three procedures for boundary definition in city LCA (*administrative*-, *density*- and *service-based* boundaries), but the lack of consensus on what a city is makes the choice difficult. *Density*- and *service-based* boundaries seem to be the most parsimonious, as we see they are the simplest ways to simulate the complexity and interdependency of cities.

Geographical boundaries of a city LCA should be defined through the *density-based* procedure, which should include cities, towns and suburbs connected with a continuous density of population. However, the functional boundaries of the city LCA should be defined through *service-based* procedure, which would help to include, in the city system, those induced activities that happen out of the geographical boundaries of the city.

If there is a need to include a service that is shared among different cities, an allocation procedure which would only account a part of its impacts in the city assessment should be used.

Four allocation procedures have been proposed for city LCAs. In any case, the chosen allocation procedure should follow the causality principle between the impact and the activity performed. In general, a *monetary-based* approach may be appropriate when other procedures fail to represent reality. However, the proposed method for allocating impacts to the producer or the consumer, depending on if the impact category under consideration is local or global (the *category-based* allocation), has been found through a survey to be the most preferred way to share responsibilities along the supply chain.

The survey results show how the *category-based* allocation procedure is the preferred by the panel of experts, by giving best marks in informativeness, lifelikeness, and accuracy, and second in influence. They also prefer *density*- and *service-based* boundaries, by giving best marks in lifelikeness and accuracy respectively.

Using the same procedures for setting the boundaries of city LCAs would facilitate comparison of results. Furthermore, increasing the use of the *category-based* allocation method would foster the generation of pro-sustainable development policies in both producer cities and consumer cities, as they will both be accounted for some of the impacts generated. In addition, this would avoid arbitrary decisions that assign 0-100% or 50-50% of the impacts to producer and consumer, keeping closer to the causality principle.

Future methodological research should concentrate on continuing finding consensus on the goal and scope phase of city LCAs. This research should preferably be carried out and agreed before too many city assessments are performed, what, given the high relevance cities are acquiring, may need a quick response.

3.3.6. References

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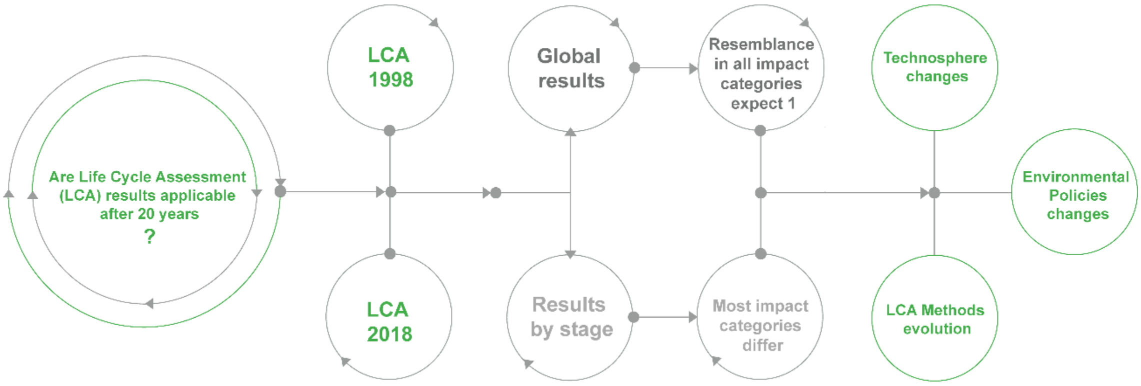

3.4. Does a Life Cycle Assessment remain valid after 20 years? Scenario analysis with a Bus Stop study[27]

[27] The information in this section is extracted from this published article: Albertí, J., Civancik-Uslu, D., Contessotto, D., Balaguera, A., Fullana-i-Palmer, P. (2019) Does a life cycle assessment remain valid after 20 years? Scenario analysis with a bus stop study. Resources Conservation and Recycling, 144 169-179. https://doi.org/10.1016/j.resconrec.2019.01.041. Web of Science Impact factor (2017): 5.120 – Quartile – Environmental Engineering Q1 (8/50); Environmental Sciences Q1 (23/242).

3.4.1. Introduction

The term *urban furniture* or *street furniture* refers to a broad number of objects and equipment installed in the urban areas for different purposes. Urban furniture is part of the urban hierarchy (Albertí et al. 2017) and modifies the built environment providing services to city inhabitants. However, it is a heterogeneous sector and not well defined, in terms of products nor functions provided. It is closely linked to the construction sector, as it may include objects such as: benches, bins, bollards, bright billboards, bus stops, fences, fountains, kiosks, lamps, luminous signals, marquees, memorials, non-luminous signals, phone boxes, planters, playgrounds, post boxes, public sculptures, public toilets, pylons, streetlamps, taxi stands, traffic barriers, traffic lights, traffic signs, tram stops, tree grates, waste receptacles and watering troughs among others. The whole variety of products concurring to constitute the urban furniture can be subdivided in macro-groups, according to different criteria such as the function that they perform (EcoSMEs 2004). The Bus Stop category is essential for urban planning and mobility, and will play a significant role for the future smart city.

LCA is considered as an environmental management tool for the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 2006d). This methodology describes and analyses the resources involved in a system under study and the emissions or wastes derived from its life cycle: from raw materials extraction to waste management activities. As main characteristics, it is important to mention that LCA: a) is an analytical method; b) follows an iterative step-wise procedure; and c) considers and interprets multiple potential environmental impacts of a product or service throughout its life cycle.

LCA is being more and more applied to the urban hierarchy, from a brick to a whole city (Albertí et al. 2018a; Balaguera et al. 2018). Many of the LCA studies found about urban furniture were performed with an eco-design purpose (Fullana et al. 1998; Fullana i Palmer 1999a, b, c; IHOBE 2010; Certainteed Corporation 2015). The aim of those studies was to highlight the life cycle stages and sub-stages where the majority of impacts were produced, in order to operate on these stages and to reduce the associated environmental burdens. According to Rieradevall et al. (1999), the subdivision of the lifecycle of urban furniture can be set in four macro stages: materials and manufacturing, installation, use and maintenance, removal and end of use.

3.4.1.1. Materials and manufacturing

Urban pieces of furniture are generally made of different materials, such as wood, metals, plastics and glass, together with more sophisticated, complex and heterogeneous components, such as electrical and electronic devices. The amount and type of materials used, the characteristics of those materials and the way the objects are produced determine the amount of impacts that are produced in this stage

(EcoSMEs 2004). According to Civancik-Uslu et al. (2018), materials form significant part of environmental profile of a product.

3.4.1.2. Installation

The installation stage generates environmental impacts by means of the tools and equipment used to anchor down the street pieces of furniture. Depending on the type of anchoring/foundation system used, heavy construction machinery and a large amount of materials may be needed.

3.4.1.3. Use and maintenance

Energy consumption, lights maintenance and emptying bins are the main activities which contribute to generate environmental impacts. The frequent cleaning and maintenance ensure a correct performance and safety of urban furniture and, in addition, reduces the need for repair. Maintenance works are various: setting parts, painting, and surface treatment and welding. Some of the factors that influence the maintenance needs are: properties of materials, level of vandalism, and (climate) characteristics of the place in which the furniture is installed.

3.4.1.4. Removal and end of life

The programmed replacement of urban furniture can be due to different causes: obsolescence, damage, or a will to renew the image of the city. The waste flows of street furniture are not produced continuously and the quantities are usually small, compared to those of other systems. Most of the waste materials are aluminium, steel or wood based, and can be easily separated and recycled. Furthermore, some reusable parts can be sent directly to the manufacturing facilities to re-enter the life cycle in an inner loop of circular economy. Both, reutilization and recycling of pieces and materials, are highly dependent on the way the furniture was designed and mounted.

In addition, according to the literature (Rieradevall et al. 1999; EcoSMEs 2004), the urban furniture sector can be subdivided in three groups which include different levels of complexity ((Table 25 and Table 26). As it can be deduced from Table 26, in order to evaluate the main part of the environmental impacts for products belonging to Group 1, it would be sufficient to apply a “cradle to gate” analysis. However, for products belonging to Group 2 and Group 3, a full “cradle to grave” assessment should be performed.

Table 25. Groups of urban furniture and environmental impact contribution of their life cycle stages. Source: Rieradevall et al. (1999) and EcoSMEs (2004)

Element type	**Life Cycle stages**							
				Maintenance		Use		
	Materials	Manufacturing	Installation	Cleaning	Repairing	Energy	Material	End of life
Group 1. Bins, benches, tree grates, fences, pylons, not luminous-signals, playgrounds, planters.	**	*	*	---	*	---	---	*
Group 2. Traffic lights, lamps, luminous signals.	***	**	***	*	***	***	**	***
Group 3. Bus stops, bright billboards and municipal information panels, kiosks, toilets for public use.	***	**	***	***	***	***	***	**

---: not relevant; *: less important; **: important; ***: very important

Table 26. Characteristics of the 3 groups of Urban Furniture. Source: Rieradevall et al. (1999) and EcoSMEs (2004)

	Group 1	**Group 2**	**Group 3**
Complexity of the products	Simple	Complex	Very complex
Environmental impact of the materials	Relevant	-	Relevant
Energy demand in the use stage	-	High	High
Complexity of maintenance	Simple	Complex	Very complex
Complexity of final disposal (due to high variety of different materials)	Simple	Complex	Very complex

The goal of section 3.4 is to find out how much and why an old LCA study remains valid or not after a period of time by re-performing an LCA of a bus stop in the city of Barcelona that was performed about 20 years ago by Randa Group for JC Decaux (Fullana et al. 1998).

3.4.2. Background

The literature regarding the application of LCA to urban furniture is scarce. The reason for that can be the small amount of studies published due to industrial confidentiality (many studies may have been kept for internal use). For instance, 45 projects exist in the website of a single consultancy (Cyclusvitae 2018). Only few studies were available in the literature (Rieradevall et al. 1999; Vallés et al. 2001; IHOBE 2010; EnerBuiLCA 2012) which aim to identify the stages requiring more improvement from an environmental point of view. Even, some of those studies were made by private consultancies and neither the results nor the methods in which they were conducted were always published. As an example, four case studies taken from EnerBuiLCA (2012) are presented in Table 27 in order to show the differences in different components of the scope of the LCA. Finally, the lack of information on temporal dimension is considered as an important limitation in LCA (Levasseur et al. 2010) and it is considered as a very recent research topic (Shimako et al. 2018).

Table 27. Four case studies of LCA of Urban Furniture. Source: adapted from EnerBuiLCA (2012)

Name of product	**Banco NOMO**	**Banco MAYO296**	**URKIA**	**FENCE**
Kind of product	Bench	Bench	Bench	Fence
Made of	Bench of pine wood Legs of zinc coated steel	Concrete	Concrete	Wood
Producer	ESCOFET	ESCOFET	PREFABRICADOS URKIA S.A.	CertainTeed
Source of the study (reference)	(EnerBuiLCA 2012)	(EnerBuiLCA 2012)	(IHOBE 2010)	(Certainteed Corporation 2015)
Performer of the study	iMat	iMat	Engineering Kideak Ingurumenaren	Sustainable Solutions Corporation for CertainTeed
Reason for carrying out the study	The will of the company to evaluate and compare the environmental impact of the benches	The will of the company to evaluate and compare the environmental impact of the benches	-	The will of the corporation to quantify and understand the environmental impacts throughout the life cycle, as a tool in the product design process, and as an input to the Building for Environmental and Economic Sustainability life cycle product database

Recognized steps in life cycle	**Manufacture**	X	X	X	X
	Distribution	X	X	X	X
	Installation	X	X		X
	Use			X	X
	Maintenance	X	X		
	Removal	X	X		
	End of life	X	X	X	X
Functional unit		Sit and rest service provided by 1 meter of useful bench installed in a public space in the center of Barcelona for 15 years	Sit and rest service provided by 1 meter of useful bench installed in a public space in the center of Barcelona for 15 years	1 concrete bench during its lifecycle of 20 years	-
LCA software		-	-	LCA Manager®	LCA Manager®
Database used		-	-	Ecoinvent 2.0	Ecoinvent 2.0
Impact assessment methodology		CML – 2001	CML – 2001	CML – 2001	CML – 2001
Impact assessment categories evaluated	**Acidification Potential**	X	X	X	X
	Criteria Air Pollutants				X
	Ecotoxicity				X
	Smog				X
	Stratospheric Ozone Layer Depletion Potential	X	X	X	X
	Natural Resource Depletion				X
	Eutrophication Potential	X	X	X	X
	Global Warming Potential	X	X	X	X
	Human Health: Cancer & Non-cancer				X
	Human toxicity	X	X	X	X
	Indoor Air Quality				X
	Habitat Alteration				X

3.4.3. Methods

3.4.3.1. Goal of the study

The original LCA study of a bus stop was initiated as a tender of Barcelona's City Council within the terms of the contract for installation and maintenance of urban furniture (Fullana i Palmer 1998). It was performed by the Randa Group for JC Decaux, which is the largest outdoor advertising corporation in the world, with the aim of identifying the environmental burdens from different life cycle stages of the bus stop in order to decrease them and better compete in the mentioned urban furniture tender (Vallès et al. 2000).

According to ISO 14044, the goal of an LCA should include the following six items (1) intended application(s) of the deliverables / results; (2) limitations due to the method, assumptions, and impact coverage; (3) reasons for carrying out the study and decision-context; (4) target audience of the deliverables / results; (5) comparative studies to be disclosed to the public; (6) Commissioner of the study and other influential actors".

Therefore, the goal of the new LCA is: (1) to compare the environmental impacts of the same product whose LCAs are separated 20 years (2) assuming that a single case of study is not enough to state it, (3) the reason of this comparison is to analyse the longevity of LCA results so as to provide the scientific community and the LCA practitioners with a reference of how LCA results evolve along the time. (6) The study has not had a commissioner even though an author of the paper from which section 3.4 derives of was the performer of the LCA 20 years ago.

3.4.3.2. Function of the product and functional unit

The function of a bus stop is to provide comfort to the user of public transport while waiting for the buses. In order to reach this goal, the bus stop should provide the following items: (i) protection from adverse weather conditions like rain, wind and sunstroke, (ii) seats, (iii) information on the transport network, and (iv) advertisement. The functional unit of the LCA is defined as: "A bus stop with an area of 4010x1705 mm used during 8 years in the city of Barcelona" designed by Norman Foster, as it was in the past study (Fullana i Palmer 1998).

3.4.3.3. Life cycle of a bus stop (system boundary)

Both studies consider the same life cycle stages. The life cycle is divided in 6 different main stages: manufacturing, installation, use, maintenance, removal, and end of life. Each stage has different processes. The whole system, with stages and processes, is presented in Figure 21.

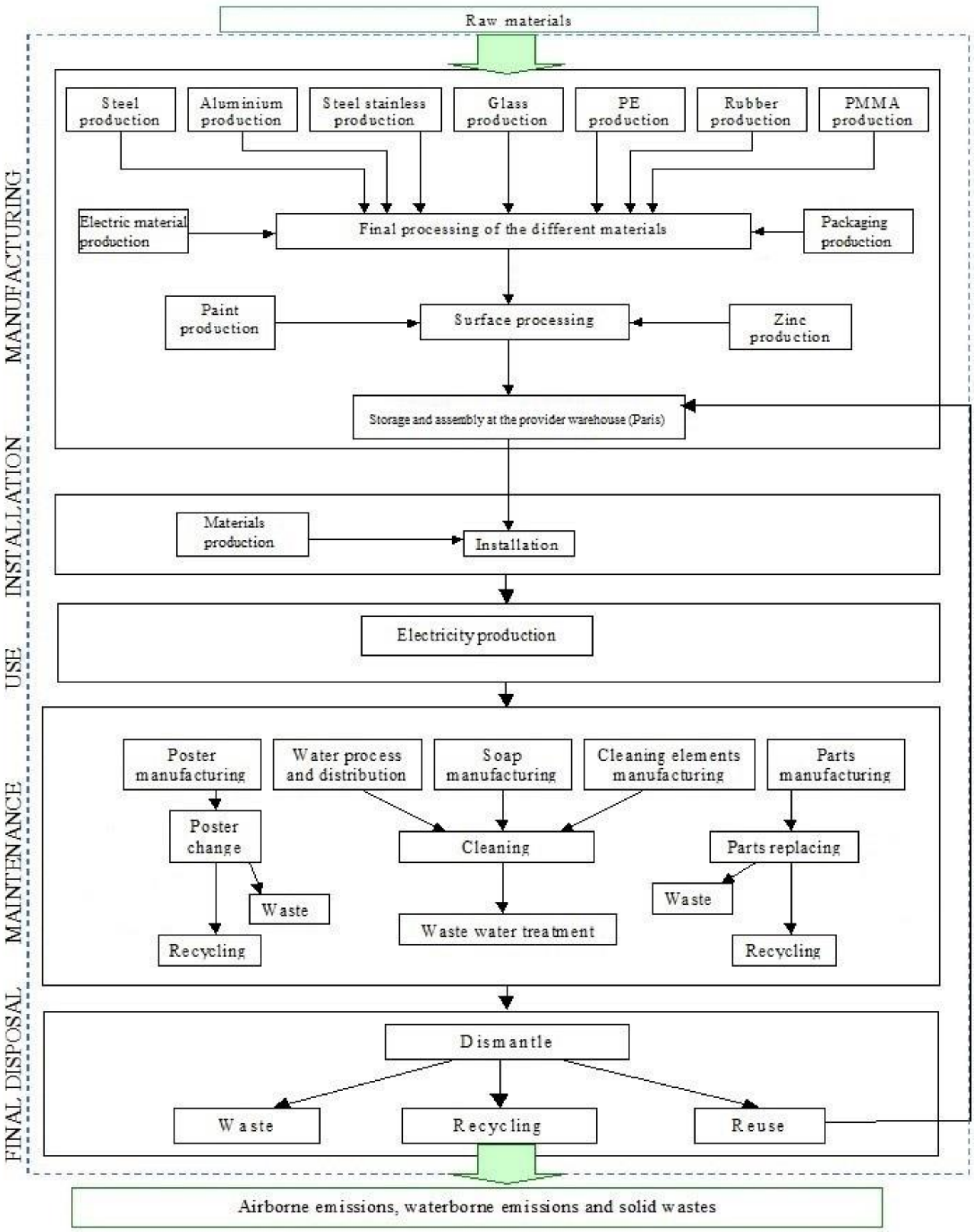

Figure 21. Life cycle of the bus stop analysed in the study. Source Fullana i Palmer (1998)

3.4.3.4. Data quality requirements

The data on which the study is based comes from the inventory of the previous study performed in 1998 by the Randa Group. These data were, at the time, revised by external experts, and correspond to central-European data for the manufacturing stage and Spanish or Catalan data for the installation, use, maintenance, and end of life stages. In addition to the data originally given by JCDecaux to Randa Group, general bibliographic data is used regarding to suppliers, in order to represent a proper mix.

In the original study, there was a preliminary estimation of the environmental impacts. The aim was to identify the steps and processes that affected the final results the most and those which were negligible. This preliminary research was followed by a deeper study that concentrated the effort on the stages with major impacts.

The differences in data assumptions and processes between the new and old LCA studies are the following (Table 28): (a) the date of the used databases; (b) the choice of some different processes depending on their availability in the databases; (c) assumptions in the manufacturing of the pieces; (d) the landfill disposal modelling; and (e) the energy mix chosen for electricity production.

Table 28. Differences between the two scenarios

<table>
<tr><th colspan="2"></th><th colspan="2">“New” LCA</th><th colspan="2">“Old” LCA</th></tr>
<tr><td colspan="2">Databases used for the model</td><td colspan="2">“Professional + extension” of GaBi6 and ecoinvent</td><td colspan="2">IVAM LCA, BUWAL 250, IDEMAT 96 and PRe4</td></tr>
<tr><td rowspan="2">Manufacturing of the materials</td><td>Steel bending</td><td colspan="2">Not taken into account</td><td colspan="2">Considered</td></tr>
<tr><td>Percentage of aluminium from recycled materials</td><td colspan="2">25%</td><td colspan="2">The percentage of secondary production was not specified</td></tr>
<tr><td colspan="2">Modelling of the landfill</td><td colspan="2">Different nature of the different categories of waste is considered:
- The posters used in the maintenance stage were disposed to the paper dump.
- All plastic materials: polyethylene, polyester and polypropylene to plastic weir.
- The pieces of glass, steel, aluminium and copper were sent to inert landfills.</td><td colspan="2">Organic or inorganic nature of the waste were considered:
- Paper and polyester to an organic landfill.
- All the other pieces to inorganic landfill.</td></tr>
<tr><td colspan="2" rowspan="4">Electricity production mix of Catalonia</td><td>Nuclear</td><td>52.5 %</td><td>Nuclear</td><td>76 %</td></tr>
<tr><td>Hydroelectric</td><td>8 %</td><td>Hydroelectric</td><td>14 %</td></tr>
<tr><td>Natural gas</td><td>28.7 %</td><td>Thermal</td><td>5 %</td></tr>
<tr><td>Thermal</td><td>0.9 %</td><td>Others</td><td>5 %</td></tr>
</table>

	Wind	5.9 %	Data source: Institut Català d'Energia (ICAEN; Fullana i Palmer 1998)
	Others renewable	0.9 %	
	Others not renewable	3.1 %	
	Data source: (ICAEN 2014; Vidal 2014)		

3.4.3.5. Software and databases

In the original study, SimaPro software was used, while in the new one GaBi 6 software is used instead. In the original study, several databases were used; IVAM LCA (IVAM UvA BV), BUWAL 250 (Greenhouse Gas Protocol 2012), IDEMAT 96 (Idemat) and PRe4 (PRé Consultants) databases, whilein the new study, almost all processes and plans used to create the model are taken from thinkstep professional + extensions database (Service Package 29) . The exceptions to that are: the manufacturing of posters for the maintenance stage (in the "changing of the posters" sub-stage), and the paper manufacturing. Since the data was not available for those process in Thinkstep database, the information is taken from ecoinvent database v3.1 (ecoinvent 2018).

3.4.3.6. Impact assessment methods

While the LCA of the new study is performed by using the CML 2001 (April 2015) impact categories, which is currently the most up-to-date version, the original study was performed using the CML 1992, which was the most up-to-date version in the year of 1998. Since only the final results of the original LCA, by stage and impact category, were available from the study performed in the past, it was necessary to re-perform it to get more detailed results, so that the differences can be better identified, if any. Furthermore, since CML 1992 is not available in GaBi anymore, the authors chose the oldest accessible method, CML 1996, as a representative for the old model impact assessment to re-perform the LCA. As this issue may be relevant, and influence the obtained results, this section also assesses the influence of the impact assessment methods (CML 2001, CML 1996 and CML 1992) on the results (Chapter 4). A summary of the impact assessment methods considered can be found in Table 29.

Although the chosen impact assessment methods belong to the same origin for the two LCA studies, which was CML, the flows considered within the impact categories have been updated. The old study was based on ISO 14040 (1997) criteria and CML 1992 method; while for the new study, ISO 14040 (2006) and ISO 14044 (2006) criteria, and CML 2001 method were used. The most important characterization factors (CF) used in the impact categories, and the emissions of the three methodologies, are evaluated in order to find the differences caused by the variations in the evaluation methodology: those of CML 1996 and CML 2001, which are already in GaBi6, while 1992 CML values are taken from the original study.

Table 29. Combinations of scenarios and methods of assessment

	Original	Re-performed study
Old study	CML1992 (old scenario for comparison, Chapter 3)	CML 1996 (old scenario for assessing the influence of the method, Chapter 5)
New study		CML 2001 (new scenario for comparison, Chapter 4)

The original study was developed considering the impact categories of Eutrophication Potential (EP), Ozone layer Depletion Potential (ODP), Global Warming Potential (GWP) and Acidification Potential (AP), to which other 3 indicators were added: energy consumption (EC), water use and solid waste production. For comparison's sake, the new study considers the same impact categories. For the indicators, in the case of EC, it is calculated as the "Primary energy demand from renewable and non-renewable resources (net calorific value)" and the water use is calculated in terms of "Total freshwater consumption (including rainwater)". Finally, the solid waste production is not considered in the new study because it was not possible to get information on how this indicator was evaluated in the original study. Therefore, it is not possible to find a corresponding environmental quantity in GaBi6.

3.4.4. Results

Since the aim of section 3.4 is to investigate the validity of an LCA study, it is essential to define clearly what can be considered as similar and as different. In a study by Ericsson Research (Guldbrandsson et al. 2011), the uncertainity limits for a carbon footprint study is investigated. It is concluded that "the uncertainty estimation of Ericsson's lifecycle carbon footprint indicate a combined uncertainty of +/- 30% for the supply chain with a confidence level of about 95%". Hanssen and Asbjørnsen (1996) found similar uncertainty range using the definition of the standard deviation for the emission variation. These authors stated that, when they consider the same product from the same manufacturer, results vary between 20-50%. Similarly, data obtained by stoichiometry result on a uncertainty range of 30% for data acquired of specific compounds by an elaborated analytical method (Meier 1997; Sonnemann et al. 2003). Therefore, since in the former studies the margin of uncertainty level for a life cycle study is around +/-30%, in this study it is decided to accept this 30% of difference as the threshold value to be able to state that the results differ.

Comparative results between the old (CML 1992) and the new (CML 2001) studies are presented in Table 30. According to the results , it can be concluded that four of the six assessed impact categories, which are EP, AP, energy consumption and water use, the two studies present similar results. On the other hand, for ODP and GWP, significant differences exist between the two studies. In Table 30, the reasoning for the differences is presented. For instance, the highest difference is observed in the case of ODP, and the reason for this significant reduction may be the ban of ozone depleting substances since 1992, which affects all the processes. In the case of GWP, the main reason of the change in the results seems to be related to the change in the electricity mix due to the reduction of nuclear energy.

Table 30. Most important factors for the differences between the two studies

	Reason for the main differences between old and new scenarios	Most affected stages	Change	
			Qualitative	**Quantitative**
EP	The change in the technosphere: reduction of the vehicles emissions (European Standard on vehicle emissions)	Installation – End of life	Decrease	-14 %
	The change in the Catalan electricity production mix: decrease of the percentage of energy from nuclear	Use		
	The change in the assessment methodology : increase of the substances considered	All, slightly		
ODP	The change in the technosphere: banning of ozone depleting substances	All	Decrease	-99 %
GWP	The change in the Catalan electricity production mix: decrease of the percentage of energy from nuclear	Use	Increase	+51 %
	The change in the technosphere: reduction of the vehicles emissions (European Standard on vehicle emissions)	End of life		
AP	The change in the technosphere: reduction of the vehicles emissions (European Standard on vehicle emissions)	End of life	Decrease	-27 %
	The change in the Catalan electricity production mix: decrease of the percentage of energy from nuclear	Use		
	The change in the assessment methodology : increase of the number of substances considered	Manufacturing – Installation - Maintenance		
Energy Consumption	The change in the databases	Installation - Maintenance	Not relevant increase	+2 %
Water Use	The change in the Catalan electricity production mix: decrease of the percentage of energy from nuclear	Use	Decrease	-23 %

Although in some categories the global results are similar or at least comparable, they have differences along the life cycle stages (Table 31). The emission categories (GWP and ODP) show different impact profiles while the resource categories show quite a similar distribution of impacts along the life cycle. The cause for these similarities in the global results is due to an impact shifting among different stages and, consequently, a casual compensation of impacts. This implies that, by chance, as they have compensated in our case study, they could not do so in others.

Table 31. Comparison of the results of the environmental impact assessment of the two case studies

Impact Category	Method	Manufacturing	Installation	Use	Maintenance	Removal	End of life	TOTAL
EP [kg Phosphate-Equiv.]	New (CML 2001)	5,06E-01	2,27E-01	2,64E-01	5,64E-01	1,20E-02	7,40E-02	1,65E+00
	Old (CML 1992)	2,95E-01	8,08E-01	1,51E-01	3,25E-01	1,47E-02	3,27E-01	1,92E+00
	(New-Old)/Old %	72%	-72%	75%	74%	-18%	-77%	-14%
ODP (steady state) [kg R11-Equiv.]	New (CML 2001)	2,76E-07	2,84E-08	2,79E-06	1,52E-05	3,71E-10	5,55E-10	1,83E-05
	Old (CML 1992)	7,72E-04	3,36E-04	1,63E-04	2,68E-04	2,23E-06	1,60E-04	1,32E-03
	(New-Old)/Old %	-100%	-100%	-98%	-94%	-100%	-100%	-99%
GWP 100 years [kg CO_2-Equiv.]	New (CML 2001)	1,24E+03	5,83E+02	1,43E+03	5,77E+02	1,32E+01	1,09E+02	3,95E+03
	Old (CML 1992)	9,88E+02	6,83E+02	3,14E+02	4,74E+02	9,62E+00	1,47E+02	2,62E+03
	(New-Old)/Old %	26%	-15%	355%	22%	37%	-26%	51%
AP [kg SO2-Equiv.]	New (CML 2001)	6,05E+00	1,28E+00	1,63E+00	2,36E+00	6,91E-02	3,11E-01	1,17E+01
	Old (CML 1992)	6,80E+00	5,24E+00	3,14E+00	2,10E+00	1,31E-01	1,95E+00	1,60E+01
	(New-Old)/Old %	-11%	-76%	-48%	12%	-47%	-84%	-27%
Primary energy demand (net cal. value) [MJ]	New (CML 2001)	1,87E+04	5,80E+03	7,35E+04	3,96E+03	1,18E+03	1,58E+03	1,05E+05
	Old (CML 1992)	1,86E+04	1,00E+04	7,47E+04	5,74E+03	1,27E+03	1,87E+03	1,03E+05
	(New-Old)/Old %	1%	-42%	-2%	-31%	-7%	-16%	2%
Total freshwater use (including rainwater) [kg]	New (CML 2001)	7,86E+03	7,26E+03	3,61E+04	6,63E+03	1,80E+03	2,36E+03	6,20E+04
	Old (CML 1992)	7,29E+03	3,91E+03	6,80E+04	5,37E+03	5,67E+00	8,01E+00	8,09E+04
	(New-Old)/Old %	8%	86%	-47%	23%	31646%	29363%	-23%

In the case of EP, on the one hand, it is observed that the contribution of end-of-life and installation stages to the final impact is decreased in the new study (Figure 22), mainly because of the environmental improvements achieved in transportation processes, and probably due to the adaptation to the European Emission Standard for Vehicles (European Commission; EC 715/2007 2007) (Table 28). On the other hand, the contribution of manufacturing and maintenance stages to the final EP has increased (72% and 74% respectively) because of the higher emissions created by the manufacturing of new pieces and posters which are included in the new model and were not in the old one.

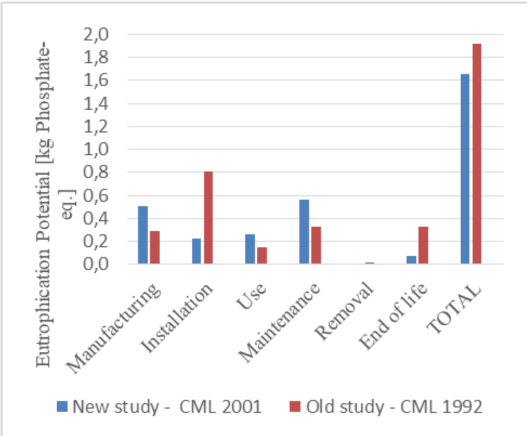

Figure 22. EP Results of the new and old studies

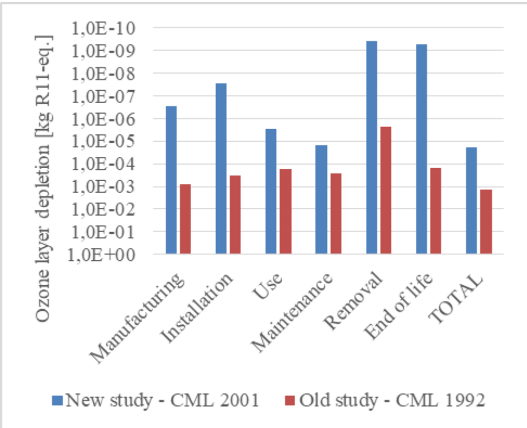

Figure 23. ODP Results of the new and old studies

The highest impact reduction is observed in the case of ODP. The results obtained in the new study for the ODP are at least 2 orders of magnitude lower than the ones obtained in the original study (Figure 23). Three causes are identified as: (i) the increased attention in the regulation of the emissions of this category (European Commission 2009; EU 517/2014 2014); (ii) the ban of the most impacting substances; and (iii) the development of new compounds that cause lower impacts (e.g., in the field of refrigeration systems (Bolaji and Huan 2013)).

For GWP, a significant increase is found at the use stage (355%). The main cause is the reduction of the percentage of electricity generated from nuclear power and an increase of the percentage of co-generation and combined-cycle sources (which have been simplified and modelled as electricity from natural gas as a proxy) in the Catalan electricity production mix (Table 28). The decrease in GWP at the end of life stage, is caused by the decrease of the emissions due to the transport activities taking place during end of life, which is the major contributor to GWP in that stage. Also, an additional assessment is made for the GWP, by taking into account the GWP category 100 years (excluding biogenic carbon). However, for the results of the original study, the GWP was assessed for a 100 years, including biogenic carbon. In order to evaluate the effect of the inclusion or the exclusion of biogenic carbon, another comparison between the results obtained with CML 2001 GWP 100 years excluding and including biogenic carbon, is studied (see section 3.4.5 and Figure 30).

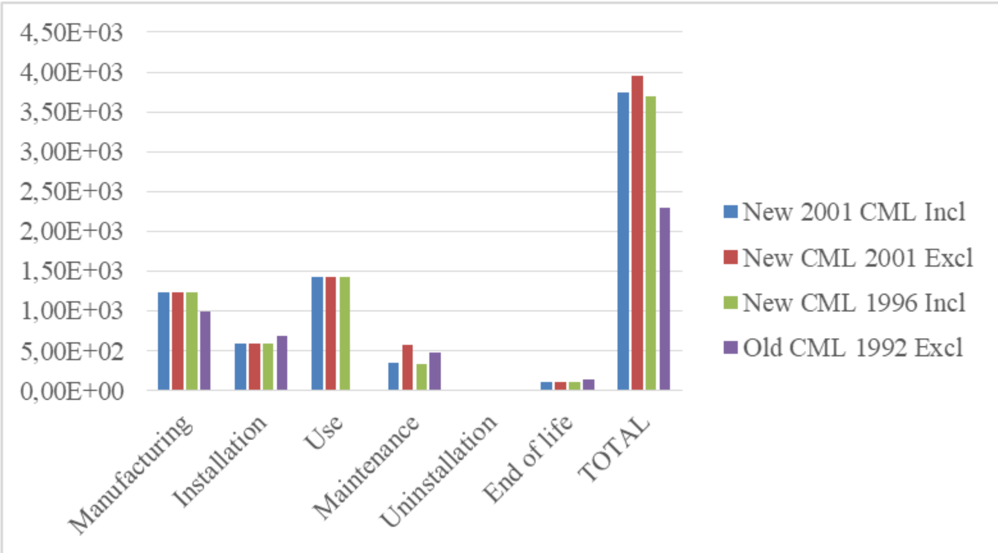

Figure 24. Results for global warming potential [kg CO_2-eq] depending on the CML method

All values in the AP category for the new study are similar or lower than the ones for the old study (Figure 25). The reduction of the AP is mainly found in the installation and end of life stages. The cause may be the increased restriction on the emissions from vehicles, according to the European Emission Standard for Vehicles (Table 28). The difference of the emissions in the use stage is, again, caused by the change in Catalan electricity mix (Table 28) and the processes used for electricity production. The NO_X emissions from natural gas combined cycle generation largely exceeded the ones produced in the nuclear facilities along its life cycle (HATCH 2014).

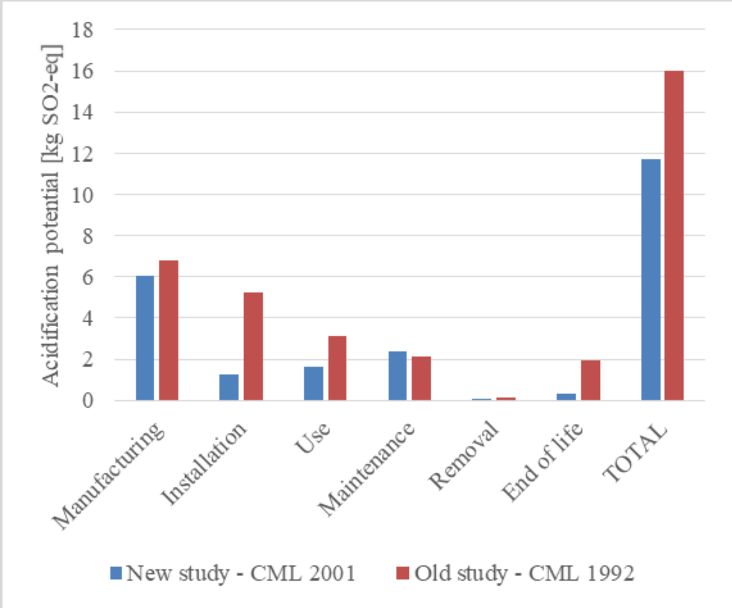

Figure 25. Results for acidification potential

The energy consumed [MJ] by the systems is the same for almost all the life cycle stages (Figure 26). The only difference is found in the installation stage where the energy consumption is slightly lower in the new study.

The highest water use occurs in the use stage (Figure 27). The differences may be due to the change in the Catalan electricity production mix (Table 28). Production of electricity from nuclear power consumes a high amount of water (Union of Concerned Scientists 2011; International Energy Agency 2012). The decrease in the percentage of nuclear power in the Catalan mix in the last 15-20 years probably caused the decrease of the water use.

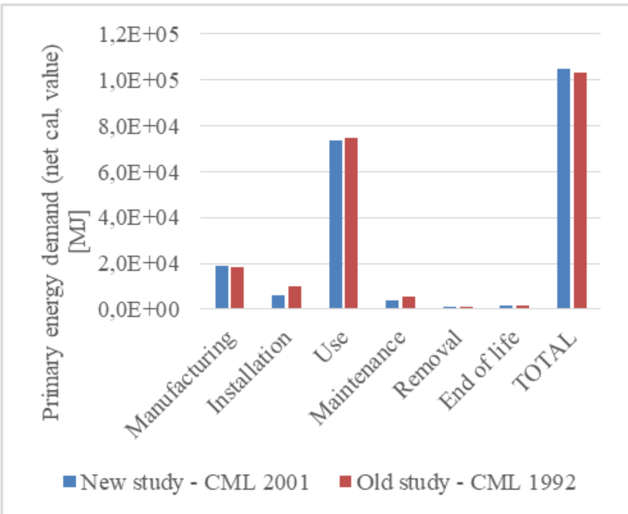

Figure 26. Results for energy consumption

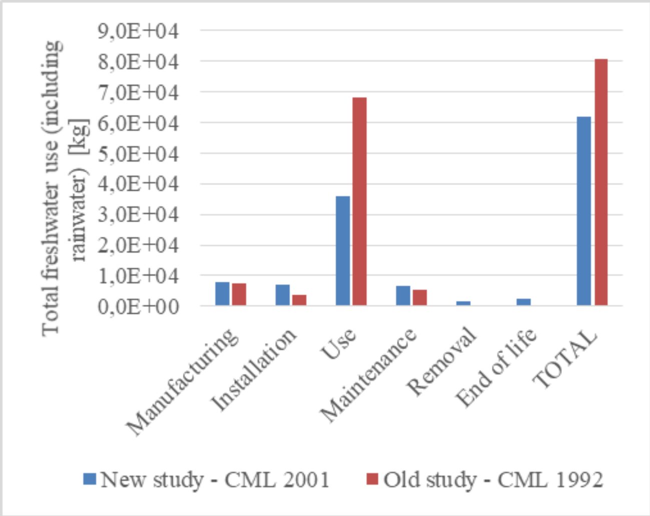

Figure 27. Results for water use

3.4.5. Discussion

In this section, the influence of the LCIA methodology (CML 1992, CML 1996, and CML 2001) evaluated for each life cycle stage (Table 32). The Life Cycle Impact Assessment applying CML1996 is used as a proxy for CML1992 as the later database is no longer available. Energy consumption and water use indicators are not included in this part, since they are not characterized within the CML methodology.

Table 32. Influence of the CML methodology in the results

	EP [kg Phosphate-Equiv.]			ODP, steady state [kg R11-Equiv.]			GWP 100 years, excl biogenic carbon [kg CO_2-Equiv.]		GWP 100 years, incl biogenic carbon [kg CO_2-Equiv.]		Acidification Potential (AP) [kg SO2-Equiv.]		
	New CML 2001	**CML 1996**	**CML 1992**	**New CML 2001**	**CML 1996**	**CML 1992**	**New CML 2001**	**CML 1992**	**New 2001 CML**	**CML 1996**	**New CML 2001**	**CML 1996**	**CML 1992**
Manufacturing	5.06E-01	3.13E-01	2.95E-01	2.76E-07	2.82E-07	7.72E-04	1.24E+03	9.88E+02	1,24E+03	1.23E+03	6.05E+00	5.08E+00	6.8E+00
Installation	2.27E-01	1.06E-01	8.08E-01	2.84E-08	2.75E-08	3.36E-04	5.83E+02	6.83E+02	5,98E+02	5.98E+02	1.28E+00	9.25E-01	5.24E+00
Use	2.64E-01	2.48E-01	1.51E-01	2.79E-06	2.97E-06	1.63E-04	1.43E+03	3.14 E+02	1,43E+03	1.42E+03	1.63E+00	1.88E+00	3.14E+00
Maintenance	5.64E+00	3.16E-01	3.25E-01	1.52E-05	1.31E-05	2.68E-04	5.77E+02	4.74E+02	3,51E+02	3.35E+02	2.36E+00	2.07E+00	2.10E+00
Uninstallation	1.20E-02	8.00E-03	1.47E-02	3.71E-10	3.95E-10	2.23E-06	1.31E+01	9.62E+00	8,71E+00	8.92E+00	6.91E-02	6.41E-02	1.31E-01
End of life	7.40E-02	1.29E-02	3.27E-01	5.55E-10	5.91E-10	1.60E-04	1.09E+02	1.47E+02	1,08E+02	1.08E+02	3,11E-01	1.06E-01	1.95E+00
TOTAL	1.65E+00	1.00 E+00	1.92 E+00	1.83E-05	1.64E-05	1.70E-03	3.95E+03	2.62E+03	3,74E+03	3.69 E+03	1.17E+01	1.01E+01	1.60E+01

In the case of EP, the values obtained for New-CML1996 are lower than those obtained with CML 1992. The results (Table 32 and Figure 28) seem sensibly influenced from the methodology chosen as total results may vary up to 66%. To confirm this, we compare the value of the CF and the number of substances considered in. The most important CF where all are similar except the ones for NH_4^+, which decreases by 20% in CML 2001 and NH_3, which increases by 6% in CML 2001. In addition, the number of the emissions considered in the assessment of EP differ. CML 1996 considers only 21 substances contributing to EP, while CML 2001 considers 118. This higher number of emissions considered is the reason that leads to an increased value of EP in most life cycle stages of the new scenario, especially in the installation stage.

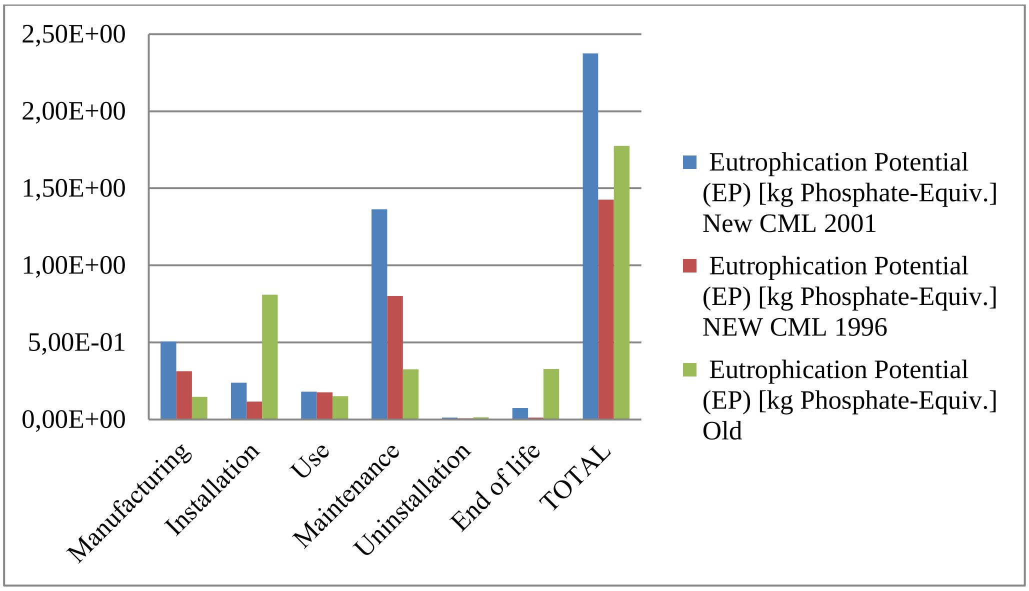

Figure 28. Results on EP depending on the CML method

Total results obtained for CML2001 and CML1996 for ODP are very similar, with differences around 3% Table 32 This proves that there is not a significant change, between the CML2001 and CML 1996 in terms of ODP. However, there is a two digit reduction in the results compared to old study in which CML 1992 is used (Figure 29). The reason for this change seems to be the ban of substances contributing to ODP all around the world (Montreal Protocol 2016).

There have been changes in the CFs which are not affected by the banning of substances in the Montreal Protocol. For example: in CML 1996 there were only 22 substances considered, while in CML 2001 there are 41 substances included. However, we believe that this is not a major reason as the number of substances has increased while the impact has significantly decreased. Thus, the modelling can also play a role in the differences between the results because there have been some updates in the databases due to the banning.

The two major contributor stages to ODP are the use stage and the maintenance stage. In the use stage the only process considered is the use of electricity. Therefore, the changes in Catalan electricity mix (Table 28) have contributed to the differences in the results, as nuclear energy production is the major contributor to ODP in electricity mix. In the maintenance stage the major process which contributes to ODP is transport and the reason for the difference in the results is the consideration of different types of trucks from different databases (Buwal in the old study and Thinkstep in the new one).

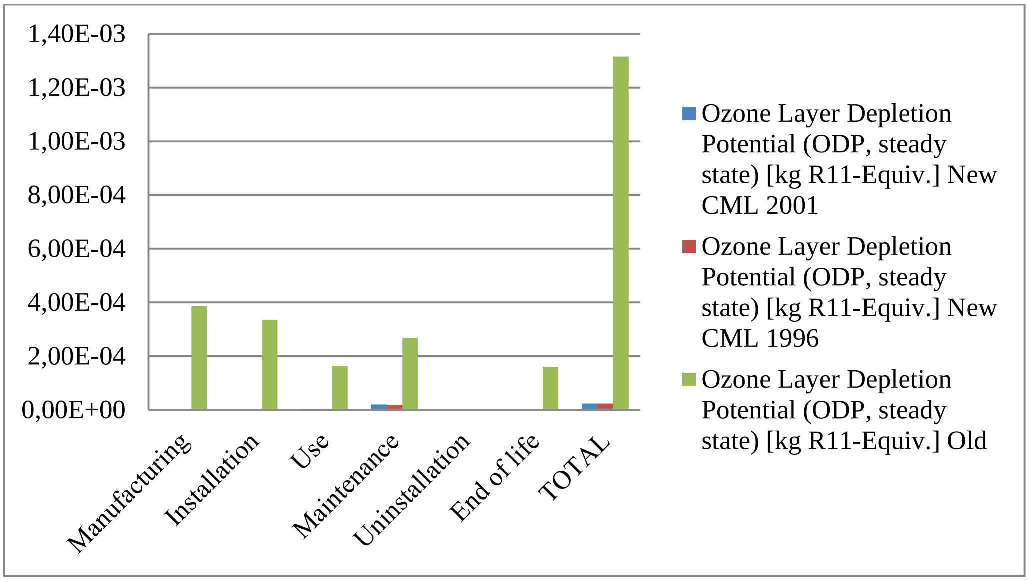

Figure 29. ODP results depending on the CML method

The main differences in GWP results occur when comparing the results between CML1992 and CML2001 and mainly in the manufacturing and the use stages. In both stages, the new study presents higher values respect to the old one.

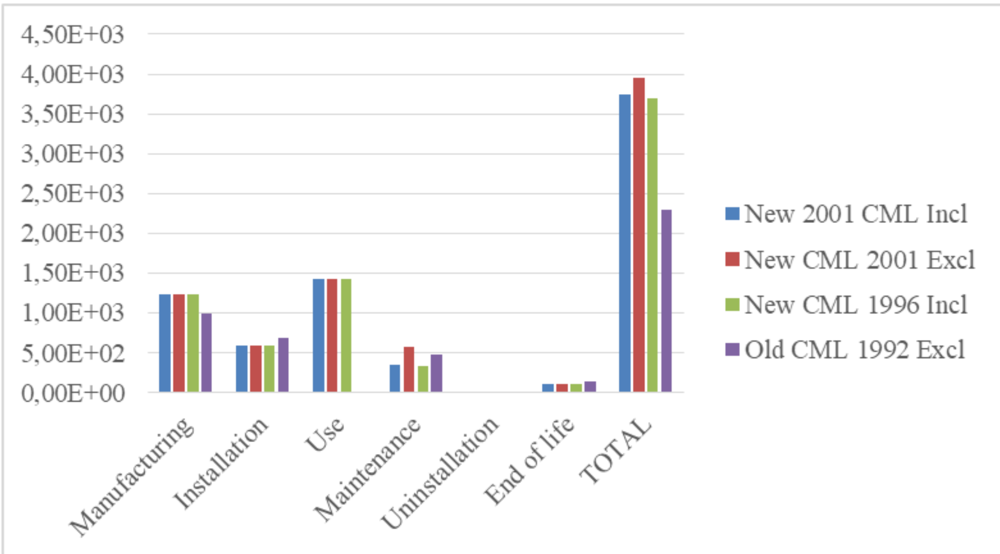

Figure 30. Results for global warming potential [kg CO_2-eq] depending on the CML method

The results (Table 32) for GWP show that the consideration or not of biogenic carbon (CML 2001) is not affecting the results (Figure 30

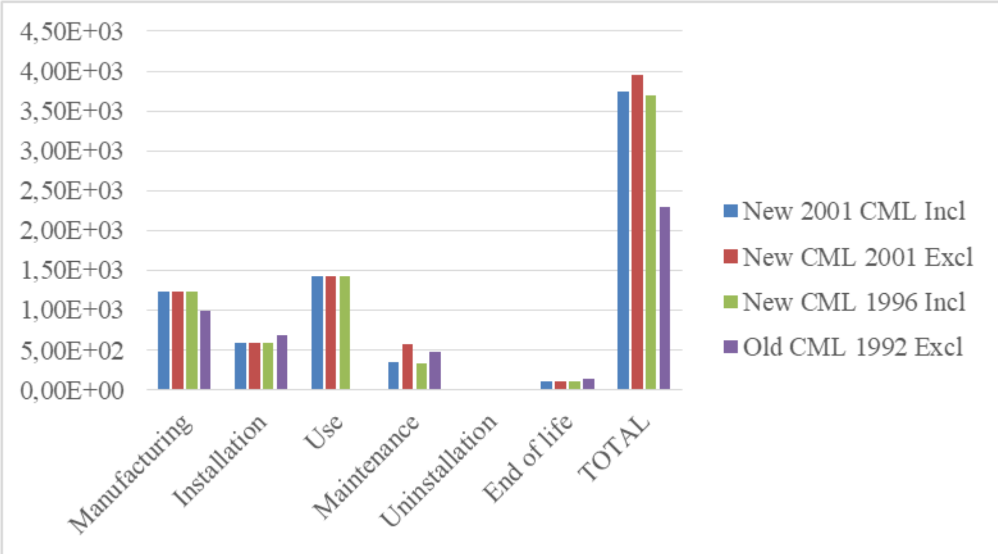

Figure 30). Only in the maintenance stage, the exclusion of the biogenic carbon implies a slight increase in the GWP impact values. The main cause for this increase is the rubber production for cleaning process. In this process the natural rubber is extracted from plants which sequestrate CO_2. In the rest of stages, and in the global result, numbers are quite the same except for the use stage in the CML 1992. This difference is kept in the global result.

Changes in the electricity mix, is the major cause for the lower values of GWP using CML1992 where nuclear electricity production had a bigger share in the mix (76% instead of the current 52%). Characterization factors have decreased in the case of N2O (from 310 to 298) while they have increased in other cases such as CH4 (from 21 to 25) or Halon-1301 (from 5600 to 7140). Another change between CML 1996 and 2001 is that the number of substances taken into account have increased from 58 to 97.

Contrarily, the CF in AP influence the result showing differences up to a 45% (Table 32). A cause is the reduction of the CF of 2001 compared to those of 1996 and 1992. The values of the CF of the CML 2001 are all different from the values of the CML 1996 and CML 1992, which are the same. The decrease in the impact results are partially caused by the increase in the SO_2/SO_x CF (from 1 to 1.2) that is probably not compensated by the decrease of the NO_2/NO_x CF (from 1.6 to 1.4) or of the Ammonia CF (from 1.88 to 1.6).

Although, CF imply a reduction in the AP values, in average, these values (Table 32 and Figure 31) obtained applying the CML1996 are more similar to the values obtained applying the CML2001 (around 12% different), than those obtained applying the CML1992 (around 45% lower). Since, in the case of the red and blue bars in Figure 31, the processes modelled are the same, it can be concluded that the reason for the difference (12%) comes from the CFs in CML methods used. As we know that the differences caused by the CFs are relatively smaller, we assume that the significant difference (45%) between new and old study occurs due to the changes in the processes used in the model of the system, for instance the transport means considered in the installation stage.

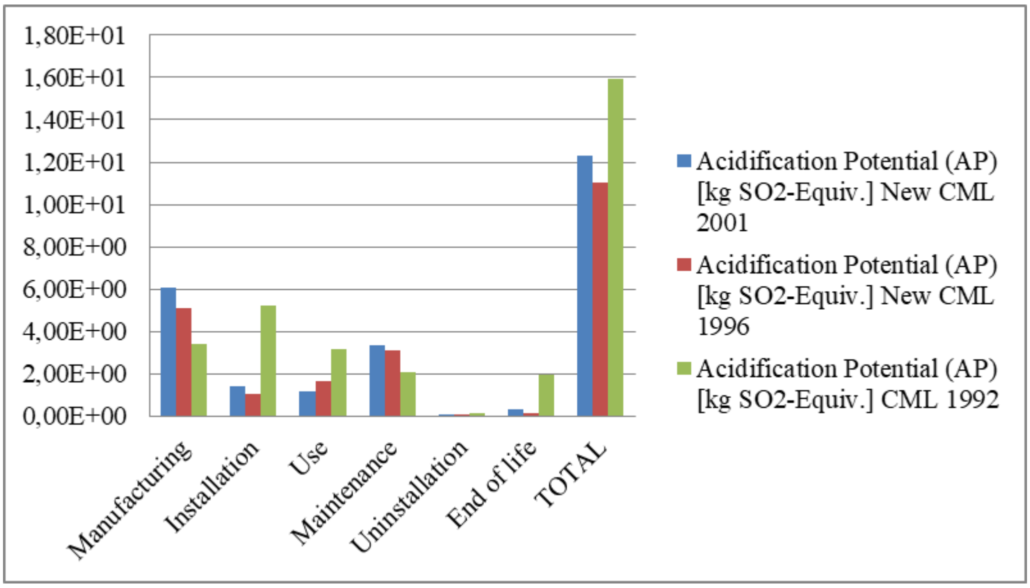

Figure 31. Results on AP depending on the CML method

3.4.6. Conclusions

An LCA of a bus stop was performed using the information of another LCA study which was performed in 1998 on the same piece of urban furniture. Results were analysed with the aim to check if the LCA study remained valid after 20 years.

Some of the impact categories (AP, EP, and energy consumption) remained valid, having differences below the range of 30%. On the contrary, ODP showed differences over the 30%, caused by changes in the production processes due to a law mandate. GWP increased, mainly in the use stage, due to changes in the technosphere (reduction of the share of nuclear power in the Catalan electricity mix). This increase is not totally compensated by the reduction of emissions of transport that are relevant at the end of life stage. The use of hydroelectric power in the Catalan electricity mix is also reduced. This is reflected in the results with a reduction in the water use impact category. However, even if, for some categories, the global results seem quite similar or at least comparable, this is not reflecting the differences within every single life cycle stage, where the 30% threshold is clearly surpassed. The global results are aligned with those from the old study because of a compensation effect by impacts increasing and decreasing at different life cycle stages.

The factors that influence the results at the inventory level are the ever-changing techno-sphere and the improvement of the environmental policies. For example:

- changes in the electricity production mix,
- changes in the operations in landfills,
- the improvement of environmentally friendly policies, such as the ban of the most ozone depleting substances, and
- the ever growing restriction in vehicle emissions, represented by the European Emissions Standard for vehicles.

The evolution of the LCIA methodologies have also been considered. The most relevant factors causing differences in the results have been found to be:

- The increase in the number of substances considered in the assessment of the impact categories. For example, in the case of EP, 21 substances were considered in CML 1996, raising to 118 substances in CML 2001.
- The different values for the CF, as highlighted in the comparison of the results obtained with the CML 2001 (April 2015 update) vs CML 1996. The highest differences in AP were caused by the variation of characterisation factors, such as those for SO_2/SO_x. In this case, the characterisation factor increased from 1 kg SO_2eq. in CML 1992 and CML 1996 to 1.2 kg SO_2eq. in CML 2001 (April 2015). Similarly happened with NO_2/NOx CF, which decreased from 0.7 in CML 1992 and CML 1996, to 0.5 in CML 2001 (April 2015).

Section 3.4 aims to contribute to the literature regarding LCA durability. Thus, it contributes to state that results from old LCAs can be taken as order of magnitude of impacts providers. So an old LCA can be used as an indicator but assuming that an old LCA imply a loss of precision. This is not the case for results within every life cycle stage.

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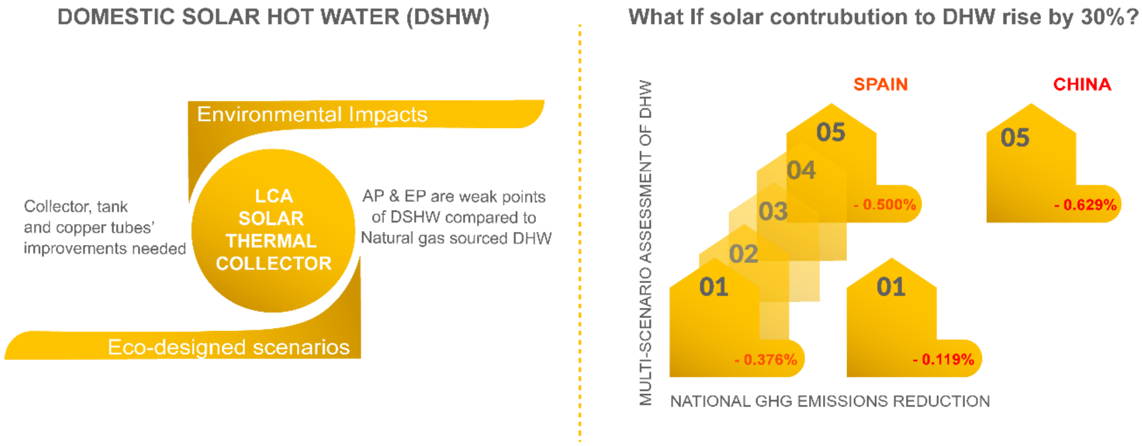

3.5. Life Cycle Assessment of a solar thermal system in Spain, eco-design alternatives and derived climate change scenarios at Spanish and Chinese National levels[28]

[28] The information in this section is extracted from this published article: Albertí, J., Raigosa, J., Raugei, M., Assiego, R., Ribas-Tur, J., Garrido-Soriano, N., Zhang, L., Song, G., Hernández, P., Fullana-i-Palmer, P., (2019). Life Cycle Assessment of a solar thermal system in Spain, eco-design alternatives and derived climate change scenarios at Spanish and Chinese National levels. Sustainable Cities and Society, 47 (2019). https://doi.org/10.1016/j.scs.2019.101467. Web of Science Impact factor (2017): 3.073

3.5.1. Introduction and background

Since the beginning of the industrial age, human populations have expanded and greatly increased access to natural resources. The exponential rise in human population has been paralleled by increased agriculture, urbanization and energy consumption. In a little over than a century, humans have already consumed a large portion of the existing fossil fuels, which took millions of years to produce (Crutzen 2002). From the 1970's, after the oil crisis, renewable energy technologies have been developed in order to supplement, and possibly ultimately replace, oil and other fossil fuels as the main source of energy (Schnitzer et al. 2007; Kamp 2008). These types of energy are produced in continuous and virtually inexhaustible ways, using energy sources such as: solar, wind, hydro, biomass, and geothermal (Dincer 2010).

3.5.1.1. The European Union's energy characteristics

Since 2004, the EU-28's net imports of energy have been greater than its primary production (EUROSTAT 2018). Regarding the fossil fuel sourced energy, according to the European Commission (EC) Green Paper published in 2002 (European Comission 2002), the EU was largely and increasingly dependent on fossil energy imported from non-EU countries. In 2002, the EU was dependant on approximately: 76% for oil, 40 % for natural gas, and 50% for coal. After 12 years, the energy import dependency increased, reaching up to the 87.7% for crude oil and the 70.4% for natural gas (EUROSTAT 2018).

As it has been known for many years already (Smithers and Smit 1997), this accelerated evolution is having important global effects beyond fossil fuels depletion per se, such as climate change induced by human-released greenhouse gases, which is causing negative impacts on society and the economy. Specifically, the building sector is responsible for around one third of the final energy consumption and for around one third of the global CO_2 emissions (IEA, 2013 and 2018).

Being aware of this situation, the European Commission set a challenge for the year 2020: all new buildings shall be nearly "zero-energy" buildings (European Parliament 2010, 2012), i.e., they should produce as much energy as they consume during their operational stage. Additionally, scientists have argued that the definition should be extended to also include other stages of the life cycle of a building (Blengini and Di Carlo 2010b; Hernandez and Kenny 2010; Passer et al. 2012; Li et al. 2013; Kylili and Fokaides 2015b). Two possible approaches to increase sustainability by reducing energy consumption in buildings can be applied: active and passive systems. In a passive building, shell systems such as windows, walls, floors, and roofs are designed to increase

– Quartile – Construction and Building Technology Q1 (12/62); Green and Sustainable Science and Technology Q2 (16/33); Energy and Fuels Q2 (39/97).

the building insulation in order to reduce the energy demand in the use stage, conducting to a lower environmental impact of the building in a life cycle perspective (Schmidt et al. 2004; Passer et al. 2012). However, once a building has been constructed, it is difficult to reduce its energy demand, and active solutions are required. These systems are designed to capture the sun's energy to convert it into heat or electricity and cover the building energy demand, like solar collectors do. Different alternatives may be used to accomplish this objective and a proper comparative assessment is needed before investment (Assiego De Larriva et al. 2014).

The European Commission recently issued the Circular Economy Package (European Commission 2015) to boost global competitiveness, foster sustainable economic growth and generate new jobs. Within this global strategy, the sustainable use of resources is essential, and two energy strategies come to front: energy efficiency and renewable energy (JRC 2015).

On average, the energy use inside a residential building attributed to the operational water heating accounts for 18-25% of the buildings total final energy (EuroACE 2004; IDAE 2014). Domestic Solar Water Heating (DSWH) is a well-proven technology used to reduce the non-renewable energy demand for providing operational DHW, and its potential to reduce domestic energy use is frequently acknowledged (Hernandez and Kenny 2012).

3.5.1.2. The Popular Republic of China's energy characteristics

China's energy development strategy can be divided into three stages since the reform and opening of the Chinese economy. In the first stage, before 1990, China's government emphasized energy self-sufficiency by adopting policies such as reducing oil burning and replacing oil with coal. The leading position of coal was strengthened in China's energy supply system in this first stage. In the second stage, during the 90s, heavy industry developed rapidly and the proportion of heavy industry exceeded 50% of China's total industrial output value. The third stage started with the 21st century, in which the central government emphasizes energy security to meet soaring demand, and pay close attention to energy-related environmental sustainability, such as lowering carbon emissions.

Nowadays, China still depends on fossil energy. In 2010, the total energy consumption was 9×10^{11} GJ, of which coal, oil, and natural gas accounted for 68%, 19%, and 4.4% respectively. New energy, which comprise hydropower, nuclear power, and wind power combined, accounted for 8.6% of the total energy consumption (NBS 2010). According to China's Energy Development Strategic Action Plan (2014-2020), efforts should be made to optimize the energy mix by increasing the share of low-carbon energy (The State Council 2014). The statistics newly released by British Petroleum (British Petroleum 2018) show that China's natural gas consumption increased by 15% in 2017, compared with to 2016, and reached 31 billion m^3 (i.e., 6.6% of 2017 total energy consumption); while solar energy grew by an amazing 76%. By 2020, the share of natural gas will contribute to above 10% according to the planning of The State Council (2014).

According to the latest evaluation the China Association of Building Energy Efficiency (CABEE 2016), the building sector consumed 20% of China's total energy, which is approximately 15% of the energy consumption by the global building sector, and this percentage is still growing (Xiao et al. 2014). To curb this rising trend, Chinese government thus formulated a series of polices. The Ministry of Housing and Urban-Rural Development planned to cut 3.4×10^9 GJ of fossil-based energy use during the 12th five-year plan (2011-2015), and 26% of this reduction was achieved from the promotion of renewable energy uses (MOHURD 2012). In 2017, MOHURD released the "Building Energy Conservation and Green Building Development Plan" to guide energy-saving actions during the 13th five-year period (2016-2020). The plan set the goal towards "ultra-low energy building systems" by using cleaner energy as a key avenue. As a major energy consumer of a building, water heating system is especially encouraged to shift to sustainable energy in China. Recently, MOHURD required to add solar systems to over 2 billion m^2 when buildings are newly developed (MOHURD 2017).

3.5.1.3. DSHW LCA case studies

Life cycle assessment (LCA) and eco-design are comprehensive and integrated methodologies that allow acting in the early stages of the product-supply chain alongside the more traditional, technical, and economic criteria (Lagerstedt et al. 2003). Moreover, LCA is considered as an appropriate tool to assess sustainability of products (Ness et al. 2007).

Product design is a critical determinant of a manufacturer's competitiveness. It has been claimed that as much as 70-80% of the costs of product development, manufacture, and use are determined during the initial design stages (Barton et al. 2001). The earlier in the product design life cycle a design team considers environmental factors, the greater the potential for cost reduction, and also environmental benefits (Mascle and Zhao 2008). In that sense, eco-design has been defined as ''the systematic integration of environmental considerations into product and process design'' (Canada 2003) and its main advantage is that these considerations could be taken into proper account in the early stages of the design process.

LCA allows the quantification of environmental impacts and the evaluation of the improvement options throughout the life cycle of a process, product or activity (Jacquemin et al. 2012). These options could be applied in different stages of the life cycle: process selection, used materials, design, end of life disposal, and system optimization (Azapagic and Cliff 1999). As detailed in the ISO standard 14040 (ISO 2006b), LCA addresses the issue of quantifying environmental impacts (e.g., the use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition, through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave), thereby avoiding burden shifting.

These characteristics make LCA a relevant and holistic methodology that allows a correct eco-design of products (Byggeth and Hochschorner 2006; Cerdan et al. 2009). In spite of this, there are often hindrances in integrating eco-design into the practice of small and medium enterprises (SMEs) (Fullana-i-Palmer et al. 2005; Le Pochat et al. 2007). With SMEs, it is essential to apply the so-called Life Cycle Management (LCM) principles (Fullana-i-Palmer et al. 2011), which aim at putting LCA into practice, especially the “Good Enough is Best” principle (Bala et al. 2010b). This is an aim that has been pursued by the LCA community for many years, especially within SETAC Europe developments, where LCA and LCM were even seen so distanced as to call them “two planets” (Rebitzer et al. 2001) or, more recently, “Ebony and Ivory” (Baitz et al. 2013b).

A variety of eco-design strategies exists, including the reduction of the amount and diversity of materials used; the improvement of the energy efficiency during the use phase; or the design for recycling, among others. The use of these strategies will depend on the type of product or service or the objective of the company (Platcheck et al. 2008; Cerdan et al. 2009; Muñoz et al. 2009; Gazulla et al. 2010; Lück 2012). The application of these strategies may entail saving raw materials and energy, as well as reducing emissions and waste, leading to a cost reduction, and allowing for a more circular economy.

In the case of solar thermal systems, LCA studies have pointed to the implementation of eco-design strategies mainly related to changes in materials and reductions in heat losses. Battisti and Corrado (2005) identified that, for a thermal collector with integrated water storage, most of the environmental impacts were associated to the production phase, specifically the tubes made of copper, leading to a replacement of this material with steel. Related to the use phase, the authors also proposed the use of an additional covering for the collector, a transparent insulating material (TIM) layer, in order to improve its performance for energy production. Also related with the covering, Chaurasia and Twidell (2001) proposed in their study the evaluation of the performance of an integrated collector with and without a TIM layer. In this case, the collector with TIM glazing was found to be more effective than the glass glazed collector by reducing the heat loss factor (UL).

Martinopoulos et al. (2013) identified the environmental impacts from the use of different materials in domestic solar hot water systems (DSWH). The net environmental gain achieved by the use of DSWH is influenced, by up to 20%, by the materials and techniques used, among others. In that study, LCAs of a range of typical DSWH were performed. Their environmental impact, as well as the influence from the use of different materials or/and manufacturing techniques on their impact, was identified. As thermal efficiency differs from system to system, their environmental performance is influenced mainly by the conventional energy substituted and, to a lesser extent, by the materials used for their production. A study comparing unglazed and glazed solar thermal panels showed that the performed LCA, using Eco-indicator 99, resulted in 198 eco-points for the DSWH with traditional glazed panels and in 18 eco-points for the unglazed one. Overall, 93% of the impact of the traditional DSWH was due to panel production (Comodi et al. 2014).

Ardente et al. (2005) identified that the direct energy used during the production process and installation is only 5% of the overall energy consumption and that another 6% is consumed in transportation along the life cycle stages. The remaining percentage is employed for the production of raw materials, used as process inputs. These results show that the direct energy requirement is much less important than the indirect one (in fact, the production processes consist mainly in cutting, welding, bending and assembling steps with a low energy demand).

(Piroozfar et al. (2016) concluded that, amongst the five solar heater types considered, the one with electric backup appeared to be the environmentally preferable one. The study also stresses the need for a life cycle approach in order to reflect environmental impacts holistically and to facilitate better decision making.

Another LCA, carried out by Allen et al. (2010), for a solar hot water system, concluded that the production phase, especially due to the production of aluminium, is a high energy intensive one and produces most of the environmental impacts of the system. The adopted eco-design solution was an increase of the recycled aluminium percentage for the collector frame. The results of the study showed around a 20% reduction in several environmental impact categories.

3.5.2. Aim of section 3.5

Although solar energy is considered as a ’clean’ form of energy, environmental impacts occur during the manufacturing, transportation, use and final disposal of the solar systems, due to the consumption of resources and the emission of pollutants. The environmental consequences of these transactions include, among others, natural resources depletion, greenhouse gas emissions and acidification. Therefore, it is necessary to evaluate solar technologies accounting for both the direct and indirect environmental impacts caused by the DSHW systems over their whole life cycle (Martinopoulos et al. 2013). These products and systems have been investigated and continuously improved in recent years (Martinopoulos et al. 2013; Comodi et al. 2014; Piroozfar et al. 2016) but there is still margin for further improvement. Some guidelines have been issued to assess the environmental impacts of building components from a life-cycle perspective (Lasvaux et al. 2014).

This paper has obtained information extracted from the RENIA project (RENIA 2012), which aimed at helping Spanish manufacturers of solar (thermal and PV) systems to optimize their products at the design level (Cerdan et al. 2009), reducing their life-cycle environmental impact, as well as to develop Environmental Product Declarations (EPD) (EN 2008). Although common in other countries, Spain has very little experience in EPDs, with few other projects such as those described in (Benveniste et al. 2011; Gazulla 2012; Passer et al. 2015).

Within this framework, this paper focuses on solar thermal collectors and tries to identify their weak points (materials, processes, components) from a life cycle perspective and to generate guidelines on how to optimize these systems in order to reduce their environmental impact. . A comparison between two systems for DHW generation is carried out in Section 3.5.3. The first system consists of a natural gas boiler (the most common source of DHW in Spain (Institute for Energy Diversification and Saving - IDAE 2016)), while the second one adds a solar contribution to the gas boiler. Results are described in Section 3.5.4.

A second exercise is also done in order to understand the potential reduction of emissions at a national level when ensuring a contribution of DSHW of at least 30% of the DHW demand. In this case, a life cycle perspective has not been taken into account because the Spanish national emissions inventory does not consider scope 3[29] emissions. Instead, the exercise focuses on the displacement of technologies, when the share of a renewable technology in the mix is increased. This issue is explored, and different results are provided, in Section 3.5.5. Although, the life cycle perspective is not included in the characterisation factors, the authors believe that this exercise is a

[29] Scope 3 emissions are all indirect emissions (except those from the generation of purchased energy) that occur in the value chain of the reporting system, including both upstream and downstream emissions.

starting point for discussing about different displacement methods and their consequences. The aim is to obtain an estimate of the directly avoided emissions and to check the consequences of choosing one displacement method or another. If a life cycle perspective were adopted with regards to national emissions, these emissions would increase. Likewise, if, in the avoided emissions due to the use of solar thermal, the whole life cycle were accounted for, then the avoided emissions would be reduced due to the emissions generated along the life cycle of the solar thermal system which, as discussed in Section 3.5.4. However, national emissions inventories still only account for direct emissions. Therefore, these are the ones that will be considered for the analysis of emissions reduction in China and Spain. The eco-design measures suggested in Section 3.5.4.2 would contribute to reducing the emissions from solar thermal systems in the indirect life cycle stages.

3.5.3. Life Cycle Assessment of two DHW alternatives

3.5.3.1. Product Systems

This LCA is focused on a product designed and sold by the Termicol Company, which was a partner in the abovementioned RENIA project. This product is a forced circulation solar system used to produce Domestic Hot Water (DHW). The LCA has been performed in line with ISO 14044 (2006). The study was performed using the LCA software GaBi and the Ecoinvent database as the main source of background data. More specifically, the Energy Systems sub-database (Dones et al. 2007) was widely used, from which the original model, named *Solar System flat plate collector for one-family house – Hot water,* was chosen and adapted to be as close as possible to the real system (Termicol 2011). Table 33 shows the adaptation and the main characteristics of the system.

Table 33. Adaptation and characteristics of the forced circulation system. Source: Dones et al. (2007) and Termicol (2011)

Characteristic	Termicol model	Ecoinvent model	Adaptation required
Collector area	3.8 m^2	4 m^2	Adapt to the real area
Absorption surface	Copper Selective	Copper Selective	-
Covering	Low iron glass (8 kg/m^2)	Low iron glass (9.12 kg/m^2)	Adapt the weight
Collector frame	Aluminium	Aluminium	-
Insulation material	Rockwool	Rockwool	-
Water tank	300 L	600 L	Adapt to real volume
Expansion vessel	18 L	25 L	-
Tubes primary circuit	Copper (3.24 kg/m^2)	Copper (2.82 kg/m^2)	Adapt to real weight
Tubes secondary circuit	Copper 7.13 kg	Copper 8 kg	Adapt to real weight
Auxiliary heating system	Natural gas boiler	No auxiliary system	Add an auxiliary system to the model
Thermal fluid	Propylene Glycol	Propylene Glycol	-
Circulation Pump	102W	102W	-
Electricity grid	Spain	Switzerland	Adapt to Spanish Mix
Life	20 years	25 years	Use 20 years as a reference

3.5.3.2. Goal and scope definition

The main objective of this LCA is to evaluate the environmental impact of a solar system with forced circulation, and to compare it with a traditional heating system that uses natural gas as its main energy source. The results of the study should allow the identification of weak points in the system and the proposal of several eco-design scenarios. A life cycle based eco-design scenario development of industrial systems allows companies to know their products and their potential improvement, giving them an advantage over their competitors and a robust way to communicate to customers in environmental terms.

The functional unit (FU) is defined as the production of 1 kWh of thermal energy to cover the DHW demand of a 6 persons house (the same as in the Ecoinvent database), located in Barcelona, Catalonia, Spain. There are two basic energy scenarios: in the first one, the use of solar energy is combined with an auxiliary heating system using natural gas to meet the demand; in the second one, a system that only uses natural gas to meet the entire demand is modelled. For both cases, the life span considered is 20 years. System boundaries are shown in Figure 32 and Figure 33, respectively.

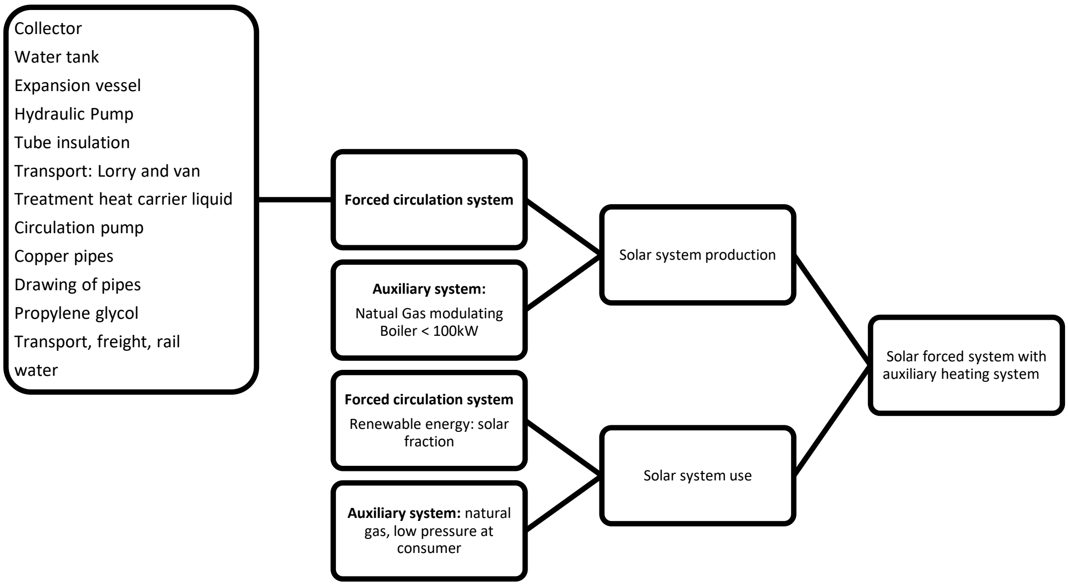

Figure 32. System boundary for the solar system with forced circulation.

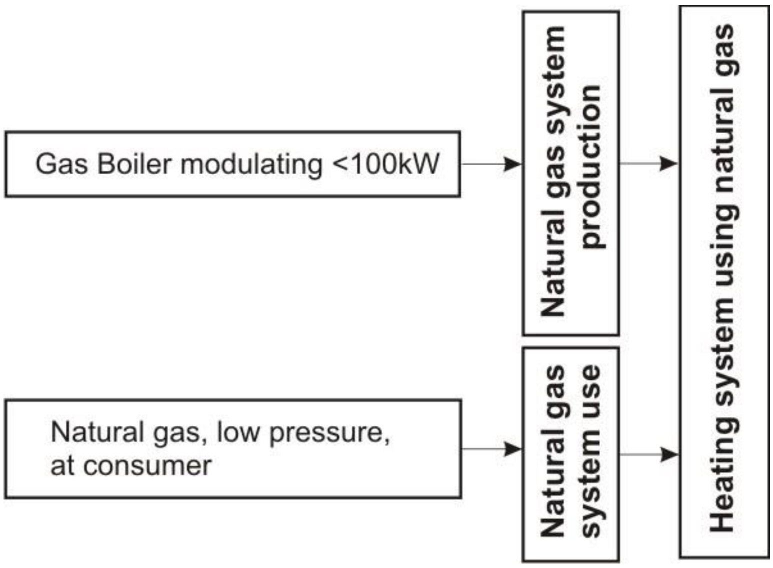

Figure 33. System boundary for the natural gas heating system.

3.5.3.3. Inventory analysis

In the Life Cycle Inventory (LCI) Analysis, data were listed for each of the components and stages for both systems (Figure 32 and Figure 33).

Due to the fact that the studied solar system includes an auxiliary heating system to meet the yearly demand of DHW, some calculations were done for the use stage in order to calculate how much of the total energy was covered by each source (solar and natural gas). Literature containing real data on use stage of solar systems is scarce. However, use and maintenance stages are relevant as they have great influence in the performance of the solar system (Hernandez and Kenny 2012).

According to the regulation established in Spain (CTE 2013), building engineers must consider that each residential building's user consumes approximately 40 L of DHW at 45ºC every day, which means that a household with, for instance, six inhabitants has a yearly demand of DHW of 3,180 kWh (Table 34). To know how much of this demand can be covered by the solar system, also called the solar contribution, two basic parameters should be taken into account: the collector thermal efficiency F_R (U_L), related to the thermal losses (U_L); and the optical efficiency FR (τα), related to the light transmission capacity of the covering (τ) and the absorption capacity of the copper surface of the collector (α) (Duffie and Beckman 2001). Producers of this type of systems usually provide values for both of these parameters. For the assessed system, the thermal efficiency is 4.086 W/(m^2 K) and the optical efficiency is 0.77. Therefore, and also considering the tank capacity and the area of the collector (78.9 L/m^2), the solar system under study is able to cover 75.6% of the yearly demand of DHW. The auxiliary heating system that uses natural gas should cover the rest. Table 34 reports values for each month and for the yearly total.

Table 34. Yearly DHW demand and solar contribution. Source: CTE (2013)

Month	Temperature cold water (ºC)	DHW demand (kWh)	Solar contribution (kWh)	Solar contribution %
Jan	9	311	157.5	50.6
Feb	10	273	174.4	63.9
Mar	11	294	222.2	75.6
Apr	12	276	233.6	84.6
May	14	268	242.5	90.5
Jun	17	234	222.5	95.1
Jul	19	225	219.4	97.5
Aug	19	225	216.4	96.2
Sep	17	234	209.7	89.6
Oct	15	260	198.6	76.4
Nov	12	276	163.9	59.4
Dec	10	303	142.8	47.1
Total		**3,181**	**2,403**	**75.6**

In the case of the traditional heating system, the entire demand is covered with natural gas: 8,781 m^3 of gas over the 20 years of life span.

3.5.3.4. Impact assessment

In order to describe the environmental impacts of the system throughout its life cycle, some categories were selected following the recommendations of the EN 15804 (2011), which contains the core rules for developing Product Category Rules (PCR) of construction products. The selected categories for emissions taken from the CML 2001 method, due to its problem-oriented perspective (Monteiro and Freire 2012), are those included in the EN 15804:

- Acidification Potential
- Eutrophication Potential
- Global Warming Potential
- Ozone Layer Depletion Potential
- Photochemical Ozone Creation Potential

The studied system is a high energy transformation product and, due to this fact, further impact metrics are used, related to the cumulative amounts of both non-renewable and total (renewable plus non-renewable) primary energy, which is directly and indirectly transformed over the system's lifetime. Both of these indicators, respectively named "non-renewable cumulative energy demand" (NR-CED) and "cumulative energy demand" (CED) are calculated including the indirect energy demand for the provision of materials. In some older literature, NR-CED is sometimes also referred to as "gross energy requirement" (GER). This type of metric is a standard requirement by the EN 15804 (2012), and it has been widely used in the scientific literatures for energy analyses (Slesser 1974; Gürzenich and Wagner 2004; Thiaux et al. 2010) including previous LCA studies co-performed by some of the authors (Ulgiati et al. 2006, 2011; Raugei et al. 2007; Puig et al. 2013), in spite of not being a standard LCA metric.

3.5.4. Results and discussion

3.5.4.1. Environmental profile of the system

Table 35 reports the results for the emission-related categories described above and shows the percentage of relative change that the solar system produces when it is compared with a traditional natural gas heating system. The comparison between the two systems can also be seen in Table 36, where the cumulative primary energy demand is listed.

Table 35. Comparison of environment impacts from natural gas system and solar system by life-cycle assessment

Category	Unit	Natural gas system	Solar system	Relative change
Acidification	kg SO_2	2.35E-04	2.50E-04	+6.2%
Eutrophication	kg PO_4^{3-}	2.48E-05	4.00E-05	+61%
Global Warming	kg CO_2	2.64E-01	9.24E-02	-65%
Ozone Layer Depletion	kg CFC11	4.07E-08	1.25E-08	-69%
Photochemical Ozone Formation	kg ethene	6.06E-05	3.60E-05	-41%

Table 36. Values for non-renewable cumulative energy demand (NR-CED) and cumulative energy demand (CED)

	Unit	Natural gas system	Solar system	Relative change
NR-CED	MJ	4.63	1.65	-64.00%
CED	MJ	4.65	5.30	+13.90%

When the solar system is compared with a traditional system that uses natural gas for DHW production, a substantially environmental improvement is obtained due to the reduction of the Global Warming Potential (-65% in Table 35). This is often identified as one of the most relevant environmental indicators nowadays. This result is directly related to the use of non-renewable primary energy (primary energy from non-renewable resources, Table 36), of which the solar system uses 64% less than the natural gas system (and, correspondingly, as expected, much more renewable energy). Improvements can also be seen in other impact categories of high relevance such as ozone layer depletion (-69%) and photochemical ozone formation (-41%).

Categories like acidification and eutrophication (especially the latter) are weak points of the environmental profile of the solar system throughout its life cycle, instead. These results can be associated with the intensive use of metals in the production phase, causing an increase in the environmental levels of acidic gases or phyto-nutrient discharges (such as nitrogen or phosphorus).

However, acidification and eutrophication are local categories that need a more detailed analysis due to their radii of emission. For instance, in the case of the natural gas system, most of the emissions that come from burning gas are produced in a smaller radius, focusing their impact on the local community. On the other hand, the emissions from the solar system are mostly due to the production of components and extraction of materials, activities which can be carried out in different locations and possibly far from each other, making the emissions more scattered. A full analysis of the above mentioned aspects is highly relevant in the analysis of local impact categories, but falls outside the scope of Section 3.5.

After comparing both systems, and as a second step of the analysis, the solar system was disaggregated into its components (Figure 32) in order to find the ones that contribute the most to each of the impact categories. As a result of this disaggregation, the collector, the tank and the copper tubes of the secondary circuit were identified as the components with the highest environmental impact in the system (Table 37).

Table 37. Components with high environmental impacts in the solar system

Category	Unit	Collector	Water tank	Copper tubes
Acidification	kg SO_2	33.8%	25.0%	8.3%
Eutrophication	kg PO_4^{3-}	23.8%	28.2%	1.8%
Global Warming Potential	kg CO_2	9.5%	14.6%	0.3%
Ozone Layer Depletion	kg CFC11	5.9%	6.6%	0.2%
Photochemical Ozone Formation	kg Ethene	17.8%	24.6%	3.0%

3.5.4.2. Potential system improvements: eco-design scenarios

Based on the detection of weak points in the analysed solar system and guided by the previously commented analyses in section 3.5.2 (Aim of this work), the following eco-design scenarios were established and evaluated:

(1) Production phase: replacement of copper tubes with galvanized steel tubes in the secondary circuit of the system.
(2) Use phase: replacement of the glass covering with a multi-wall polycarbonate covering.
(3) Production phase: increase of the percentage of secondary (recycled) aluminium for the collector frame.

The described changes do not affect the system durability or its need to any additional maintenance.

3.5.4.2.1. Eco-design scenario 1: galvanized steel tubes

The main objective of this material substitution is to reduce the impact within the acidification and eutrophication categories by using a material that is widely used in Spain for tube production (galvanized steel). The virtual change of material was carried out taking into the consideration of the dimensional and functional equivalence between tubes, changing from 7.14 kg of copper to 16.5 kg of galvanized steel.

The use of galvanized steel would yield a reduction of 5.77% in the acidification category for the solar system (Table 38) and a small reduction in the photochemical ozone formation potential, too. The reduction of these impacts is a positive result that could help to improve the environmental profile of the solar system. The values for primary energy demand (Table 39) would increase by a small proportion, demonstrating that the heavier steel tubes would be slightly more energy-intensive than the existing copper ones.

3.5.4.2.2. Eco-design scenario 2: Polycarbonate covering

The main objective of changing the covering material from glass to a multi-wall polycarbonate layer is to reduce the thermal losses and, therefore, obtain an increased efficiency of the collector and a higher solar fraction using less natural gas as an auxiliary source for heating.

Multi-wall polycarbonate is known as an excellent material for insulation and it has been used before in other solar collectors (Chaurasia and Twidell 2001). The selected material is a 10 mm thick two-wall polycarbonate. As the new material implies a change in the collector efficiency, the new data has to be included in the calculation for the new solar fraction. This type of polycarbonate has an optical efficiency FR (τα) of 0.69 (lower than that of glass) and a thermal efficiency FR (UL) of 3.2 W/(m2K). These values mean that polycarbonate has a lower capacity to let light pass through the covering, but compensates for that with lower thermal losses, obtaining a new solar fraction of 76%, which can be considered a similar value to the one obtained with the glass cover.

The gain in solar fraction is minimal (0.4%), and this performance can also be observed in the results for the emissions and primary energy demand (Table 38 and Table 39).

3.5.4.2.3. Eco-design scenario 3: Recycled aluminum for the collector frame

The aluminium used to produce the collector frame is initially a "wrought alloy" consisting of 90% virgin or primary and 10% secondary (from new scrap) aluminium (Eco-invent Data Base v 2.2., 2009). The objective of this scenario is to use a smaller percentage of primary aluminium in order to reduce the environmental impact of the collector. In order to take this into account in the analysis, a new type of aluminium is selected from the database ("cast alloy"), which contains 20% of primary aluminium, 47% of secondary aluminium from new scrap and 33% secondary aluminium from old scrap. The typically lower tensile strength of all cast alloys is assumed not to be a problem for the collector frame. In addition, since the environmental profile of these aluminium alloys primarily reflect their primary/secondary compositions, irrespective of the specific manufacturing process ("cast" vs. "wrought"), wrought alloys could conceivably also be produced starting with a higher percentage of secondary aluminium (albeit probably not at the same price point, because of higher scrap rejection ratios).

In the case of Spain, aluminium collection and recycling still has a very long way to go. Results from the use of more recycled aluminium show a reduction in all of the emission impact categories (Table 38), especially in the acidification potential, eutrophication and photochemical ozone formation, demonstrating that the use of recycled aluminium results in less impact in terms of emissions. The use of primary non-renewable energy in this scenario would decrease by 2.2%, which is a positive result from less use of energy to extract and produce virgin aluminium (Table 39).

Table 38. Emission values for the eco-design scenarios

Category	Unit	Original solar system	Steel tubes	Polycarbonate	Recycled aluminium
Acidification	kg SO_2	2.50E-04	-5.77%	+0.6%	-4.63%
Eutrophication	kg PO_4	4.00E-05	+0.51%	+0.8%	-3.50%
Global Warming	kg CO_2	9.24E-02	+0.83%	-1.5%	-2.67%
Ozone Layer Depletion	kg CFC_{11}	1.25E-08	+0.48%	+0.7%	-1.14%
Photochemical Ozone Formation	kg C_2H_6	3.60E-05	-0.91%	-0.8%	-3.60%

Table 39. Primary energy demand for the eco-design scenarios

Category	Unit	Original solar system	Steel tubes	Polycarbonate	Recycled aluminium
Primary energy from renewable raw materials	MJ	3.65	0%	0%	-0.2%
Primary energy from resources	MJ	1.65	+0.9%	-0.9%	-2.2%

3.5.5. National scenarios on addressing climate change

3.5.5.1. Climate change mitigation targets

The result of the COP21 held in Paris was the parties' commitment to establishing a global response to keep the global temperature increase below 2ºC above pre-industrial levels during this century. This idea was written in the Paris Agreement (PA) (UNFCCC 2015), which Spain ratified on 22nd April 2016. During the COP 22, the parties worked on practical (working programme (UNFCCC 2016a)) and financial (UNFCCC 2016b) aspects on how to implement the PA. Although Spain has not submitted them yet, under the PA the different parties are invited to upload their Intended Nationally Determined Contributions (INDCs) in a clear, transparent and understandable manner. These data will define the amount of reduction in CO_2-eq emissions that the country is expected to contribute so as to achieve the global goal.

China became the world largest carbon emitter in the world from 2007, and is the world largest residential energy consumer (Nejat et al. 2015). On June 30, 2015, China submitted its INDC to the UNFCCC for preparing the COP21. Based on China's national circumstances and development stage, the Chinese government proposed several goals towards 2030, including achieving the peaking of carbon dioxide emissions; a reduction of carbon dioxide emissions per unit of GDP of 60-65% compared to 2005 levels; an increase in the share of non-fossil fuels in primary energy consumption up to around 20%; and an increase in the forest stock volume by around 4.5 billion cubic meters with respect to 2005 levels.

In the following sub-sections the potential reduction of national emissions in the event that an increase of the share of solar thermal generation for DHW generation is mandated by the national governments is assessed. The amount of CO_2 emission reduction depends on the criteria chosen to replace current sources of DHW generation. In the case of a single installation described in Section 3.5.3 and 3.5.4, the comparison was based on the avoided emission of a natural gas boiler. The reason for this choice is that natural gas is the main source of DHW generation in Spain. However, when assessing a wider scope, such as the avoided emissions at a country level, it is considered that a broader view of the substituted technologies should be applied.

Thus, five methods for technology displacement are explored: (i) mix, the most probable technologies to be substituted by the new technology (Solar thermal) are proportional to the current mix for DHW generation; (ii) most used, the increase of the share of DSWH implies a reduction in the most used technology; (iii) positive, the increase of the share of DSWH implies a substitution of a marginal mix of those technologies that have a positive growth trend (between 2011 and 2015); (iv) negative, the increase of the share of DSWH implies a substitution of a marginal mix of those technologies that have a negative growth trend (between 2011 and 2015); and (v) polluting, the increase of the share of DSWH implies a reduction in the most polluting technologies, depending on their characterization factor (CF).

3.5.5.2. Spanish National scenarios

The Spanish household system uses around 614453 TJ/year (Institute for Energy Diversification and Saving - IDAE 2016), of which approximately 19% is used for DHW generation. The energy sources and related CO_2emissions for DHW generation in 2011 and 2015 can be found in Table 40.

Table 40. Energy source and CO_2 emissions in Spain for DHW production. Source: IDAE (2016)

SPAIN	DHW 2011 [MWh]	% DHW 2011	DHW 2015 [MWh]	% DHW 2015	CF [t CO_2/MWh]	Emissions [t CO_2]
Coal	0	0.0%	0	0.0%	0.317	0.00E+00
Propane	7.18E+06	18.9%	5.41E+06	17.7%	0.234	1.27E+06
Diesel	1.79E+06	4.7%	1.86E+06	6.1%	0.263	4.89E+05
Natural Gas	2.12E+07	55.7%	1.50E+07	49.1%	0.182	2.73E+06
Solar thermal	1.55E+06	4.1%	2.39E+06	7.8%	-	0.00E+00
Geothermal	3.49E+04	0.1%	3.49E+04	0.1%	-	0.00E+00
Charcoal	1.28E+05	0.3%	6.98E+04	0.2%	-	0.00E+00
Wood	5.94E+05	1.6%	6.05E+05	2.0%	-	0.00E+00
Pellet	0	0.0%	0	0.0%	-	0.00E+00
Other Biomass	0	0.0%	0	0.0%	-	0.00E+00
Electricity	5.58E+06	14.7%	5.24E+06	17.1%	0.267	1.40E+09
TOTAL	**3.80E+07**	**100.0%**	**3.06E+07**	**100.0%**	**1.92E-01**	**5.88E+06**

Current Spanish legislation (CTE 2013) states that at least 30% (and up to 70% depending on the climatic zone) of the DHW production in new construction must be sourced by solar thermal technology. Table 41 shows the hypotheses used and the resultant reduction of emissions which may happen at the national level, if the above mentioned 30% is applied to all residential buildings in the country, based on the five different methods (Mth).

Table 41. Baseline scenario, hypothesis, and results on five methods for technology substitution

		Spain
BASELINE	National Emissions [t CO_2]	3.29E+08
	Year Reference	2015
	Demand DHW [MWh]	3.06E+07
	Current Contribution DSHW [MWh]	2.39E+06
	Current Share DSHW [%]	7.8
	Current Mix DHW [t CO_2-eq/MWh]	1.92E-01
	Current Emissions [t CO_2-eq]	5.88E+06
HYPOTHESIS	Demand DHW	Constant
	Suggested Share DSHW [%]	30
	Suggested contribution DSHW [MWh]	9.19E+06
MIX Mth	Displaced Demand of DHW – mix [MWh]	6.80E+06
	Mix Displaced [t CO_2-eq/MWh]	1.92E-01
	Resulting Mix [t CO_2-eq/MWh]	1.92E-01
	Emissions Reduction [t CO_2-eq]	1.31E+06
	% of National Emissions Reduction [%]	**0.397**
MOST USED.Mth	Displaced Demand – most used (Natural Gas) [MWh]	6.80E+06
	Mix Displaced [t CO_2-eq/MWh]	1.82E-01
	Resulting Mix [t CO_2-eq/MWh]	1.52E-01
	Emissions Reduction [t CO_2-eq]	1.24E+06
	% of National Emissions Reduction [%]	**0.376**
POSITIVE Mth	Displaced Demand – positive marginal mix [MWh]	6.80E+06
	Marginal Mix displaced [t CO_2-eq/MWh]	2.25E-01
	Resulting Mix [t CO_2-eq/MWh]	2.00E-02
	Emissions Reduction [t CO_2-eq]	1.53E+06
	% of National Emissions Reduction [%]	**0.466**
NEGATIVE Mth	Displaced Demand – negative marginal mix [MWh]	6.80E+06
	Marginal Mix displaced [t CO_2-eq/MWh]	2.55E-01
	Resulting Mix [t CO_2-eq/MWh]	1.49E-01
	Emissions Reduction [t CO_2-eq]	1.33E+06
	% of National Emissions Reduction [%]	**0.403**
POLLUTING Mth	Displaced Demand – most polluting [MWh]	6.80E+06
	Mix displaced DHW [t CO_2-eq/MWh]	2.42E-01
	Resulting Mix [t CO_2-eq/MWh]	1.38E-01
	Emissions Reduction [t CO_2-eq]	1.65E+06
	% of National Emissions Reduction [%]	**0.500**

The five methods suggested have been applied displacing, in all cases, 6.80E+06 MWh of energy sourced by different technologies. This amount of energy has displaced: (i) *mix*: the 2015 mix of technologies; (ii) *most used*: natural gas; (iii) *positive*: a mix of 86% diesel and 14% wood (Table 42) (although it has a positive trend, Solar Thermal technology in the marginal positive mix is not considered, as it makes no sense to consider that promoting more solar will lead to displacement of solar); (iv) *negative*: a mix of 74% natural gas, 21% propane, 4% electricity, and 1% charcoal (Table 43); and (v) *polluting*: all diesel, and 4.94E+06 MWh of propane are substituted by Solar generation (Table 44).

Table 42. Positive method marginal mix

	DHW 2011 [MWh]	% DHW 2011	DHW 2015 [MWh]	% DHW 2015	2015-2011 [MWh]	% Marginal	CF [t CO_2/MWh]	Emissions [t CO_2]
Diesel	1.79E+06	5	1.86E+06	6	6.98E+04	86	0.263	1.84E+04
Solar Thermal	1.55E+06	4	2.39E+06	8	8.38E+05	0	0	0.00E+00
Wood	5.94E+05	2	6.05E+05	2	1.16E+04	14	0	0.00E+00
TOTAL					8.15E+05		2.25E-01	1.84E+04

Table 43. Energy displaced by technology applying the negative method

DHW source	DHW 2015 [MWh]	% Marginal	Increase of each technology
Solar Thermal	-	-	+6.80E+06 MWh
Propane	5.41E+06 MWh	**-21**	-1.44E+06 MWh
Natural Gas	1.50E+07 MWh	**-74**	-5.04E+06 MWh
Charcoal	6.98E+04 MWh	**-1**	-4.75E+04 MWh
Electricity	5.24E+06 MWh	**-4**	-2.76E+05 MWh

Table 44. Energy displaced by technology, depending on its emissions generated per unit of energy

DHW source	DHW 2015 [MWh]	CF [t CO_2/MWh]	Increase [MWh]	Remaining [MWh]	Remaining to be displaced
Solar Thermal	2.39E+06	-	+6.80E+06	9.19E+06	6.80E+06 MWh
Diesel	1.86E+06	0.263	-1.86E+06	0.00E+00	4.94E+06 MWh
Propane	5.41E+06	0.234	-4.94E+06	4.70E+05	0.00E+00 MWh

3.5.5.3. Chinese National scenarios

The residential sector accounted for approximate 25% of China's total CO_2 emission and reached up to 320 $MtCO_2$ in 2011 (Nejat et al. 2015). However, China lacks the statistical data related to DHW. This is the reason why data from Zheng et al. (2014) is taken. Zheng, through a household survey, obtained that DHW share was 14% of Chinese household energy consumption in 2013. These authors also defined the structure of

Chinese DHW energy consumption mix as: 43% electricity, 31% natural gas, 25% solar and 1% other. Similarly, the DHW energy mix of China in 2015 was calculated based on a national DHW survey (People's Daily Online, 2016), showing that the DHW energy mix of Chinese household was composed of 38% electricity, 37% natural gas, 21% solar and 4% others. Based on the two surveys, the emissions, derived from the DHW energy mixes in 2013 and 2015, for the case of China were calculated and summarized in Table 45.

Table 45. Energy uses of China's DHW and equivalent carbon emissions

China	DHW 2013 [MWh]	% DHW 2013	DHW 2015 [MWh]	% DHW 2015	CF [t CO_2/MWh]	Emissions 2015 [t CO_2]
Electricity	2.14E+08	57.63	2.06E+08	51.3	0.9625	1.99E+08
Natural Gas	8.97E+07	24.14	1.23E+08	30.6	0.182	2.24E+07
Solar thermal	6.51E+07	17.52	6.13E+07	15.2	-	0.00E+00
Other	2.60E+06	0.7	1.17E+07	2.9	0.9625	1.12E+07
TOTAL	**3.72E+08**	**100.0**	**4.03E+08**	**100.0**	**5.77E-01**	**2.32E+08**

Note: CF represents carbon emission categorization factor, and Other CF is assumed to be represented by electricity because of the dominant role of air heat pump technology fuelled by electricity.

In contrast with the Spanish case, in China's scenario a mandatory target for the contribution of solar technology in DHW production does not exist. Therefore, the considered scenarios for the increase of the Chinese energy demand of the DHW production sourced by solar thermal technology are the same than the solar contribution target of the Spanish national scenario (30%). The hypotheses and results of the Chinese national scenario based on the five different methods are shown in Table 46.

Table 46. Baseline scenario, hypotheses, and results on five methods for technology substitution of China's DHW scenarios

		China
BASELINE	National Emissions	9.10E+09 t CO_2
	Year Reference	2015
	Demand DHW [MWh]	4.03E+08
	Current Contribution DSHW [MWh]	6.13E+07
	Current Share DSHW [%]	15.2
	Current Mix DHW [t CO_2-eq/MWh]	5.77E-01
	Current Emissions [t CO_2-eq]	2.32E+08
HYPOTHESIS	Demand DHW	Constant
	Suggested Share DSHW [%]	30%
	Suggested contribution DSHW [MWh]	1.21E+08
MIX Mth	Displaced Demand of DHW – mix [MWh]	5.95E+07
	Mix displaced [t CO_2-eq/MWh]	5.77E-01
	Resulting Mix [t CO_2-eq/MWh]	5.77E-01
	Emissions Reduction [t CO_2-eq]	3.43E+07
	% of National Emissions Reduction [%]	**0.377**
MOST USED Mth	Displaced demand – most used (Natural Gas) [MWh]	5.95E+07
	Mix displaced [t CO_2-eq/MWh]	9.63E-01
	Resulting Mix [t CO_2-eq/MWh]	4.35E-01
	Emissions Reduction [t CO_2-eq]	5.73E+07
	% of National Emissions Reduction [%]	**0.629**
POSITIVE Mth	Displaced Demand – positive marginal mix [MWh]	5.95E+07
	Marginal Mix displaced [t CO_2-eq/MWh]	3.48E-01
	Resulting Mix [t CO_2-eq/MWh]	3.48E-01
	Emissions Reduction [t CO_2-eq]	2.07E+07
	% of National Emissions Reduction [%]	**0.227**
NEGATIVE Mth	Displaced Demand – negative marginal mix [MWh]	5.95E+07
	Marginal Mix displaced [t CO_2-eq/MWh]	9.63E-01
	Resulting Mix [t CO_2-eq/MWh]	4.35E-01
	Emissions Reduction [t CO_2-eq]	5.73E+07
	% of National Emissions Reduction [%]	**0.629**
POLLUTING Mth	Displaced Demand – most polluting [MWh]	5.95E+07
	Mix displaced DHW [t CO_2-eq/MWh]	1.82E-01
	Resulting Mix [t CO_2-eq/MWh]	5.50E-01
	Emissions Reduction [t CO_2-eq]	1.08E+06
	% of National Emissions Reduction [%]	**0.119**

Note: China's national carbon emission is cited from IEA, 2018.

Table 47. Positive method marginal mix for China's scenarios

	DHW 2013 [MWh]	% DHW 2013	DWH 2015 [MWh]	% DHW 2015	2015-2013 [MWh]	% Marginal	CF [t CO_2/MWh]	Emissions [t CO_2]
Natural gas	8.97E+07	24.1	1.23E+08	30.6	3.35E+07	79	0.182	**6.08E+06**
Other	5.94E+05	0.7	6.05E+05	2.9	9.07E+06	21	0.9625	**8.37E+06**
TOTAL					4.26E+07		3.48E-01	**1.48E+07**

In Table 46, for all cases, 5.95E+07 MWh sourced by the different technologies are replaced by the same quantity of solar technology. This amount of energy has displaced: (i) *mix*: of the 2015 mix of technologies; (ii) *most used*: electricity; (iii) *positive*: a mix of 79% natural gas and 21% other (Table 47); (iv) *negative*: electricity (the same as "most used"); (v) *polluting*: all natural gas substituted by solar generation.

3.5.6. Conclusions

Carrying out an LCA of a forced solar thermal system to provide DHW to a six-person house led to the identification of environmental advantages and weak points when compared to a traditional (natural gas) heating system. Whereas the solar system already showed an important improvement in relevant global impact categories such as global warming, ozone depletion and formation of photochemical ozone, there is still room for improvement. Solar thermal technologies can count on another advantage, namely their high energy density (amount of energy generated per m^2 of occupied roof). On the other hand, their fundamental weak points are in the acidification and eutrophication categories, in which impacts were shown to be higher than for the conventional systems. In particular, the water tank, the collector and the copper tubes of the secondary circuit were found to be the components with the largest environmental impact.

The analysis led to the proposal of several eco-design scenarios. Specifically, the change of material in the tubes of the secondary circuit from cooper to galvanized steel showed a relevant improvement, especially in the acidification category. The use of a higher percentage of recycled aluminium in the collector frame also produced improvements in all studied categories. Instead, replacing the cover glass in the collector with a polycarbonate cover produced an almost exact match for the solar fraction and also for the environmental impacts, and was therefore not found to be a particularly effective eco-design strategy.

The potential reduction of emissions for the Spanish context, taking into account the increase of use of solar thermal technologies, varies depending on the DHW generation technologies displaced. The decarbonisation of the energy mix and the electrification of the heating technologies will probably lead to a reduction in the avoided impacts of DSHW. However, nowadays there is still a lack of DSHW. A potential shift to renewable technologies of 22.2% of the energy used in DHW is possible. This would imply a reduction in between 1.24E+06 and 1.65E+06 tonnes of CO_2-eq emitted per year, corresponding between 0.38% and 0.5% of the total (329 Mt) CO_2-eq emissions in Spain in 2015.

By replacing electricity and natural gas with solar thermal technology for DHW in different Chinese national scenarios, between 0.119% and 0.629% of the Chinese total CO_2-eq emitted in 2015 can be reduced. Therefore, China has more progress to shift into solar DHW and contribute to global GHG mitigation.

Future research should focus on exploring the feasibility of producing the systems derived from the suggested eco-design scenarios at an industrial (manufacture) level, and their affectations in the installation stage. In addition, consensus on which is the most appropriate displacement method should be found so as to allow policy makers to better predict the variation of emissions if a new policy is implemented.

3.5.7. References

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Chapter 4. Discussion

4.1. Introduction – cities, the object of study

The discussion in scientific fora in the field of cities which can be found in section 3.2, and talks with some actors that foster sustainable cities around the globe (ICLEI, New Cities Foundation, UN Habitat, Life Cycle Initiative, and Contruction21, among others) leads to state that there is still work to do on defining what a city is. “A city is a city”. We all “know” what a city is but a definition is needed.

There is not a clear definition of what urban systems are (Albertí et al. 2017). Nevertheless, cities are a hot topic. There is a trend to empower cities since 2008 (UNFCCC 2008), but we still do not know what empowering cities means. Are we referring to the empowerment of the administrative city? The greater city? The city region?

Even though no answers have been found in the literature, both the European Commission and the Organization for Economic Cooperation and Development have been working on an agreed definition about the limits of a city (EUROSTAT; EUROSTAT and OECD 2011). The UN has a different approach, gathering how nations define what is *urban* (UN 2005). Each year since 1948, the UN Statistics Division publishes a demographic yearbook. In its table 6 of the year 2015 version (UNDESA 2015b), the demographic yearbook includes a definition of what “urban” means. Despite this is not a direct definition of what a city is, there are similarities between the proposals suggested by the three abovementioned organizations.

Among all the suggested definitions of what a city is, there is a background pattern which includes the following differentiae:

i. Population, people living within the boundaries;
ii. area;
iii. a derived index of the former two, such as population density;
iv. administrative boundaries, designation from another administrative level or by law, this is, an area with an existing administrative municipality;
v. orography or geographical morphology;
vi. land use, historic centres, urban consolidated areas, number of dwellings;
vii. services provided;
viii. economic aspects considered or setting which is the main economic sector.

This differentiae has been used to define the limits of the system, although, in some cases such as (i) or (iv), the differentiae includes the term to be defined. In any case, these differentiae do not solve the issue of the function of a city, the system under study, which is the first item of the scope of any LCA.

4.2. Holistic perspective of city LCA

More than 60 standards, guidelines, rules, case of studies, and indexes have been reviewed, and some gaps have been found. There are methods which consider a life cycle perspective, but do not consider the three dimensions of sustainability. Other methods take this sustainability consideration but lack of using a life cycle perspective. Even in those cases where the life cycle perspective was used, only Greenhouse Gases (GHG) were usually accounted for.

The requisites above are to detect problem shifting and to allow comparison. Trade-offs are commonly identified in assessment methods in fields such as the economy or the environment. If the method considers the three dimensions of sustainability, a life cycle perspective, and multi-impact considerations, the trade-offs become controlled. Problem shifting between the different dimensions of sustainability may be better found. Problem shifting among the life cycle stages can be detected because it is considered in the method. Finally, problem shifting between different impact categories becomes controlled as long as those impact categories have been considered in the assessment. Therefore, although the trade-off is not avoided, the analyst or the decision taker, has a broader view of the problem so that can choose for the right option in each case.

4.3. Goal and Scope of city LCA

The goal and the scope items set in an LCA define the way the system will be assessed. From a goal perspective, the study may be focused on: simply environmental evaluation, self-comparison for eco-design or eco-innovation improvements, or comparison between other similar systems. From a scope perspective, the study may proceed on only some of the life cycle stages or/and some of the impact categories. Moreover, LCA usually focuses only on the environmental dimension of sustainability.

As introduced in section 3.2, the definition of the goal and scope of a city LCA developed in this thesis has been influenced by the following criteria:

(i) holistic point of view,
(ii) including several environmental impacts,
(iii) a Life Cycle perspective, and
(iv) the possibility to compare the results among different cities or urban regions.

Comparison is a key issue as it is the criterion that allows benchmarking which is a driver for improvement. Results provided nowadays, for instance by the work carried out by the Carbon Disclosure Project or C40, are not as useful as they could be. Which is the usability of knowing that Barcelona emits 4.05E+06 t CO_2-eq or that Zurich emits 1.82E+06 t CO_2-eq? Barcelona and Zurich can follow themselves along time and see if they are emitting more or less t CO_2-eq, in absolute terms, than previous years. However this information does not allow these two cities to be compared to each other. Even more, is it correct to make a time series of the emissions of Barcelona? How can one compare the Barcelona's emissions in 2018 with the ones of 1982? Is it the same Barcelona? Has it the same number of inhabitants? And even more important, do these inhabitants live the same way? Do they have the same level of prosperity?

The answers to these questions come with the questions themselves. To allow a comparison of results, these should be normalized by two main characteristics of the city: the number of inhabitants and how do these inhabitants live? (Albertí et al. 2018a).

These two characteristics are what this thesis set as the technical performance of the functional unit. The former depends on the boundaries of the city considered and should always be coherent. Firstly, coherency must happen between the boundary and the inventory. If the assessment includes only the administrative limits, both the scope 1 (direct) emissions (cita GHG Protocol) and the number of inhabitants should be limited to this geographical area. Secondly, there must be coherence when seeking to compare two different cities. For instance, it would have no sense to compare administrative Zurich with greater Barcelona (Albertí et al. 2018b).

Which is the best way to measure how do inhabitants live? The function of a city was set by Aristotle in the IV century BC. Aristotle related the function of a city to the happiness of their inhabitants (Clayton 2017). In this thesis, the term "happiness" is changed to the term "prosperity", assuming that prosperity and happiness are closely linked. Accepting this premise, the suggested functional unit adjusting factor is the City Prosperity Index (CPI).

The CPI was developed by UN Habitat in 2015 (Moreno and Murguía 2015). This internationally recognized compound index fulfils the requirement of inclusion of the social and economic dimensions in the LCA through the adjustment (normalization) of the functional unit (Albertí et al. 2018a). However, the use of this index implies an assumption: the prosperity of a city equals that of its inhabitants. Although this is not strictly true, as CPI is a mean value of the prosperity of all city inhabitants, this assumption allows the use of the index in LCA. Other simplifications are developed in section 4.4.

4.4. Other considerations and simplifications

There are two causes which difficult an approach to Life Cycle Sustainability Assessment (LCSA) of cities. The first cause is due to the complexity of the system to be adressed (Albertí et al. 2017) which may be the reason why currently city assessment have only beenapplied partially.

The second cause is due to the complexity of the LCSA by itself (Finkbeiner et al. 2010). A LCSA includes an LCA, a Life Cycle Costing, and a Social LCA. Thus, although LCSA of cities is the final goal to achieve in this thesis, a first step has been taken by taking a LC perspective through the use of a LCA and by including the other two dimensions of sustainability using the CPI as an adjusting factor of the functional unit of a city LCA.

The complexity of both the LCA method and the system under study makes the endeavour quite difficult, even in the case that a full LCSA is not performed. This simplified-LCSA, although not being a fully fledge LCSA, fulfils the requirements set in the research objectives.

4.4.1. City definition and its boundaries

City boundaries are a relevant characteristic within the city definition (Albertí et al. 2018b) and a required item for LCA (ISO 14044 2006). This thesis (section 3.3.3.1) includes several procedures for the definition of the boundaries of a city. Among the proposals, a differentiation between the geographical and the functional boundaries of a city is suggested.

Geographical boundaries are based on the continuity of the population density. Although the European Commission and the OECD provide a possible threshold value to differentiate between urban and rural areas, the aim of the section 3.3.4.1 is to set the procedure for defining the geographical boundaries, rather than the specific threshold on which some consensus should be sought internationally.

Functional boundaries are suggested to be set depending on the services induced by the city under study. They are based on the provision of services to the city under study, regardless of their geographical location. However, from a life cycle perspective, these services may imply the accountancy of activities which happen on cities located in far areas throughout the World. The functional boundaries set should determine which activities are relevant or not for the assessment, no matter the place where the activity takes place, following the usual LCA criteria. Although a service-based procedure is suggested for defining the functional boundaries, a cut off criterion would need to be set in future research so as to make the procedure feasible.

4.4.2. Allocation procedures

Current city assessment allocation practices focus either on consumption, production, or monetary based approaches (Albertí et al. 2018b). These are allocation procedures described in standards and guidelines (section 3.3.3.2), which in most cases even prioritize the parameters to be used so as to assign environmental burdens.

This allocation procedures have been useful at a product and even at an organizational level. However, thinking from a macroscopic consequence perspective, the implications of choosing one or another allocation procedure may not be fair (Albertí et al. 2018b). Using those procedures may imply the allocation of the burden not necessarily to those that have induced the generation of the environmental burden, which separates from the causality principle. Furthermore, the people or the ecosystem that suffer from the burdens generated are not on the focus of the abovementioned procedures.

Consumption and production based procedures, used in guidelines such as those suggested by WRI et al. (2014) or PAS 2070 (2014), are based on 0% or 100% metrics. Even though this is an often used mechanism due to its simplicity, the possibility to share responsibility is not possible within these schemes. The monetary based procedure fulfils this deficiency. However, sharing the burden based on economic values does not necessarily mean that this allocation is fairly done. Other arbitrary allocation procedures such as 50%-50%, used for instance in the case of commuting, do neither fit with the cause-effect criterion.

Instead, the impact category-based procedure created and suggested in this thesis, provides a new perspective on how to share the burdens of an activity. This procedure focuses on whether the impacts are local or global rather than discussing on who is the inducer of the impact: the consumer or the producer. This way, the ecosystems and citizens that suffer from the impact become the main actors. When those ecosystems and citizens are affected at a global level, it is suggested that the impact is transferred to the consumer city. Contrarily, when the ecosystems and citizens affected are local, the impacts remain in the city where these are generated.

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Chapter 5. Conclusions and recommendations

5.1. Overall conclusions

1. The review of current city assessment methods has highlighted the lack of consensus on the definition of a city. The research carried out in this thesis contributes to provide answer to this issue.

2. No available methods for a city LCA have been found. A first set of goal and scope definition items have been developed: goal, function, functional unit, and reference flow.

3. The use of the City Prosperity Index as a normalizing factor of the technical performance of the city fulfils the objective of having a methodology able for comparison.

4. No procedure, for drawing the city boundaries, has been found to be widely accepted. To solve this challenge, two types of city boundaries have been suggested: functional and geographical boundaries.

5. How to allocate burdens between connected cities is another major challenge. In this thesis four ways are proposed and one novel method is preferred (the category based allocation procedure): to allocate depending on the nature of the impact category, whether it is local or global. This change on the allocation procedure could affect, if accepted, the way national emissions inventories are performed sharing the environmental burdens between the producer and the consumer.

6. City systems last very long and it is important to know for how long city LCAs results are to be trusted. On how to measure this, a case study on a city component has been performed, finding that LCA do not last 20 years.

7. The application of changes within the technosphere will be needed to improve cities environmental behaviour, i.e. the achievement of SDGs' targets will imply the substitution of technologies that modify the electricity mix, the Domestic Hot Water mix, the mobility patterns, etc. However, the consequences on the choices of system substitution when credits are calculated is not clear. Therefore, the thesis assesses which are the consequences of choosing one displacement method or another, finding that the election of the displacement method can increase five times the expected reduction of emissions.

5.2. Specific conclusions

Current methods (Section 3.1)

1. City assessments seldom consider the three dimensions of sustainability (sometimes two of them), being the environmental one the most usual. This dimension is represented mostly by the global warming potential in emissions of CO_2 equivalents.
2. The LC perspective has been applied up to a neighborhood scale in the construction hierarchy, without consensus for the Functional Unit neither at neighborhood level nor at urban one, for which very few references can be found in the literature.
3. The existing methods seldom take into account indirect (Scope 3) impacts;
4. The existing methods do not correctly adjust the functional unit of the assessed city to its function; consequently, they are not prepared to perform comparative assertions among cities or regions.

City definition (Section 3.1)

5. Although the OCDE and the European Commission provide a named "harmonized definition" of a city, it still has not reached international consensus. In addition, the city definitions provided by the WBCSD or the BSI are ambiguous.
6. Taking into account the diferentiae appearing is a starting point to find consensus on this definition. The most commonly found differentiae among city definitions are:
   i. Population, area, or a derived index from the two such as population density;
   ii. administrative boundaries, designation from another administrative level or by law, this is, an area with an existing administrative municipality;
   iii. orography or geographical morphology characteristics;
   iv. land use, historic centres, urban consolidated areas, number of dwellings;
   v. services provided;
   vi. economic aspects considered or setting which the economy main sector should be, if any.
7. Using the population density discontinuity as a delimitation parameter, for setting what is included in a city and what isn't, can be a practical solution. However, terrain singularities must require additional considerations.

Goal and scope items for a city LCA (Section 3.2 and 3.3)

8. LCAs lack of social and economic information. The use of the City Prosperity Index (CPI) has been proposed as an adjustment on technical performance within the Functional Unit of the city LCA, which allows comparison on sustainability.
9. The proposal has been tested in 18 cities delivering that the ranking of cities depending on the impact they generate varies if the FU is adjusted to the function using the CPI.
10. Two type of boundaries have been found to be useful for a city. On the one hand, geographical boundaries determine the limits of the urban area under study and are useful for determining which impacts are local, and which impacts are not. On the other hand, the functional boundaries of a city determine the set of

processes/activities, and their environmental impacts, which are relevant for the assessment, no matter the place where the activity takes place.

11. Three procedures for boundary definition in city LCA (administrative-, density- and service-based boundaries) have been assessed. Density- and service-based boundaries seem to be the most parsimonious, as they are simple ways to take into account the complexity and interdependency of cities. Geographical boundaries of a city LCA should be defined through the density-based procedure, which should include cities, towns and suburbs connected with a continuous density of population. Finally, functional boundaries of the city LCA should be defined through service-based procedures, which would help to include, in the city system, those induced activities that happen out of the geographical boundaries.
12. Four allocation procedures have been proposed to distribute impacts among cities in LCA: producer-, consumer-, monetary-, and category-based. A monetary-based approach may be appropriate only when other procedures fail to represent the reality through causality. The proposed category-based allocation assigns impacts to either the producer or the consumer, depending on whether the impact category under consideration is local or global.
13. A survey among 83 international experts has found this latter to be the most preferred way to share responsibilities along the supply chain.

Validity of LCAs (Section 3.4)

14. LCAs validity along time has been found to be dependent, at the inventory level, on the ever-changing techno-sphere and the improvement of the environmental policies; while, at impact level, on the evolution of impacts models and characterisation factors. This has been found through comparing a Bus Stop LCA with the same one performed 20 years ago. Should this case study be taken as categorical, after those years, LCA results could only be taken as a rule of thumb.

Substitution methods (Section 3.5)

15. Cities are complex systems whose energy supply infrastructure is currently quickly evolving. When a new (energy) technology enters a system, it will substitute one or a mix of current technologies of (energy) generation: the so-called marginal one. It is fundamental to preview which would be the change in the amount of emissions generated by the system once a new technology enters the system. Depending on the substituted method used the prevision of emissions reduction can vary up to five times.

5.3. Limitations of the study and future research

Some of the methodological items needed to perform a city LCA have not been addressed yet.

a) Within the Goal and Scope: additional allocation procedures, data and data quality requirements, cut-off rules, impact categories recommendations, critical review considerations, reporting format;
b) Within the Inventory Analysis: data collection alternatives, unit process descriptions, process exclusions;
c) Within the Impact Assessment: need of new categories, normalisation and weighting recommendations, introduction of other areas of sustainability; and
d) Within Interpretation: indications on gravity analysis, uncertainty analysis, sensitivity analysis, completeness analysis, consistency check, limitations, etc.

The definition and setting of these issues would facilitate the generation of a city LCA related standard.

Unfortunately, this thesis lacks of a pilot case study, which would have been useful to refine the suggested method. This situation may be solved through external additional funding for the project. However, the lack of refinement through a case of study was partly compensated by a survey to a panel of more than 80 international experts who provided their feedback in section 3.3.4.3. In any case, future research should certainly focus on developing pilot case studies.

Specifically, assessing the applicability and acceptability of the suggested allocation procedures through a case study is found essential. For instances, the choice between the current consumption- or production-based allocation methods has raised many discussions along the scientific community in the case of CO_2-eq emissions. The proposed category-based allocation should be disclosed and double checked with more examples to provide evidence on its advantages in front of the currently used ones.

External funding would allow a cooperation-based project with other research groups. Hopefully, the application to EU programmes, such as COST action, could facilitate the involvement of other institutions to discuss methodological terms and find consensus.

Finally, the use of the CPI as a normalizing factor for environmental impacts derives into an eco-efficiency indicator, for which more research should be done. The thesis has not assessed the adequacy of the weighting method used to calculate the CPI. The interactions between social, economic and environmental dimensions of sustainability are complex and further research could contribute to determine its adequacy.

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