Industrial ecology as a discipline for the analysis and design of sustainable urban settlements

Doctoral Thesis

Jordi Oliver i Solà

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Sapere aude

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E. ACRONYMS

ACPA	American Concrete Pavement Association
ADP	Abiotic Depletion Potential
AENOR	*Asociación Española de Normalización y Certificación* / Spanish Association for Standardisation and Certification
ANCOP	*Agrupación Nacional de Constructores* / Spanish Builders Association
AP	Acidification Potential
ASTM	American Society for Testing and Materials
CH	Ecoinvent process valid for a situation in Switzerland
CHP	Combined Heat and Power
DE	Ecoinvent process valid for a situation in Germany
DfE	Design for the Environment
DIS	Draft International Standard
DMC	Domestic Material Consumtion
EFA	Energy Flow Accounting
EKC	Environmental Kuznets Curve
EMAS	Eco-Management and Audit Scheme
EMS	Environmental Management Systems
EP	Eutrophication Potential
EU	European Union
Eurostat	Statistical Office of the European Communities
FDIS	Final Draft International Standard
FU	Functional Unit
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GLO	Ecoinvent process valid for any situation
GWP	Global Warming Potential
ha	Hectares
HTP	Human Toxicity Potential
ICAEN	*Institut Català de l'Energia* / Catalan Energy Agency
ICS	International Classification for Standards
ICTA	*Institut de Ciència i Tecnologia Ambientals* / Institute of Environmental Science and Technology
IEC	International Electrotechnical Commission
IS	International Standards
IS	International System of Units
ISA	International Federation of the National Standardizing Associations
ISIE	International Society for Industrial Ecology
ISO	International Organization for Standardization
JTC	Joint Technical Committee
KOE	Kilogram of Oil Equivalent
kWh	kilowatt hour
LA21	Local Agenda 21
LCA	Life Cycle Assessment
LCI	Life-Cycle Inventory
LCIA	Life Cycle Impact Assessment
LPG	Liquid Petroleum Gas

MEFA	Material and Energy Flow Accounting
MFA	Material Flow Accounting
MJ	Mega Joules
MPa	Mega Pascal
MS	Microsoft Corporation
NAFTA	North American Free Trade Agreement
ODP	Ozone layer Depletion Potential
PAS	Publicly Available Specifications
PE	Polyethylene
POCP	Photochemical Ozone Creation Potential
RER	Ecoinvent process valid for a situation in Europe
RGRA	Revue Générale des Routes et des Aérodromes / General Magazine of Roads and Airports
SAGE	Strategic Advisory Group on the Environment
SC	Subcommittee
SEOPAN	*Asociación de Empresas Constructoras de Ámbito Nacional* / Spanish Association of Construction Companies
SETAC	Society for Environmental Toxicology and Chemistry
SosteniPrA	Sustainability and Environmental Prevention Research Group
TC	Technical Committee
TOE	Tonne of Oil Equivalent
TR	Technical Reports
TS	Technical Specifications
UAB	*Universitat Autònoma de Barcelona* / Autonomous University of Barcelona
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNSCC	United Nations Standards Coordinating Committee
UPC	*Universitat Politècnica de Catalunya* / Technical University of Catalonia
USA	United States of America
VTT	Technical Research Centre of Finland
WCED	World Commission on Environment and Development
WG	Working Group
WSSD	World Summit on Sustainable Development

F. PREFACE

The present doctoral thesis was developed within the research group on Sustainability and Environmental Prevention (SosteniPrA), at the Institute of Environmental Science and Technology (ICTA), of the Universitat Autònoma de Barcelona (UAB) from March 2005 to April 2009.

The document is structured in six chapters. **Chapter I** constitutes the introduction to the theoretical framework of the thesis. I introduce here the concepts of *weak* and *strong* sustainability, the role of cites for achieving sustainability, an explanation and historical review of Industrial Ecology, the state of the art of ISO standards of sustainability in construction and the general objectives of the thesis.

Chapters II to V include the chapters with research content on three levels of the urban system (Table F.1.) and compile the work on service sector ecology, pavements and energy infrastructures presented in the papers cited below. Each of these chapters has its own specific introduction for the precise field that is analyzed, a discussion and a summary of the main conclusions. The original contents of the papers have been respected to the utmost, which implies that small duplicities may appear in some introductory or methodological comments.

Chapter II

- Oliver-Solà J, Nuñez M, Gabarrell X, Boada M, Rieradevall J (2007) Service sector metabolism: accounting for energy impacts of the Montjuïc urban park in Barcelona. Journal of Industrial Ecology 11(2): 83-98.

Chapter III

- Oliver-Solà J, Josa A, Rieradevall J, Gabarrell X (2009) Environmental optimization of concrete sidewalks in urban areas. International Journal of Life Cycle Assessment. In Press.

Chapter IV

- Oliver-Solà J, Gabarrell X, Rieradevall J (2009) Environmental impacts of natural gas distribution networks within urban neighborhoods. Applied Energy 86(10): 1915-1924.

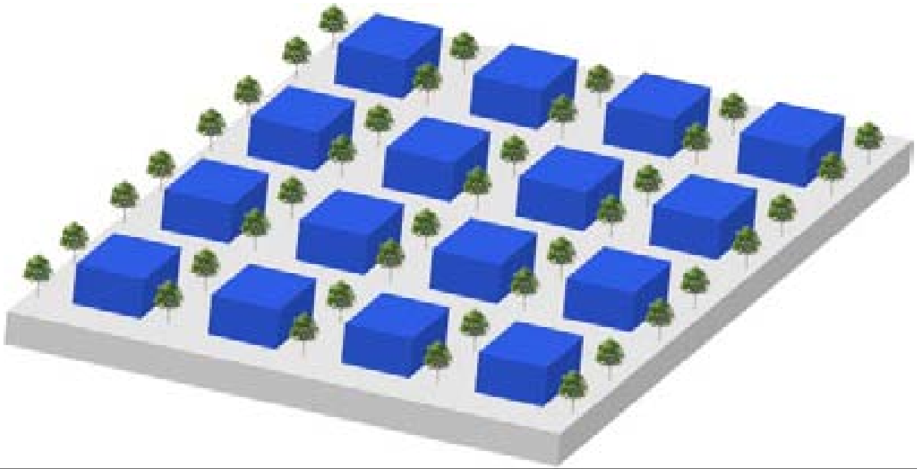
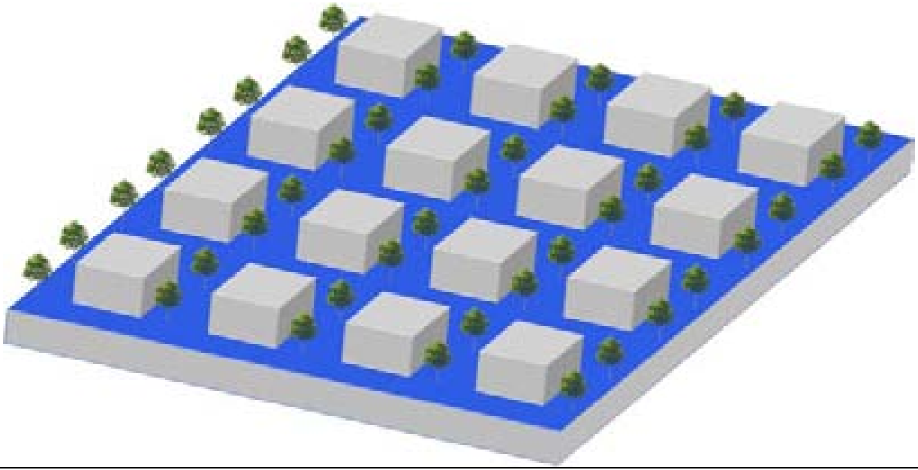
Chapter V

- Oliver-Solà J, Gabarrell X, Rieradevall J (2009) Environmental impacts of the infrastructure for district heating in urban neighborhoods. Energy Policy, Under revision since December 2008.

Finally, **Chapter VI** contains the general conclusions and insights for further research.

All references in this document follow the style recommended by the International Journal of Life Cycle Assessment, but using the complete title of international journals instead of abbreviations.

Table F.1. Content of the chapters and representation of an urban scenario with the three levels analyzed in this dissertation.

Chapter	Content and urban subsystem analyzed
Chapter I	Introduction, justification and objectives
Chapter II	Service sector metabolism 
Chapter III	Environmental optimization of concrete sidewalks 
Chapter IV and V	Environmental impacts of natural gas and district heating distribution networks 
Chapter VI	General conclusions and further research

With this doctoral thesis SosteniPrA takes its first steps in the environmental analysis of urban systems. Within this framework many applied research projects have been developed in parallel (see Table I.2 for the complete list), where the results obtained in the basic research have been transferred and put into practice in projects of great social benefit. For instance, I have actively participated in two proposals for sustainable districts in Barcelona: Sant Andreu (Figure F.1.) and Vallbona (Figure VI.1); the first being a conceptual proposal presented orally at the World Sustainable Building Conference 08 (Melbourne, 21-24 September 2008) and developed jointly with a multidisciplinary team led by the architects Lluís Grau and Felip Pich-Aguilera; and the second the elaboration of the Master Plan in a project led by Barcelona Regional SA.

Figure F.1. Conceptual image of the sustainable district proposed in Sant Andreu (Barcelona).

Background projects in the field of urban sustainability done in parallel to this thesis

Besides the research papers presented in chapters II to V of this dissertation, over the last four years I have participated in a large number of applied research projects. The most relevant ones, linked with urban sustainability are presented in Table F.2.

Table F.2. List and description of the most relevant projects of SosteniPrA in the field of urban sustainability in which I have participated.

Scale of application	Project	Brief description	Contractor / Partners
Neighborhood	Master Plan of an Eco-Neighborhood in Vallbona (Barcelona)	Preparation of the first Master Plan for a sustainable neighborhood in Catalonia	Barcelona Regional
	Eco-Social-Neighborhood in Granollers (Barcelona)	Proposal of environmental improvement strategies for a social neighborhood	Adigsa (Government of Catalonia)
	Greater Helsinki Vision 2050	Proposal for a Master Plan for the Greater Helsinki Region within the International ideas competition.	Duran & Grau, Pich-Aguilera Architects, UPC
	Sustainable district in Sant Andreu (Barcelona)	Proposal of an idea for a Master Plan for a sustainable neighborhood in Sant Andreu (Barcelona).	Duran & Grau, Pich-Aguilera Architects, UPC
	Combined Rational and Renewable Energy Strategies in Cities, for Existing and New Dwellings to ensure Optimal quality of life (cRRescendo)	EU 6th Framework Project, partially developed in Viladecans (Barcelona). LCA of a proposal for district heating infrastructure.	EU – Viladecans City Council
	Environmental self-sufficiency urban indicators for water, wastes, energy and materials.	Design and application of environmental self-sufficiency urban indicators to different scales.	Spanish Ministry of the Environment A042/2007/3-10.1
Buildings	Energy audits in municipal buildings	Analysis and diagnosis of the energy consumption in three municipal buildings in Viladecans (Barcelona).	EU – Viladecans City Council
	Garden Tower	Proposal of a skyscraper with large projecting gardens and low material and energy requirements. First prize from the jury in the Ideas competition for new residential spaces VISESA (*Vivienda y Suelo de Euskadi*)	Pich-Aguilera Architects, BOMA, Sostre Cívic
	Urban waste collection and storage centre	Design of a new installation for the selective waste reception and storage.	For Barcelona City Council, in collaboration with ArQuiSol.

Although the elaboration of the dissertation and the participation in these projects has occurred in parallel, there has been clear feed-back between them. Theoretical concepts learned in the basic research have been applied to practical projects, reverting into societal benefits. And viceversa, the pragmatic approach required by applied projects has made the research more realistic and close to its practical application. Figure F.2. shows a diagram extracted from the Greater Helsinki Vision 2050 project, in which the incorporation of environmental quantitative data reinforced and supported the formal design decisions.

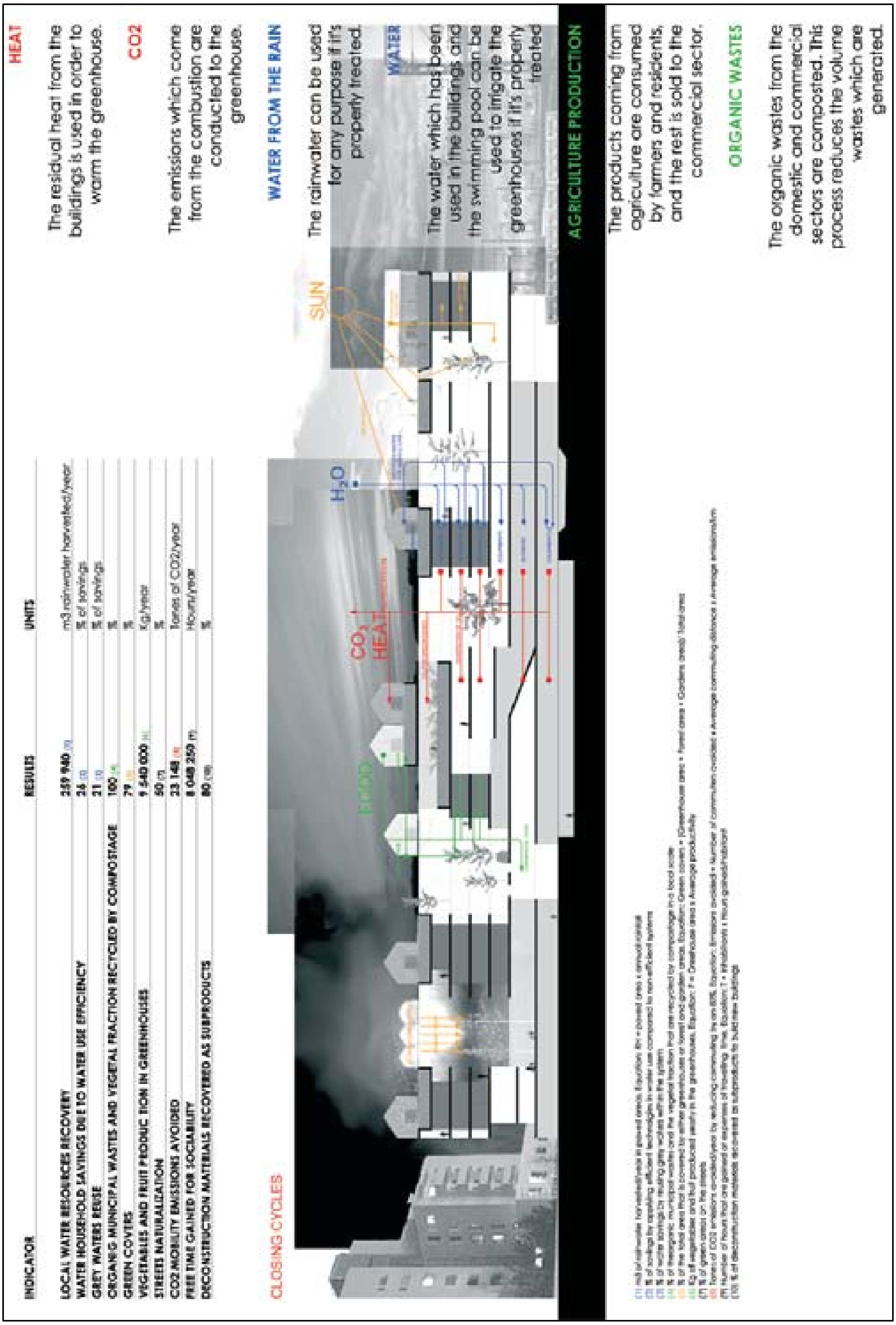


Figure F.2. Metabolic flows within a building calculated for the Greater Helsinki Vision 2050 competition.

CHAPTER I

INTRODUCTION, JUSTIFICATION AND OBJECTIVES

I.1. *WEAK* vs. *STRONG* SUSTAINABILITY

Sustainability is the condition or characteristic of a process that can be maintained indefinitely without progressive diminution of valued qualities inside or outside the system in which the process operates or the condition prevails (Holdren et al. 1995).

The concept of sustainable development was presented in 1987 in the Brundtland Report (WCED 1987), in which it was proclaimed that sustainability had to be the central goal of environmental policy, based on three main pillars: ecological integrity, economic prosperity and social equity, picking up on the inheritance of the concepts "Place, Work and Folk" formulated by the Scottish biologist and urban planner Sir Patrick Geddes seven decades before (1915).

In this context, the sustainable development of societies and economies can be understood as the necessary way to make current welfare levels in western countries compatible with the welfare of the future generations of all the species all over the planet. This welfare does not only consist of protecting the natural environment to ensure its preservation; but is also an ambitious goal in which social, economic and environmental criteria have to be combined in order to attain an optimum state of inter and intragenerational equity (Van Hauwermeiren, 1998).

The kind of sustainability promoted by the Brundtland report has been called *weak* sustainability, because it implies that sustainability can be achieved with a growth economy, without recognizing that that growth is intricately linked to environmental degradation, and can't be decoupled from it. In fact, the idea that economic growth is necessary in order for environmental quality to be maintained or improved is an essential part of the sustainable development argument promulgated by the World Commission on Environment and Development in *Our Common Future* (WCED 1987).

Williams and Millington (2004) reviewed the concepts of *weak* and *strong* sustainability, asserting that:

Weak sustainability argues that one needs to expand the stock of resources. This can be done by developing renewable resources, creating substitutes for non-renewable resources, making more effective use of existing resources, and/or by searching for technological solutions to problems such as resource depletion and pollution.

On the contrary, *strong sustainability* argues that the demands that we make of the Earth need to be revised so that, for instance, we consume less. In this view, in consequence, rather than adapt the Earth to suit ourselves, we adapt ourselves to meet the finitudes of nature.

Weaker sustainable development, therefore, adopts an anthropocentric discourse on the relationship between people and nature. This is composed of three strands: the perception that people are separate from nature; the idea that nature is a "resource" to be used for the benefit of society or individuals; and the view that we have the right to dominate nature. Taken together, these three strands represent what might be considered a Judaeo-Christian conceptualization of the connection between people and nature.

At the heart of *weaker* sustainable development is implicit optimism. There is confidence that people will be able to find a solution to any environmental problems that arise. They will be able to enhance the stock of “resources”. Technological progress, it is assumed, will enable people to manipulate the Earth to meet their enormous demands of it. Any problems that arise will thus be solved through technological development.

On the other hand, the common belief surrounding *stronger* sustainability theorists is the view of the Earth as finite and their concession that no inhabitable future is possible unless the demand-side of the equation radically alters by rethinking our attitude towards nature as well as our view of economic progress and “development” (e.g. Capra and Spretnak 1985; Ekins and Max-Neef 1992; Goldsmith et al. 1995; Fodor 1999; Henderson 1999; Latouche 2006). For these analysts, the *weaker* versions of sustainable development are much more about “sustaining development” rather than sustaining environment, nature, ecosystems or the Earth’s life support systems (Williams and Millington 2004).

More plainly it could be said that *weak* sustainable development focuses on the resource-side of the equation so as to conjoin resources and demands while *strong* sustainable development focuses on limiting the demands made of the Earth.

An illustrative example of the differences between *weak* and *strong* interpretations of sustainability is the case of the evolution of energy demand in the European Union (EU–25). Although energy intensity has decreased (rate of Gross Domestic Product (GDP) growth > rate of energy consumption growth) in the defined period, the total energy consumption has continued increasing (Figure I.1), resulting in higher environmental impact.

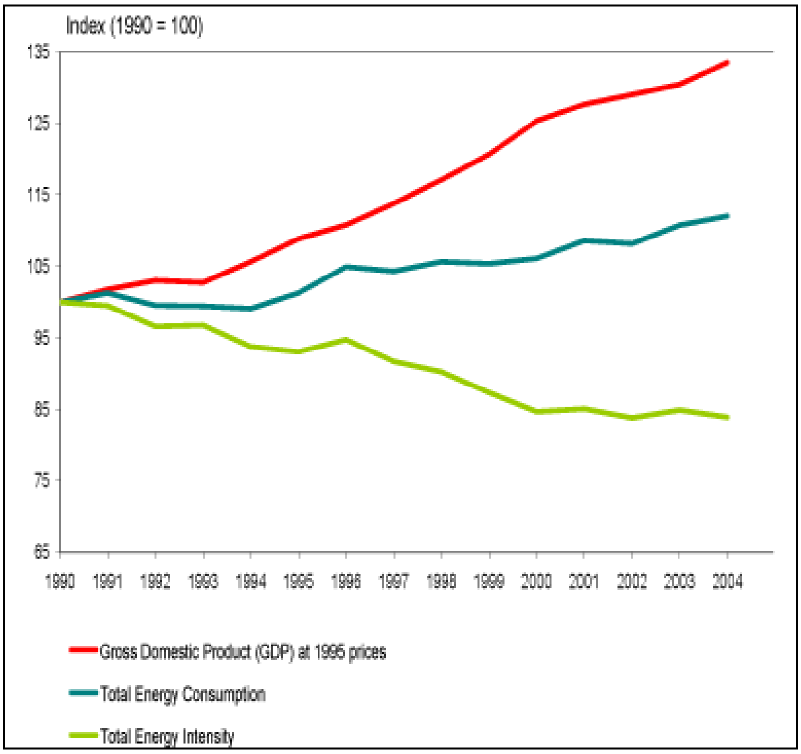


Figure I.1. Trends in total energy intensity, gross domestic product and total energy consumption, EU-25.
Source: European Environment Agency (2007)

From a *weak* sustainability point of view, in recent decades the system has improved its environmental performance because the energy efficiency (Euros produced per unit of energy) has increased. However, from a *strong* sustainability perspective the system is progressively more resource depleting and polluting.

The paradox is that it is possible (and common) to improve energy efficiency by using more energy. What matters for the environment, however, is not how efficient we are in consuming energy, but the total amount of energy and resources that are consumed.

This explains why, since its formulation in 1987, the practical application of the sustainability concept has failed successively. The reason is that it was inscribed within productivist economic systems formulated in the 19th century, in a still colonialist Europe, which completely ignored the physical limits of the Earth and intended to grow infinitely on a finite planet.

In short, we can say that when we attach the sustainable adjective to the concept of development, we are not questioning the development pattern that has dominated the planet for the last two centuries, but merely adding an ecological component to it. What is more doubtful is whether this will be enough to solve the problems that our society has created (Latouche 2006).

I.1.1. Economic growth entails environmental depletion

The inflow or consumption of a system's materials can increase over time, either materializing or diminishing. This decrease is called dematerialization. Dematerialization can also be *strong* or *weak*, depending on whether there is a total decrease, in absolute terms, or whether the dematerialization happens in relative terms. Relative or *weak* dematerialization can be per capita or per unit of GDP. There are also systems where after a stage of dematerialization there is an upturn in inflows and consumption, a phenomenon known as rematerialization (Ayres and Ayres 2001).

Traditionally the service sector has been considered to be a dematerialized sector because the energy and material requirements for producing a unit of economic output seemed to be lower. This prejudgment stimulated the analysis of the energy requirements of a large number of service facilities performed in the present thesis (chapter II).

The dematerialization theory is usually represented by the environmental Kuznets curve (EKC)[1]. The EKC concept emerged in the early 1990s out of Grossman and Krueger's (1991) study of the potential impacts of the North American Free Trade Agreement (NAFTA) and Shafik and Bandyopadhyay's (1992) background study for the 1992 World Development Report. EKC represents a hypothetical relationship between various indicators of environmental degradation and income per capita. In the early stages of economic growth degradation and pollution increase, but beyond some level of income per capita (which will vary for different indicators) the trend reverses, so that at high-income levels economic growth leads to environmental

[1] This theory was named after Kuznets (1955) who hypothesized income inequality first rises and then falls as economic development proceeds.
Simon Kuznets (Kharkov, Russia 1901 – Cambridge, USA 1985) won the Nobel Prize in 1971 for pioneering the use of a nation's gross national product to analyze economic growth.

improvement. This implies that the environmental impact indicator is an inverted U-shaped function of income per capita (Figure I.2) (Stern 2003).

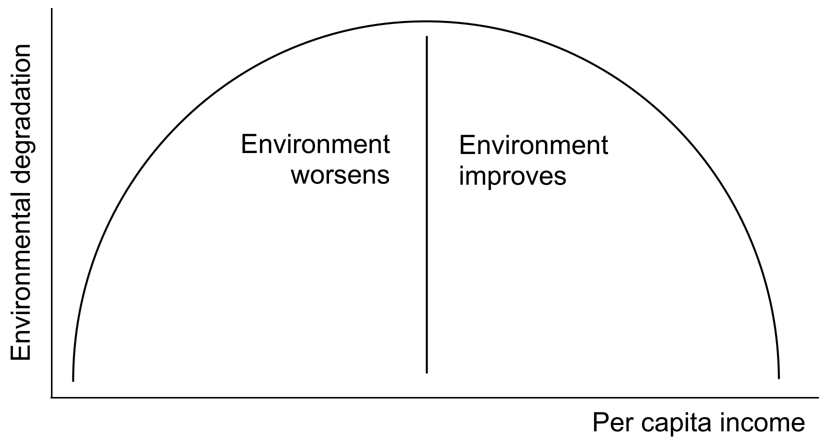


Figure I.2. Environmental Kuznets curve.

However, when Jänicke et al. (1989) measured the hypothesis of dematerialization; the results obtained showed that between 1970 and 1985 a separation between economic growth and use of resources was produced (weak dematerialization), but in the late eighties and in the 1990s this trend was inverted in some countries like Germany, Belgium, France and the United States.

Other authors like De Bruyn and Opschoor (1997), defend positions similar to those of Jänicke et al. (1989), explaining that the *weak* phenomena of decoupling among economic growth and natural resource consumption in western countries reached its end at the end of the 1980s and were followed by episodes of strong rematerialization during the 1990s, inverting the EKC and causing an N-shaped curve rather than an inverted U.

These results provided data for the discussion about the limited possibilities of dematerialization in absolute terms for the service sector and showed that the current form of rending services also requires an important material basis for operation. In fact, when econometrics are taken into account and used appropriately results show that the EKC does not exist (Perman and Stern 2003).

Still not aware that *weak* sustainabilty is unable to solve the environmental problems caused by the western lifestyle; some theorists have proposed an *ecoliberal* or *ecokeynesian* version of green taxes to achieve a capitalism that, without abandoning the infinite growth utopia, is less destructive of the environment (Riechmann 1995). Other theorists, partisans of *strong* sustainability, and followers of Georgescu-Roegen[2] thermodynamic approaches to economy, have proposed an alternative for the productivist economic models, named *Degrowth*. *Degrowth* is a topic that has become a major subject of debate, not just within the counter-globalisation

[2] Nicholas Georgescu-Roegen (Constanța, Romania, 1906 – Nashville, Tennessee, 1994) was a Romanian mathematician, statistician and economist, best known for his 1971 book *The Entropy Law and the Economic Process*, which situated the view that the second law of thermodynamics governs economic processes. Georgescu-Roegen presented *Degrowth* as an inevitable consequence of the limits imposed by nature (Georgescu-Roegen 1979). He is also considered one of the key intellectual progenitors of ecological economics.

movement but also in the wider world (Latouche 2004). The concepts behind this theory will not be examined here, because such an explanation would essentially lie beyond the scope of this thesis. However, it is important to mention that Industrial Ecology is a discipline that can fit in the context of *strong* sustainability (Oliver-Solà 2005), especially in the field of environmental optimization of the service sector and neighborhoods.

I.1.2. First steps towards *strong* sustainability are possible on a neighborhood scale

The Kyoto protocol, signed by 160 countries, pledges reductions in greenhouse gas (GHG) emissions by at least 5% in relation to 1990 levels (UNFCCC 1998). However, besides the global concern and action to mitigate GHG emissions, national-level policies are increasingly being supplemented with city-scale actions to mitigate climate change (Ramaswami et al. 2008). In this sense, in February 2009, more than 350 cities across Europe committed themselves, by signing the Covenant of Mayors, to going beyond the EU's energy objective of reducing 20% CO_2 emissions by 2020. With this initiative of the European Commission in partnership with the Committee of Regions, the representatives of over 60 million citizens will work together to achieve the common goal of reducing GHG emissions and using energy more wisely.

In this sense, Marshall (2008) notes that although much attention to mitigating climate change has focused on alternative fuels, vehicles, and electricity generation, better urban design represents an important yet undervalued opportunity.

Much research into urban design has focused on the need for more sustainable design on the city scale, but this thesis, as Engel-Yan et al. (2005) suggest, focuses on the design of sustainable neighborhoods. The incorporation of sustainability principles in neighborhood design is important because many of the problems encountered on the macro-city scale are in fact cumulative consequences of poor planning at the micro-neighborhood level. In addition, most of these decisions are well within the reach of local governments and leaders and can reduce long-term carbon emissions (Marshall 2008).

It also has to be considered that, besides the direct environmental benefits, ecostrategies for the public spaces in neighborhoods or in service facilities provide an example of urban environmental management being close to citizens.

I.2. CITIES AS A CORNERSTONE FOR SUSTAINABILITY

Old cities are growing (in some cases dramatically) and new ones are emerging worldwide. Despite representing only 2.7% of the world's surface area (UN 2007), the world's cities are responsible for 75% of the world's energy consumption (consuming both direct and indirect energy embodied in key urban materials such as food, fuel, concrete, water supply, etc.), and 80% of GHG emissions (Ash et al. 2008).

The growth and urbanization of the global human population over the past 300 years has resulted in the construction of cities of unprecedented size and form (Decker et al. 2000). Nowadays urban areas are expanding worldwide as statistics for urban population share reach figures of 80% in America, 70% both in Europe and Oceania and even 50% on a global level; and this increasing urban share is going to reach figures of 70% worldwide by 2050 (UN 2008). Consequently, cities have become the primary human habitat in the presently ''industrialized'' countries. Along with the sheer growth in terms of human numbers, the mass migration of people to cities is arguably the most significant human ecological event of the past 100 years. Nevertheless, the human ecological dimension of the phenomenon has gone virtually unnoticed (Rees 1997).

Although the technical literature treats urban ecology mainly as the ecology of nonhuman species in cities (Rees 1997) there is a need for integrated research into urban areas (Pickett et al. 1997), at least for two reasons. First, urban areas represent novel combinations of stresses, disturbances, structures, and functions in ecological systems (McDonnell and Pickett 1990; Sukopp 1990; Waring 1991). Therefore, understanding how urban ecosystems work, how they change, and what limits their performance, can add to the understanding of ecosystems in general. Second, the spread of urbanization into agricultural land and in some cases into relatively wild forest, chaparral, or steppe, is one of three major global impacts of humans (Vitousek 1994). The process of urbanization in its broadest sense converts land that has been studied by traditional ecological approaches into systems that require a clearer appreciation of the roles of humans (Thomas 1955; Forman 1995).

I.2.1. European and Global Strategies for a Sustainable Urban Development

Aware of the relevance of cities for sustainability, the International Community, European Union and local networks have promoted several strategies for sustainable urban development.

I.2.1.1. International level

On a global scale, the analysis of the problems and the research into solutions for the urban environment were the main goals of the 2nd United Nations Conference on Human Settlements (HABITAT II), also called the City Summit, which took place in Istanbul in 1996. The conference addressed two themes of equal global importance: "Adequate shelter for all" and "Sustainable human settlement development in an urbanizing world".

The main political document that came out of the Habitat II conference was the Habitat Agenda, which contains over 100 commitments and 600 recommendations on human settlement issues.

Also the conclusions for the World Summit on Sustainable Development (WSSD) in Johannesburg (2002) pointed out the importance of sustainable management in urban planning, where the economic, social and environmental aspects have to be integrated.

Sustainable Urbanization was the joint message of UN-HABITAT and the Habitat Agenda Partners presented at WSSD. During the conference, a *Coalition for Sustainable Urbanization* (UN-HABITAT 2002) was launched involving over 50 partners and countless local authorities all of whom have joined in partnership to develop a number of joint projects and programmes for strengthening local capacities for sustainable urbanization.

I.2.1.2. European level

On a European level much importance has been given to territorial and urban planning with sustainable criteria. The Green Paper on the Urban Environment (1990) presented for the first time a complete revision and description of the challenges in the field of urban environment and proposed a series of actions on a European level.

As early as 1997 sustainable development became a fundamental objective of the EU when it was included in the Treaty of Amsterdam as an overarching objective of EU policies.

At the Gothenburg Summit in June 2001, EU leaders launched the first EU Sustainable Development Strategy based on a proposal from the European Commission. This 2001 strategy was composed of two main parts. The first proposed objectives and policy measures to tackle a number of key unsustainable trends while the second part, arguably more ambitious, called for a new approach to policy-making that ensures the EU's economic, social and environmental policies mutually reinforce each other.

The Gothenburg declaration formed the core of the EU's policies towards sustainable development. But these also encompassed other programmes and commitments, such as the commitments made at the 2002 World Summit on Sustainable Development in Johannesburg and the Millennium Development Goals agreed in 2000. The EU Sustainable Development Strategy was renewed and approved by the European Council in 2006.

The Thematic Strategy on the Urban Environment (2006) was set to contribute to improving the quality of the urban environment, making cities more attractive and healthier places to live, work and invest in, and reduce the adverse environmental impact of cities on the wider environment, for instance as regards climate change.

The initiatives developed from this moment by the EU and European local authorities within the framework of the sustainable urban management are summarized in Table I.1.

Table I.1. Chronology of European initiatives for a sustainable urban management.

Year	Initiative
1990	The Green Paper on the Urban Environment
1991	Creation of the EU Expert Group on the Urban Environment
1993	Sustainable Cities Project
1994	I European Conference on Sustainable Cities and Towns (Aalborg). Charter of European Cities and Towns towards Sustainability (the Aalborg Charter)
1996	European Sustainable Cities. Report II European Conference on Sustainable Cities and Towns (Lisbon).
1997	Communication from the Commission - Towards an Urban Agenda in the European Union
1998	Communication from the Commission - Sustainable Urban Development in the European Union: A Framework for Action 5th Environment Action Programme (1998-2002)
2000	III European Conference on Sustainable Cities and Towns (Hanover).
2001	Towards More Sustainable Urban Land Use: Advice to the European Commission for Policy and Action. Advisory Report by EU Expert Group on the Urban Environment to the European Commission European Sustainable Development Strategy “A Sustainable Europe for a better world: A European Strategy for Sustainable Development” (Gothenburg Summit) Directive 2001/42/EC of the European Parliament and of the Council on the assessment of the effects of certain plans and programmes on the environment
2002	6th Environment Action Programme (2002-2012) Towards More Integrated Implementation Of Environmental Legislation In Urban Areas. Advisory Report by EU Expert Group on the Urban Environment to the European Commission
2003	European Common Indicators – Development, Refinement, Management and Evaluation Final Report.
2004	IV European Conference on Sustainable Cities and Towns (Aalborg).
2006	Thematic Strategy on the Urban Environment EU Sustainable Development Strategy was renewed and approved by the European Council
2007	V European Conference on Sustainable Cities and Towns (Seville).

I.2.2. Towards a new culture of sustainable urban design

Any neighborhood designed to be correctly integrated with the environmental characteristics of its surroundings will be, for sure, more efficient and sustainable than another that hasn’t been designed taking these criteria into account. In this sense, the design of Eco-Neighborhoods in different geographical locations can have very disparate formal results, due to the different requirements and priorities of each site.

I.2.2.1. Examples of European Eco-Neighborhoods

There are several Eco-Neighborhoods in operation world-wide, and some European cities with Eco-Neighborhood experiences in progress are Sutton (Great Britain), Greenwich Millennium Village (Greenwich, Great Britain), Växjö (Sweden), and the neighborhoods of Vauban and Risefeld (Freiburg, Germany), Sütdstad (Tubingen, Germany), Vesterbo (Copenhagen, Denmark), Eva-Lanxmeer (Culemborg, The Netherlands), Viikki (Helsinki, Finland), Vallbona (Barcelona, Catalonia), etc.

Of these, the two more notorious are the ones in Freiburg (Germany): Risefeld and Vauban. Freiburg is considered the ecological capital of the EU and has become a world-wide reference as a model eco-city. The spirit of the city of Freiburg is brought to the extreme in the neighborhood of Vauban, created in the nineties, four kilometers from the center on the land of an old French military base. All of the houses have been built using low energy consumption criteria and have solar panels. Moreover, there are about one hundred “passive houses”, i.e., that produce more energy than what they consume.

80% of the water comes from rain harvesting, and there is a pilot program for reusing the wastewater from the houses in a bio-gas plant, together with the organic solid wastes. The neighborhood gives priority to pedestrians, and there are three times less vehicles than in the rest of the city. In addition, those citizens who have a car have compromised by leaving it parked on the outskirts of the neighborhood. In the internal streets the speed limit is 5 km/h, and to help the residents live without cars, the basic services (schools, market, shopping center...) are guaranteed to be easily accessible on foot or bicycle.

Vauban also has a carsharing service, with five cars that the residents can use without the need of having owning them. Those who have committed to life without cars receive annual passes for the tram that connects them with the city center, which is also connected through a bicycle lane with Vauban. In the case of Risefeld the planning forced a reduction in energy consumption between 40 and 60% with respect to conventional buildings; to regenerate wastewater in order to reuse it as to reload aquifers and the limitation of vehicle speed to 30 km/h.

The case of Växjö (Sweden) is also remarkable since it has become one of the centers of reference in the implantation of renewable energies. Right now renewable energy already covers more than one third of the city’s needs, and the plan is to reach 50% by 2010.

In the city of Växjö, emissions decreased by 32% per capita from 1993 to 2007. And in parallel the economy of the city has increased by 50% over the same period. One of the keys for this drastic reduction in CO_2 emissions has been the change in the heating system. At the moment 90% of the thermal energy is obtained from certified biomass obtained in a close controlled exploitation. The use of fossil fuels has been limited to vehicles. However, the use of biodiesel is increasing and citizens are encouraged to buy low emission vehicles.

More than a third of the electricity consumed in the city of Växjö comes from local plants that use renewable energy sources, like the above mentioned biomass, but also biogas -produced in the same city- and wind and solar energy, with collectors in the roofs of the public buildings. Efforts have focused not only on substituting some of the most polluting sources with other more respectful types, but also on reducing the total energy consumption. Some strategies that have been implemented are energy efficiency in the public lighting, energy efficiency requirements for new buildings, or the creation of more lanes for bicycles, more itineraries for the public transport system and a fleet of carsharing with a free parking lot.

I.3. INDUSTRIAL ECOLOGY

Duchin and Hertwich (2003) made a concise and clarifying description and historical review of Industrial Ecology for the *Ecological Economics Encyclopedia*, in which they described Industrial Ecology as a young field, with intellectual roots in engineering and management. Industrial Ecology is mainly concerned with tracking flows and stocks of substances and materials, especially those whose cycles are heavily influenced by industrial activities, as a basis for reducing the impact of the production process on the environment.

Although the term Industrial Ecology is relatively recent, the concept of assimilating industrial ecosystems with natural ones was already used in the 19th century (Fischer-Kowalski 1998, Fischer-Kowalski and Hüttler 1999). In 1969, Ayres and Kneese (1969) using a related but different biological metaphor, came to call the precursor of Industrial Ecology “industrial metabolism”. The metabolism of the industrial system would be described through detailed “material balances,” which could be compiled for a production unit, such as a factory, or a geographic unit as small as a village or as large as a continent.

Industrial Ecology, however, goes further and not only aspires to describe the material and energy flows but also seeks to understand how the industrial society works and what its interrelations with the biosphere are, in order to make them compatible.

According to Duchin and Hertwich (2003) the name “Industrial Ecology” emerged independently in several places. Probably the first use of the term was by Japanese research and planning groups studying how to reduce their country’s dependence on resources (Watanabe 1972). The term was next used in the title of a Belgian study of national energy and material flows (Billen et al. 1983) and in a manual on cleaner production and material cycling by a German industrialist (Winter 1988). Industrial Ecology was introduced in the Anglo-Saxon countries through an article by Robert Frosch and Nicholas Gallopoulos, “Strategies for Manufacturing” (Frosch and Gallopoulos 1989), that appeared in a special issue of Scientific American devoted to Managing Planet Earth and can be said to have launched the field. The authors argued that environmental constraints require new ways of thinking about industrial production. According to the old conception, the production process absorbs inputs from the environment, transforms them into both useful products and waste, and then discharges the waste. However, current levels of population and affluence have put substantial pressure on the environment. Even more worrisome for the environment, according to this argument, is the fact that the populations of the developing countries are still growing and have every reason to aspire to the material standards of living of the rich countries. In order to meet these future demands without unacceptable environmental damage, the authors concluded that decision makers in industry need to “mimic” in their production facilities the operation of ecosystems in nature that generate no waste because of intricate channels for reusing residuals.

The field of Industrial Ecology was officially established at a meeting at the National Academy of Engineering in 1992 with support from the AT&T Foundation (now the Lucent Foundation). The first issue of the Journal for Industrial Ecology appeared in 1997, and Gordon Research

Conferences in Industrial Ecology have taken place every other year since the first in 1998. The International Society for Industrial Ecology (ISIE) was announced in 2001 (Ehrenfeld 2002). The first International Conference in Industrial Ecology was held in Leiden, the Netherlands, in the same year, following Ann Arbor (2003), Stockholm (2005), Toronto (2007) and Lisbon (2009). In parallel with these events, a growing number of university departments offer courses directly related to Industrial Ecology, especially in North America, Europe and Asia.

According to the ISIE (2009) Industrial Ecology provides a powerful prism through which to examine the impact of industry and technology and associated changes in society and the economy on the biophysical environment. It examines local, regional and global uses and flows of materials and energy in products, processes, industrial sectors and economies and focuses on the potential role of industry in reducing environmental burdens throughout the product life cycle.

Industrial Ecology asks us to understand how the industrial system works, how it is regulated, and its interaction with the biosphere; then, on the basis of what we know about ecosystems, to determine how it could be restructured to make it compatible with the way natural ecosystems function (Erkman 1997).

I.3.1. Areas of research in Industrial Ecology

The field encompasses a variety of related areas of research and practice, including (ISIE, 2009):

- material and energy flow studies ("industrial metabolism").
- dematerialization and decarbonization.
- technological change and the environment.
- life-cycle planning, design and assessment.
- design for the environment ("eco-design").
- extended producer responsibility ("product stewardship").
- eco-industrial parks ("industrial symbiosis").
- product-oriented environmental policy.
- eco-efficiency.

This thesis has gone into most of these issues, although in different depth.

If achieving sustainability has to be a global and common goal, it is necessary to apply the Industrial Ecology concepts on different scales. Not only will the processes have to be optimized, but using the appropriate tools, the whole system will have to be analyzed and optimized as a whole. Some of systems analyzed and tools used by Industrial Ecology are summarized in Table I.2.

Table I.2. Systems analyzed and tools used in Industrial Ecology projects.

System	Tools
Product	Life Cycle Assessment (LCA), ecodesign
Process	Design for Environment (DfE), cleaner production, use of by-products
Industry	Environmental Management Systems (EMS) such as ISO or EMAS
Industrial estate	industrial symbiosis, analysis of material and energy flows
City or region	analysis of material and energy flows

This thesis brings an innovative perspective to Industrial Ecology by extending the analysis of product systems to civil works in the urban environment, and including service estates in urban areas within the scope of Industrial Ecology.

I.3.2. Industrial Ecology tools relevant for this thesis

To fulfill the goals of sustainability, several tools to support decision-making have been developed. The following sections explain the three most relevant ones for this thesis.

I.3.2.1. Life Cycle Assessment (LCA)

LCA is the area that accounts for the largest number of articles in the *Journal of Industrial Ecology*, the most sessions at professional meetings (Duchin and Hertwich 2003) and the *International Journal of Life Cycle Assessment* is devoted exclusively to this tool. With its origins in engineering and much of its practice associated with industrial consulting, LCA's objective is to quantify the environmental burden imposed by an industrial product or process. This involves measuring or estimating the material and energy inputs and releases to the environment associated with the product at all stages from the extraction and processing of inputs through the use and eventual disposal of the product.

The principal professional society for LCA is the Society for Environmental Toxicology and Chemistry (SETAC) (Consoli et al. 1993), which defined LCA as:

"Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal" (SETAC 1993)

The ISIE has also become a professional home for this kind of work, with its ties both to materials and energy use on the one hand and to decision-making processes on the other.

The scientific community has developed classifications, conventions and definitions, standards, shared software and shared databases for carrying out its work both in research settings and through consulting industry and governments, clients who require standardization of assumptions and methods. To achieve this, the scientific community has worked closely with the International Organization for Standardization (ISO), a network of worldwide institutions that develops common technical specifications, to produce standards (such as ISO 14,040 to 14,049) that define LCA, including environmental management standards, and environmental labels and claims (ISO 14,023).

In 1993 the ISO Technical Committee 207 started working on the development of international standards of LCA leading to the non certifiable 14,04X series:

- *ISO 14,040:1997 Environmental Management – Life Cycle Assessment – Principles and Framework.*
- *ISO 14,041:1998 Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis.*
- *ISO 14,042:2000 Environmental Management – Life Cycle Assessment – Life Cycle Assessment.*
- *ISO 14,043.2000 Environmental Management – Life Cycle Assessment – Life Cycle Interpretation.*
- *ISO/TR 14,047:2003 Environmental Management – Life Cycle Assessment – Examples of application ISO 14042.*
- *ISO/TR 14,049:2000 Environmental Management – Life Cycle Assessment – Examples of Application of ISO 14041 to goal and scope definition and inventory analysis.*

More recently, in 2006, 14,04X series were updated to improve the readability, while leaving the requirements and technical content unaffected, except for errors and inconsistencies.

- *ISO 14,040:2006 Environmental Management – Life Cycle Assessment – Principles and Framework* provides a clear overview of the practice, application and limitations of LCA to a broad range of potential uses and stakeholders, including those with a limited knowledge of life cycle assessment.
- *ISO 14,044:2006 Environmental Management – Life Cycle Assessment – Requirements and guidelines*, is designed for the preparation of, conduct of, and critical review of, life cycle inventory analysis. It also provides guidance on the impact assessment phase of LCA and on the interpretation of LCA results, as well as the nature and quality of the data collected.

ISO 14,040:2006 and ISO 14,044:2006 replace the previous standards (ISO 14,040:1997, ISO 14,014:1999, ISO 14,042:2000 and ISO 14,043:2000). The new standards were developed by the technical committee ISO/TC 207, Environmental management, subcommittee SC5, Life cycle assessment.

Thus defined, the standard practice of LCA includes four steps (Figure I.3): definition of the goal and scope of a project, inventory analysis to identify and quantify inputs and outputs at every stage of the life cycle, assessment of the impact of these inputs and outputs, and interpretation of the significance of impacts (Guinée et al. 2001). These phases are not followed just one after the other. It is an iterative process, which can be followed in different rounds achieving increasing levels of detail (from screening LCA to full LCA), or which may lead to changes in the first phase because of the results of the last phase.

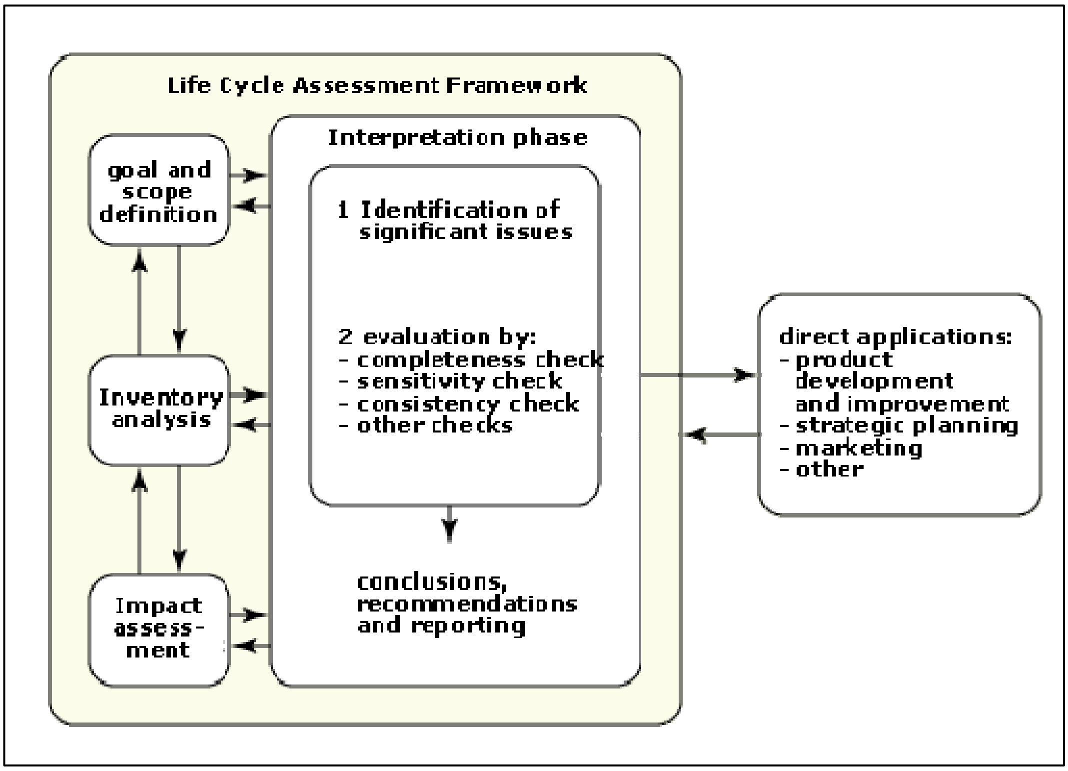


Figure I.3. Phases of an LCA study (ISO 14,040:2006).

Despite this high degree of formal standardization, there is still a great deal of discretion in decisions regarding the modeling of the input inventory and the impact assessment. A recently launched collaboration between SETAC and the United Nations Environment Programme (UNEP) is the UNEP/SETAC Life Cycle Initiative (2003) intended to further develop life cycle analysis and expand its use.

An LCA aims to characterize the environmental impact of actual or hypothetical products as a basis for comparing them. It quantifies the environmental stressors, such as emissions and resource use, associated with a "functional unit" of product. An LCA is commonly conducted on the basis of average process characteristics (rather than marginal ones) and hence assumes a set of linear relations between amount of product and impact.

Fundamental challenges faced in an LCA are delimiting the system's boundary for the particular product and identifying all environmentally significant production processes. It has been estimated that process chain analysis, which identifies direct inputs and outputs only, accounts for about half of the product's impact, while the other half is distributed among a large number of individually insignificant upstream processes (Lave et al. 1995; Lenzen 2001).

The challenge in the impact assessment step is to evaluate the significance of hundreds of inventory items in terms of a small number of indicators (Hertwich et al. 1997). Environmental stressors may be aggregated to impact categories such as climate change, ozone depletion, human toxicity, ecosystem toxicity, and biotic resource depletion. Alternatively, impact can be reported in terms of damage categories, such as years of life lost due to cancer or an estimate of the monetary cost of damage (Steen and Ryding 1991).

An extensive literature reflects a lively debate on methodological issues. However, unlike a cost-benefit analysis, LCA results are usually not reduced to a single figure, which avoids problem-shifting from one impact category to another.

I.3.2.2. Energy Flow Accounting (EFA)

The Material and Energy Flow Accounting (MEFA) framework is a tool to empirically analyse important aspects of the interaction process between nature and culture in a way that can link socioeconomic dynamics (e.g. monetary flows, lifestyles or time allocation) to biophysical socio-economic stocks and flows and these, in turn, to ecosystem processes (Haberl et al. 2004).

The EFA is part of the MEFA framework, together with Material Flow Accounting (MFA), which has received most attention (e.g. Eurostat 2001, Eurostat 2002, Matthews et al. 2000), and the Human Appropriation of Net Primary Production (HANPP) (Vitousek et al. 1986).

EFA can be derived from energy statistics supplemented by agricultural and forestry data (Haberl 2001a) and can be applied to supra-national entities such as the European Union (Eurostat 2002) or to sub national entities such as economic sectors (Schandl and Zangerl-Weisz 1997), cities or regions (Brunner et al. 1994).

Energy flow accounts consistent with current MFA standards have been established on the national level for Austria from 1830 to 1995 (Krausmann and Haberl 2002) and on the village level for both contemporary and historical agricultural societies (Grünbühel et al. 2003; Haberl 2001b; Krausmann 2004).

I.3.2.3. Ecodesign

Ecodesign can be defined as "the ensemble of actions intended to improve a product with respect to the environment in its initial design stages by improving its function, selecting less harmful materials, applying alternative processes, improving transport and use and minimizing environmental impact during the final stages of treatment." (Rieradevall 2007)

Ecodesign is a new approach to product and process design. It is based on identifying environmental aspects connected with the product life cycle and includes these aspects in the design process at the early stage of product development. Environmental aspects are taken into account on the same level as other essential aspects such as function, safety, ergonomics, endurance, quality and costs. The additional criterion is a projected estimation based on environmental influence.

The multidisciplinary and integrative approach required by ecodesign processes is fulfilled by the joint work of scientists and designers.

Concerning urban systems, a sustainable development for cities ensures basic environmental, social and economic services for all members of the community without endangering the viability of the natural, artificial and social surroundings they depend on, by reducing resource consumption and emissions in conditions of equality and social welfare. Ecodesign presents itself as one of the key tools in the move towards a more sustainable city. Within urban systems, one of the most important subsystems is public space. A lot of effort has been put into improving the environmental performance of buildings, but still very little research has focused on the ecodesign of public space, which may represent about 30% of the total urban surface.

I.4. ISO STANDARDS OF SUSTAINABILITY IN CONSTRUCTION

SosteniPrA researchers are expert members of ISO/TC 59/SC 17/WG 5, and contribute to the definition of sustainability indicators for civil engineering works on an international level. This participation is an effective method of transferring knowledge from basic research to society.

ISO (derived from the Greek *isos*, meaning "equal"), is the world largest standards developing organization composed of representatives from 157 national standards bodies (ISO 2009a).

ISO was born from the union of two organizations - the ISA (International Federation of the National Standardizing Associations), established in New York in 1926, and the UNSCC (United Nations Standards Coordinating Committee), established in 1944.

In October 1946, delegates from 25 countries, meeting at the Institute of Civil Engineers in London, decided to create a new international organization, of which the object would be "to facilitate the international coordination and unification of industrial standards". The new organization, ISO, officially began operations on 23 February 1947. Since then, ISO has published more than 16,500 International Standards (ISO 2009b).

I.4.1. Documentation generated by ISO and processes for their elaboration

International Standards (IS)

IS are identified in the format *ISO[/IEC][/ASTM] [IS] nnnnn[:yyyy] Title*, where *nnnnn* is the number of the standard, *yyyy* is the year published, and *Title* describes the subject. *IEC* for *International Electrotechnical Commission* is included if the standard results from the work of ISO/IEC JTC1 (the ISO/IEC Joint Technical Committee). *ASTM* is used for standards developed in cooperation with ASTM International. The date and *IS* are not used for an incomplete or unpublished standard, and may under some circumstances be left out of the title of a published work (ISO/IEC 2004, 2008). Table I.3 shows the figures for international standards for the year 2008.

Table I.3. ISO work items and international standards in figures for the year 2008 (on 31 December).

Sectors as based on the International Classification for Standards (ICS)	Work items* on 31 December 2008		International Standards on 31 December 2008	
	Number	%	Number	%
Generalities, infrastructures and sciences	421	11	1,544	9
Health, safety and environment	194	5	699	4
Engineering technologies	974	26	4,829	27
Electronics, information technology and telecommunications	737	20	2,990	17
Transport and distribution of goods	325	9	1,896	11
Agriculture and food technology	145	4	1,023	6
Material technologies	769	21	4,264	24
Construction	141	4	376	2
Special technologies	42	1	144	1
TOTAL	**3,748**	**100**	**17,765**	**100**

* Work in progress in 2008
Source: ISO (2009a)

Besides International Standards, ISO also publishes Technical Reports, Technical Specifications, Publicly Available Specifications, Technical Corrigenda, and Guides. Figure I.4 links the ISO deliverables with the steps of Standards development.

Technical Reports (TR)

TR are issued when a technical committee or subcommittee has collected data of a different kind from that which is normally published as an International Standard (ISO/IEC 2004, 2008) such as references and explanations. The naming conventions for these are the same as for standards, except for the use of *TR* instead of *IS* in the report's name.

Technical Specifications (TS)

These can be produced when there are future possibilities of agreement on an International Standard, but for which at present (ISO/IEC 2004, 2008):

- the required support for approval as an International Standard cannot be obtained,
- there is doubt on whether consensus has been achieved,
- the subject matter is still under technical development, or
- there is another reason precluding immediate publication as an International Standard

Publicly Available Specifications (PAS)

PAS are documents that respond to an urgent market need, representing either (ISO/IEC 2004, 2008):

- a consensus in an organization external to ISO or IEC, or
- a consensus of the experts within a working group

Publicly Available Specifications are named by a similar convention to Technical Reports, using *PAS* instead of *TR*.

Technical Corrigendum

These are amendments to existing standards because of minor technical flaws, usability improvements, or that intend to extend applicability in a limited way (ISO/IEC 2008).

ISO Guides

These documents give rules, orientation, advice or recommendations relating to international standardization (ISO/IEC 2004). They are named in the format *"ISO[/IEC] Guide N:yyyy: Title"*.

Additional information on ISO deliverables can be found on the ISO website (ISO 2009c).

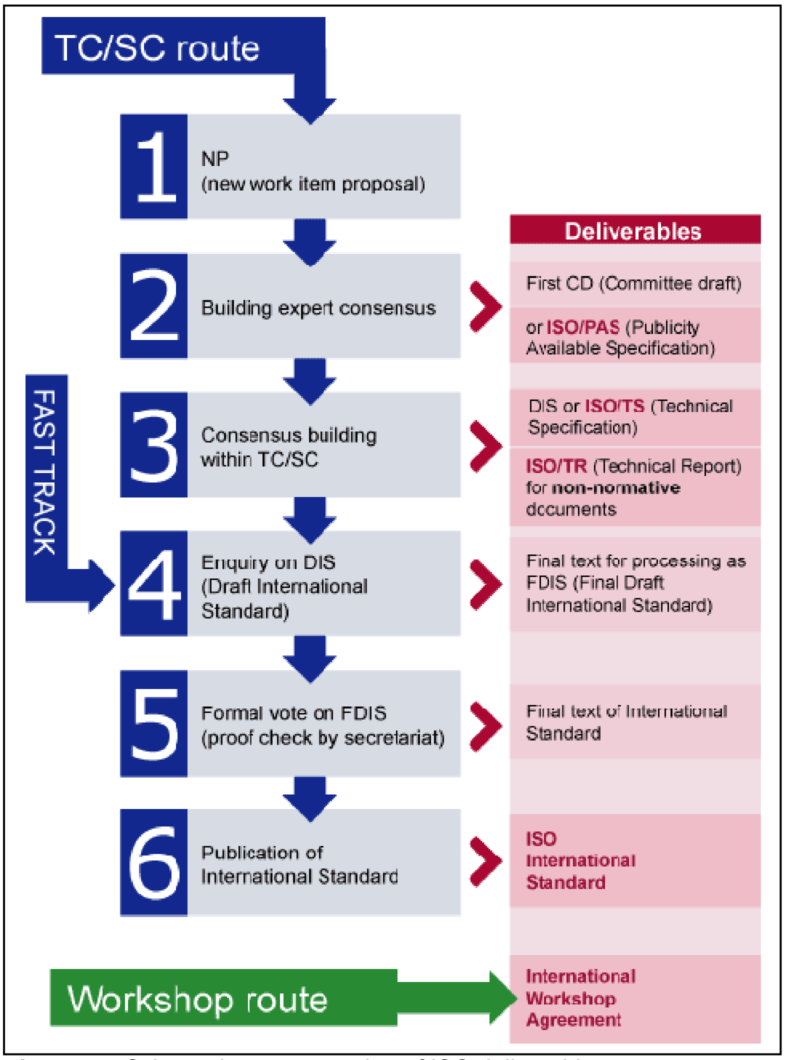


Figure I.4. Schematic representation of ISO deliverables.
Source: ISO (2009c)

The development of ISO Standards follows a regulated process described in sections I.4.1.1 and I.4.1.2, according to ISO guidelines (2009d).

I.4.1.1. Who develops ISO standards?

ISO standards are developed by technical committees, (subcommittees or project committees) (see Figure I.5 for an example of ISO/TC 207 structure) comprising experts from the industrial, technical and business sectors which have asked for the standards, and which subsequently put them to use. These experts may be joined by representatives of government agencies, testing laboratories, consumer associations, non-governmental organizations and academic circles.

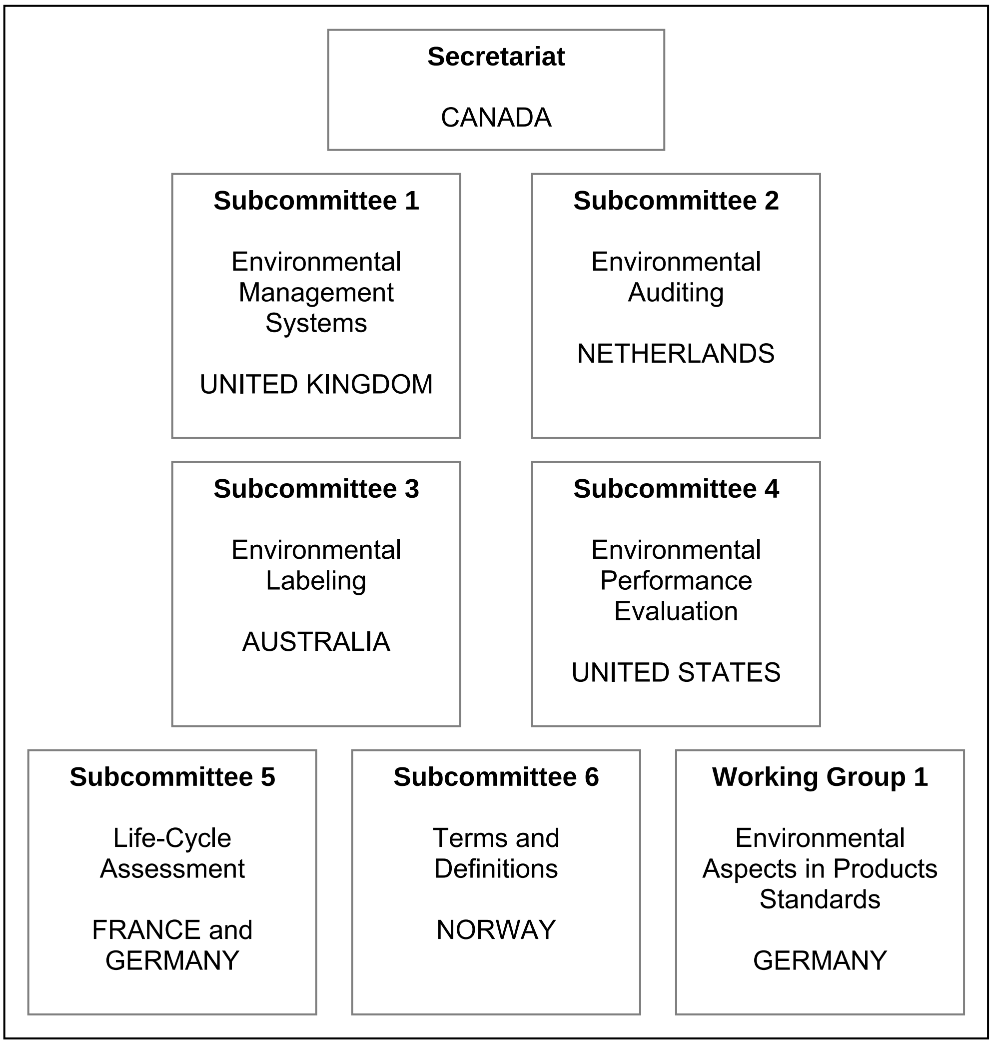


Figure I.5. ISO/TC 207 Environmental Management Structure.
Source: Cascio et al. (1996)

Proposals to establish new technical committees are submitted to all ISO national member bodies, who may opt to be participating, observer or non-members of the committee. The secretariat (i.e. the body providing the administrative support to the work of the committee) is allocated by the Technical Management Board (which itself reports to the ISO Council), usually to the ISO member body which made the proposal. The secretariat is responsible for nominating an individual to act as chair of the technical committee. The chair is formally appointed by the Technical Management Board.

Experts participate as national delegations, chosen by the ISO national member body for the country concerned. National delegations are required to represent not just the views of the organizations in which their participating experts work, but those of other stakeholders too. National delegations are usually based on and supported by national mirror committees to which the delegations report.

According to ISO rules, the national member body is expected to take account of the views of all parties interested in the standard under development. This enables them to present a consolidated, national consensus position to the technical committee.

International and regional organizations from both the business and the public sector may apply for liaison status to participate in developing a standard, or to be informed about the work. Such "organizations in liaisons" are accepted through voting by the relevant ISO committee. They may comment on successive drafts, propose new work items or even propose documents for "fast tracking", but they have no voting rights.

I.4.1.2. How ISO standards are developed

ISO launches the development of new standards in response to sectors and stakeholders that express a clearly established need for them.

An industry sector or other stakeholder group typically communicates its requirement for a standard to one of ISO's national members. The latter then proposes the new work item to the relevant ISO technical committee developing standards in that area. New work items may also be proposed by organizations in liaison with such committees. When work items do not relate to existing committees, proposals may also be made by ISO members to set up new technical committees to cover new fields of activity.

The national delegations of experts of a committee meet to discuss, debate and argue until they reach a consensus on a draft agreement. The "organizations in liaison" also take part in this work. In some cases, advanced work within these organizations means that substantial technical development and debate has already occurred, leading to some international recognition and in this case, a document may be submitted for "fast-track" processing. In both cases, the resulting document is circulated as a Draft International Standard (DIS) to all the ISO's member bodies for voting and comment.

If the voting is in favor, the document, with eventual modifications, is circulated to the ISO members as a Final Draft International Standard (FDIS). If that vote is positive, the document is then published as an International Standard.

For a document to be accepted as an ISO International Standard, it must be approved by at least two-thirds of the ISO national members that participated in its development and not be disapproved by more than a quarter of all ISO members who vote on it.

I.4.2. Environmental Management Standards

ISO's portfolio of generic management systems standards was extended beyond quality during the 1990s after the United Nations Conference on Environment and Development (UNCED), also known as the Earth Summit, held in Rio de Janeiro in 1992.

The focus on environmental standards intensified in the preparatory period leading up to the Earth Summit, in which ISO and its partner IEC became directly involved. UNCED wanted to ensure that business was fully engaged in the process.

However, environmental concerns were not new in ISO. For example, ISO technical committees developing standards for air and water quality were established in 1971.

In August 1991, ISO and IEC formally established the Strategic Advisory Group on the Environment (SAGE) to study the situation and make recommendations. The SAGE process had two major end products:

1. a series of ISO/IEC recommendations on environmental management, which were submitted to the UNCED preparatory conference in January 1992; and
2. in October 1992, a recommendation to create a new ISO technical committee to develop standards in the area of environmental management.

The second recommendation led to the creation in 1993 of ISO/TC 207, *Environmental management*, which held its inaugural plenary session in Toronto in June of 1993. Its first standard, ISO 14,001, *Environmental management systems - Specification with guidance for use* was published in 1996.

In its scope of work for TC 207, the Technical Management Board integrated a key concept from ISO 9,000 quality management standards. That concept was that management standards were process standards and, as such, were not to specify end goals (Cascio et al. 1996).

I.4.3. ISO/TC 59/SC 17 Building Construction / Sustainability in building construction

There is an increasing demand, in both the private and public sectors, to understand sustainable construction practices, because their implementation improves the environment and economic aspects and the social relationships with the different stakeholders involved in the process, such as administrations, private developers or citizens.

Besides, there is a need for a standard to guide on the application of the existing ISO 14,000 standards to infrastructures. This interest also applies to civil engineering works, a sector that has reached enough maturity to develop more specific indicators and assessment methods.

The work to develop such a guide has been going on since 2002 within the subcommittee ISO/TC 59/SC17, which in turn is divided into five working groups (WG) (Table I.4).

Table I.4. Working groups of the TC 59/SC 17.

Subcommittee/Working Group	Title
TC 59/SC 17/WG 1	General principles and terminology
TC 59/SC 17/WG 2	Sustainability indicators
TC 59/SC 17/WG 3	Environmental declaration of products
TC 59/SC 17/WG 4	Environmental performance of buildings
TC 59/SC 17/WG 5	Civil engineering works

Source: ISO (2009e)

The subcommittee ISO/TC 59/SC 17, with 19 participating countries and 10 observing countries, acknowledged at the 5th plenary meeting held from 8th to 12th October 2007 in Seoul that there was a need for new work to be initiated within the SC focusing on the sustainability of civil engineering works. It also agreed to form the WG5 with the appointment of Mr. Antonio Burgueño as convener and with secretarial support from AENOR (the Spanish standardization organization).

This working group seeks to develop guidance for using and defining sustainability indicators and applying sustainability assessment methods for civil engineering works as defined in ISO 6707-1:2004 *Building and civil engineering -- Vocabulary -- Part 1: General terms*.

The specific objectives for ISO/TC 59/SC 17/WG 5 are:

- Analysis of the existent documents provided by SC 17.
- Contribution to the works related to preparing a document on guidelines for the application of the General Principles on sustainability described in ISO/FDIS 15392, primarily led by WG1.
- Contribution to the formulation of the general framework of sustainability indicators, task which is to be led primarily by the WG2.
- Development of a core set of sustainability indicators for civil engineering works.
- Analysis of existing environmental assessment methods and criteria applicable to civil engineering works, from the sustainability point of view.
- Contribution to the formulation of the general framework for methods of assessment for environmental performance of construction works.

I.4.4. AEN/CTN/198 Sustainability in Construction

The AENOR Standing Committee approved in 2008 the setting-up of the work group AEN/CTN198 *Sustainability in Construction*. At the inaugural meeting of the committee, held in Madrid on 28th February 2008 it was agreed to set up three sub-committees (Table I.5), in turn divided into working groups.

Table I.5. Subcommittees for AEN/CTN/198.

Subcommittee	Title	Comment
AEN/CTN198/SC1	Building construction	-
AEN/CTN198/SC2	Civil engineering works	This SC acts as a “mirror” and leader for ISO/TC 59/SC 17/WG 5
AEN/CTN198/SC3	Materials and products	-

AEN/CTN198/SC2 is chaired by Mr. Antonio Burgueño, and acts as a reference and leader for ISO/TC 59/SC 17/WG 5. The main focus of the debate in this group since its creation has been the development of a core set of sustainability indicators for civil engineering works.

SosteniPrA researchers are members of AEN/CTN/198 and regular participants at AEN/CTN198/SC2 meetings. In addition, I have coordinated since December 2008 the AEN/CTN198/SC2/WG2 on sustainability indicators for civil engineering works.

I.5. JUSTIFICATION AND OBJECTIVES

I.5.1. Justification

Sendra (2008) calculated through MFA that 60% of the total Catalan Domestic Material Consumption (DMC) for the year 2001 was attributable to the construction sector. This sector accounts for 55 million tonnes per year, 59% of which is used in civil works and 41% in building construction.

In addition, construction is a key strategic sector in the Spanish economy. In 2006, Gross Added Value represented 10.9% of GDP, 13.9% of employment and 58.7% of investment. 448,446 companies (14% of the total number of companies), of these, 500 with over 199 workers were working in the sector. The total population employed in construction was 2,542,900 with an estimated turnover of 173,508 million Euros (ANCOP-SEOPAN 2007).

Despite the extraordinary relevance of civil works to the material and economic flows, very little research has been done to foster their environmental optimization.

The newly developed urban patterns and Eco-Neighborhoods center their efforts on reducing energy consumption in the use stages in the residential and mobility spheres. However, this dissertation focuses on the study, from an Industrial Ecology perspective, of strategies for optimizing the metabolism of the service sector and the inclusion of environmental criteria in the design and selection of materials and processes used by urban infrastructures in the public space of cities. Both are subsystems that have yet to receive the scientific attention they deserve.

The analysis of the metabolism and environmental impact of complex systems, like cities, is fairly new. This analysis requires the use of solid disciplines and quantitative tools that provide the deepest approach and make fewer assumptions, as in the case of the service sector and urban infrastructures small errors may have a multiplying effect.

Industrial Ecology as a discipline and the tool of LCA, sometimes coupled with MEFA, are suitable for the environmental analysis of urban systems. However, their application is still at an initial stage.

An illustrative exercise for analyzing the state of the art has been carried out using the *ISI Web of Knowledge* search engine (ISI Web of Knowledge 2009). According to the results found in the *ISI Web of Knowledge* for each combination of key words (Table I.6), it can be concluded that the number of papers that use the LCA approach to study products and processes is one order of magnitude greater than those papers studying cities, urban areas or infrastructures with the same approach. Therefore, it can be understood that LCA is still a fairly new tool in urban topics.

Table I.6. Results found in the *ISI Web of Knowledge* for each combination of key words. Lifecycle, Life-cycle and LCA are different ways of explaining the same concept proposed by different authors. The % columns are a normalization referred to the highest value.

Key words		Title only	%	Title, abstract and key words	%
Lifecycle or Life-cycle or LCA	Product	252	100.0	2,851	64.5
	Process	115	45.6	4,422	100.0
	Urban	24	9.5	358	8.1
	City	15	6.0	285	6.4
	Infrastructure	10	4.0	301	6.8

There is an urgent need for the integration of quantitative environmental data in urban planning processes. The results obtained in this thesis, provided by the application of EFA and LCA to urban systems, may be of interest to energy companies and civil engineers in charge of designing and building urban infrastructures and managing service facilities, as well as to public officials and decision makers trying to integrate environmental criteria in the municipal planning processes of new and existing neighborhoods.

I.5.2. Objectives

I.5.2.1. General objectives

The main objective of this thesis is to prove that Industrial Ecology, with its systemic perspective, methodologies and tools is a suitable discipline for the environmental analysis of urban subsystems such as service facilities, sidewalks and energy distribution networks.

Other general objectives are:

- Open new research fields in Industrial Ecology: the service sector
- Demonstrate that it is possible and useful to apply LCA to quantify the environmental impact of infrastructures in the public space of cities and underground distribution networks.
- Provide quantitative and objective environmental inventories to facilitate decision making and green public investment in urban planning processes.
- Quantify the potential environmental impact of civil works in the public space of cities, such as standard neighborhood and in-house distribution networks and concrete sidewalks.
- Transfer ecodesign methodology to larger scales in order to improve cities from an environmental perspective.
- Propose strategies for a reduction in absolute values of the environmental impact of cities.
- Extend the application of LCA to complex urban systems, solving the consequent barriers to which ISO 14,04X series subject the definition of a functional unit.

I.5.2.2. Specific objectives

Buildings - Service sector in cities

- Quantify the energy demand and greenhouse gas emissions of different service facilities.

Public space - Concrete sidewalks

- Quantify the potential environmental impacts of the three most common types of concrete-based sidewalks to identify which type is environmentally preferable based on certain functionality
- Assess the potential environmental savings to be gained from matching each type of sidewalk use to the specific functionality that it fulfills.
- Provide environmentally oriented design strategies for the future eco-redesign of the public space of cities.

Infrastructures - Energy distribution networks

- Compile an inventory of materials and processes.
- Identify which subsystems and elements from the analyzed infrastructures are the most environmentally relevant
- Determine whether building density is a determining factor for the environmental impact per dwelling in a natural gas distribution network.
- Propose strategies for the ecodesign of urban infrastructures for the distribution of energy.
- Put the impact of a district's heating and natural gas infrastructures into perspective.

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CHAPTER II

SERVICE SECTOR METABOLISM

ACCOUNTING FOR ENERGY IMPACTS OF THE MONTJUÏC URBAN PARK IN BARCELONA

Oliver-Solà J, Nuñez M, Gabarrell X, Boada M, Rieradevall J (2007) Service sector metabolism: accounting for energy impacts of the Montjuïc urban park in Barcelona. Journal of Industrial Ecology 11(2): 83-98.

ABSTRACT

This chapter evaluates, from an industrial ecology perspective, the energy performance of the services inside an urban system and determines their global environmental impact. Additionally, this study determines which are the most energy demanding services and the efficiency of their energy use per visitor and per surface area unit.

The urban system under study is the Montjuïc urban park in Barcelona, Catalonia, Spain, which can be considered a services system. In this case study we distinguished the different patterns of consumption among the service fields and, by studying each field individually, found the most efficient facilities and identified the most critical services based on energy use per visitor or per square meter. These findings are based on the use of EFA, LCA, and the energy footprint to analyze the Park's technical energy consumption.

Electricity consumption represents nearly 70% of the total energy consumed by the services at Montjuïc Park. The forest surface area required to absorb the CO_2-equivalent emissions produced by the life cycle of the energy consumed at Montjuïc Park represents 12.2 times the Park's surface area. We conclude this chapter by proposing the incorporation of the methods of industrial ecology within the study of parks containing multiple services to improve energy management, and as a result, to raise the global environmental performance of the service sector.

II.1. INTRODUCTION

The study of anthropogenic systems and their physical flows provides information about system metabolism and the associated environmental costs (Rueda et al. 1998). This approach, adopted by the Urban Ecology and Industrial Ecology disciplines, has proved to be fruitful for conceptualizing the relationship between societies and their natural environments (Haberl 2001a, 2001b). By analogy with the biological notion of metabolism, this approach is used to analyze physical exchange processes (material and energy flows) between human societies and their natural environments, as well as the internal material and energy flows of human societies (Ayres and Simonis 1994; Fischer-Kowalski 1998).

Odum (1989) argues that ecological concepts can be used as a guide for human systems design and functioning. Decker and colleagues (2000) point to industrial metabolism (Ayres and Simonis 1994), Industrial Ecology (Socolow et al. 1994), and regional metabolism (Baccini 1996) as other nomenclature given to the energy and material accounting of human activities.

The metabolic perspective considers industry, or cities, from the point of view of traditional ecology, but instead of studying natural ecosystems, the fields of study are the industrial and urban ecosystems, considering these as systems integrated in the biosphere. This stands in contrast with the tendency to consider humankind and our habitats separate from the surrounding natural environments (Naredo and Carpintero 2003).

Over the past 30 years, there has been significant concern about the environmental impact of the industrial sector, whereas very little attention has been given to the service sector. In part, this occurred because of the change in the character and composition of industrial economies that took place during the 1980s and 1990s, whereby the service sector has come to represent between 60 and 70% of the GDP of such economies (Carpintero 2003).The dominant types of service-related activities have appeared to require less energy and fewer materials than industry and agriculture (Heiskanen and Jalas 2000). This disconnection of economic growth from natural resource use has been referred to as “delinking” (Carpintero 2003) or decoupling (van der Voet et al. 2005).

Authors such as Jänicke and colleagues (1989) and De Bruyn and Opschoor (1997) defend the argument that the relatively *weak* signs of dematerialization and the delinking of economic growth and the use of natural resources in developed countries came to an end in the late 1980s, and were followed by instances of *strong* rematerialization during the 1990s.These findings provide matter for discussion regarding the real chances for dematerialization in the service sector and the achievement of sustainable development. These findings likewise support the concept that the provision of certain commercial, financial, and social services requires infrastructure to sustain them properly. Consequently, like industry, the service sector also owns and needs an important material base with which to operate (Carpintero 2003).

In the mid-1990s, Jespersen (1994) explored, through input-output tables, the energetic intensity of more than 100 economic sectors, including those sectors belonging to heavy industry and those related to the service sector, and reached the following conclusion: The equivalent of 1 million euros of GDP from the private service sector—including hotels, trade, and transportation—required nearly the same energy intensity as the industrial sector (6.9 terajoules [TJ] compared with 8.4 TJ). Furthermore, a notable relationship between industry and services must be taken into account, as many industrial activities have fed the growth of service companies by outsourcing part of the work that industrial entities had traditionally performed for themselves, such as accounting, consulting, and computing (Carpintero 2005).

Some types of services exhibit a higher degree of dematerialization than do others. By applying MFA and EFA it is possible to identify the properties that distinguish these different types of services, monitor their consumption, and assess the overall intensity of the service sector in relation to its use of natural resources. Through this process, it becomes clear whether a society has used those services that are less intensive in their consumption of natural resources—promoting dematerialization to some extent or, on the contrary, has experienced growth in the more energetically and materially demanding types of services, thus favoring environmental deterioration.

The tool of LCA has been used to evaluate the global environmental impact of energy consumption in the Montjuïc Park service facilities. Urban systems represent a new area of study wherein LCA can be applied to calculate the environmental impact of such complex systems.

Research on the environmental impact of the service sector is relatively new (for discussion, see Rosenblum et al. 2000; and Suh 2006) and much remains to be explored, in particular, the possible synergies between the various subsectors of the service sector. The energy analysis of multiple service facilities that is proposed in this chapter reveals something that the analysis of each facility on its own would not: that is, the system perspective.

This chapter focuses on the analysis and evaluation of the technical energy flow (energy used in technical equipment for providing heat, light, mechanical work, and data processing) of the service facilities of Montjuïc Park—from an Industrial Ecology perspective but applied to the service sector. The chapter also aims to determine the system's global environmental impact and energy footprint, as well as to identify the most energy demanding services and to provide an energy profile for each type of service and its efficiency of energy use per visitor and per surface area unit.

Several significant dimensions are not included in the analysis in this chapter: first, the energy consumed by visitors and workers when traveling to and from Montjuïc Park, although a rough approximation has been made for the energy consumed in transportation of workers and students within the limits of the Park. Second, the effect that the Park might have on reducing the heat island effect in the surrounding neighborhoods is not addressed; this effect has proven to be noticeable in other cities (Ca et al. 1998; Yu and Hien 2006). Third, the energy embodied in the materials in the products, buildings, and other anthropogenic structures in the Park is not calculated. Finally, the energy value of the biomass in the Park is not included, as it is produced and then exported to a composting facility outside the system.

The absence of these analyses does not affect the final goal of this chapter, which focuses on the assessment of the technical energy flow within the limits of the Park and the global environmental impacts of its consumption.

II.2. METHODOLOGY

II.2.1. Study area

The area under study is the Montjuïc urban park in the southern part of Barcelona (approximate area 450 hectares [ha]). Montjuïc Park includes important sporting facilities (e.g., the "Lluís Companys"[3] Olympic Stadium) and cultural and leisure facilities closely linked to the dynamics of the city of Barcelona. Montjuïc is, in fact, a mountain, 183 meters high; it was first urbanized for the Universal Exhibition in 1929 and later underwent its biggest change when the main sports facilities for the 1992 Olympic Games were located there. Montjuïc Park is an unusual mix of nature and services, as it contains no factories and very few people live inside its administrative limits. Montjuïc Park maintains an outstanding natural heritage along with several other parks, gardens, and free urban spaces that have been naturalized over the years (e.g., old abandoned quarries). At the same time Montjuïc is one of the most visited urban parks in the world with approximately 14.5 million visitors in 2004 (Barcelona City Council Montjuïc Division 2005).

An important determining criterion for the selection of the study area was its high degree of complexity, as it can be considered a system of services. In Montjuïc Park we find the following different types of services: education, schools, and universities; sports, installations for the practice of all kinds of sports; culture, museums, and theaters; an economic, international trade fair center; and leisure activities, parks, gardens, and fountains.

Although Montjuïc Park is a unique space in Barcelona, there are many other urban parks around the world with very similar characteristics (e.g., Ekoparken, Stockholm; Central Park, New York City; El Retiro, Madrid; Bois de Boulogne, Paris), which also have very diverse types of services. Similar projects have been conducted in regional parks around Barcelona (Boada and Rieradevall 2003, 2005) but this is the first to be done in an urban park.

The anthropogenic energy flow of Montjuïc has been divided into three main subsystems:

1. Gardens: energy consumption by gardeners' machinery and vehicles in the 222.1 ha of parks and gardens.

2. Street lighting: energy consumption by the 2,955 street lights—with 3,752 bulbs—and by ornamental lighting.

3. Buildings: energy consumption taking place within the various service buildings (energy embodied in materials has not been considered) (Table II.1).

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[3] Lluís Companys i Jover (June 21, 1882 – October 14, 1940) was a Catalan politician and lawyer, President of the *Generalitat de Catalunya* (Catalan Government) from 1934 and during the Spanish Civil War. Exiled after the war, he was captured and delivered to the regime of Francisco Franco by the Gestapo, which executed him in 1940.

Table II.1. Types of services and corresponding facilities of Montjuïc Park (constituting the Buildings subsystem).

	Number		Number
Cultural field		**Field of sports**	
Museums	10	Stadiums and open air pitches	10
Theatres	4	Sports center	1
Educational field		Swimming pools	3
Nurseries	3	**Other facilities**	
Primary schools	8	International trade fair	1
Secondary schools	3	Multifunctional center	1
Special schools for the disabled*	2	Center for art crafts, restoration, and museums	1
University centers	2	Funicular railway	1

* Schools for children with special requirements (deaf and mentally disabled)

Figure II.1 is a schematic representation of the study area, showing the different subsystems and their associated energy flows.

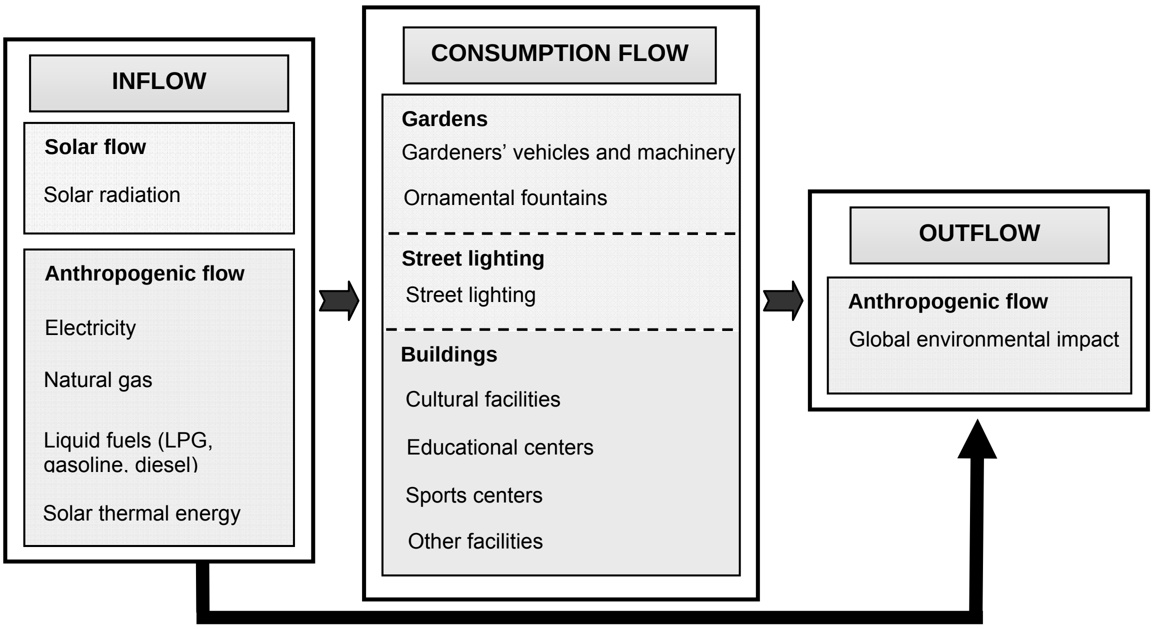

Figure II.1. Energy flow methodology applied to Montjuïc Park.

II.2.2. Tools

The use of integrated tools is needed for the study and evaluation of an urban park, which represents a previously underinvestigated type of service system. These tools include the following: EFA; LCA; and energy footprint.

II.2.2.1. Energy Flow Accounting

An EFA method consistent with MFA has been applied following the methodology proposed by Haberl (2001a, 2001b)[4], and by Krausmann and Haberl (2002). In practice, it is based on an exhaustive compilation of the invoices for fuels and related energy carriers — electricity, natural gas, liquid petroleum gas (LPG), gasoline, diesel, and solar thermal energy — for the service facilities of the entire Park. The reference year is 2004, which can be considered representative of events that took place in the Park and its climatic conditions.

Three kinds of flows are distinguished: inflow, energy sources used in the Park facilities; consumption flow, location and quantity of energy consumed by the facilities; and outflow, global environmental impact due to energy consumption within the Park's facilities.

The energy accounted for is that used for the facilities' day-to-day functions (e.g., lighting, heating and air conditioning, and use of machines/equipment).

As part of wider research but not included in this chapter (due to lack of high-quality data), the fuel consumption within the limits of the Park for the transportation of Montjuïc's workers, students, and parents[5] was estimated. (Because we had no data available on the point of origin of these people, it was impossible to determine fuel consumption outside the Park.) As there were no existing mobility studies that accounted for the kinds of vehicles used, four scenarios were designed to determine the energy consumption depending on the percentage of use of each type of vehicle. For the most and least energy demanding scenarios (those with a uniquely high use of private vehicles and public transport, respectively) the annual energy consumption for transport inside the Park's limits accounted for 12.5% and 1.8%, respectively, of the total annual energy consumed within the Park. It must be underlined, however, that the real fuel consumption is much higher as only the consumption inside the Park's limits was taken into account here, having no information available on the workers' and students' origin.

At the same time the method distinguishes between solar energy flow and anthropogenic energy flow. The method also allows differentiation of energy consumption among the gardens, street lighting, and buildings subsystems. This distinguishes between energy use in the parks and gardens, in the buildings and facilities, and on the roads and streets.

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[4] The methodology proposed by Haberl (2001a, 2001b) has been generally followed, with the major exception that the energy embodied in the materials in the products, buildings and other anthropogenic structures has not been calculated. In the Montjuïc Park there is an annual production of biomass of 2,315 tonnes, which has a net calorific value of 171.68 TOE/year (considering 80% of water content). This means that the domestic extraction would account only for the 3.4% of the Park energy balance. The biomass-embodied energy is not considered in the balance because it is produced and exported out of the system.

[5] We considered "compulsory" transportation in this calculation, that is, transportation used by people who have no other choice but to travel within the Park to get to work or school.

Following this methodology, the overall final energy balance obtained reflects the consumption of each energy source, the portion of consumption used by each type of service, and the impact that this generates.

Considering solar energy flow, approximately 50% of the solar radiation that reaches the upper layers of the atmosphere arrives at the Earth's surface. Of this, half is absorbed by the oceans and the other half by the land, where a fraction of approximately 0.2% is absorbed by plants (Strahler and Strahler 1997).

II.2.2.2. Life-Cycle Assessment

The analytic tools of life-cycle inventory (LCI) and life-cycle impact assessment (LCIA) included in LCA — which is governed by the ISO 14,041 (1998) and ISO 14,042 (2000) standards — have been used to evaluate the global environmental impact of the energy consumption of this urban system. Notice that this analysis is restricted to technical energy, as in the work by IDAE (2000) and by Gagnon and colleagues (2002), although in these studies the focus was only on electricity generation.

Of all the steps included in the LCIA methodology (ISO 14,042), only the classification and characterization steps have been conducted here so as to exclude the normalization and valorization steps to avoid subjectivity in the analysis.

In the classification step, each environmental burden is linked to one or more impact categories, whereas in the characterization step the contribution of each burden to each impact category is calculated by multiplying each burden by a characterization factor (Guinée et al. 2001). The classification and characterization method used has been CML 2000 (Guinée et al. 2001). The impact categories analyzed are abiotic depletion, global warming, ozone layer depletion, human toxicity, photochemical oxidation, acidification, and eutrophication.

For each source of energy the raw material extraction, production, stocking, transportation, and consumption processes have been taken into account, which have been calculated with the aid of the Ecoinvent database associated with SimaPro V.6.0. In the case of electricity, the Spanish electricity generation profile has been taken into consideration (coal 35.1%; nuclear 29%; hydropower 15.3%; natural gas 8.2%; imports 5.2%; petrol 4.6%; wind 2.3%; cogeneration 0.2%; and other 0.1%).

The contribution of a given source of energy to an impact category is represented by the corresponding characterization factor. These factors are usually expressed in connection with a reference compound that for a specific category is considered to have a characterization factor valuated as 1. The results obtained are expressed in equivalent units of the reference compound.

II.2.2.3. Energy Footprint

Wackernagel and Rees (1996) suggest three different approaches for converting fossil energy consumption into a corresponding land area representing biocapacity:

1. Estimate the required area of land needed to produce a contemporary biologically produced substitute for liquid fossil fuel.
2. Calculate the land area required today to absorb the amount of CO_2 released from burning fossil fuels.
3. Calculate the land area needed to regenerate natural capital at the same rate as fossil fuel is being consumed.

Wackernagel and Rees (1996) adopt the second method in their case studies. The first and third methods are proposed from the resource provision perspective, and the second method from the environmental assimilation perspective. Both the resource provision and the environmental assimilation perspectives show the dependence of humanity on nature, and thus are the main concerns of ecological footprint analysis (Ferng 2002).

In this chapter, the energy footprint, one component of the ecological footprint, is defined as the area required for sequestering the amount of CO_2 emissions generated by burning fossil fuels, for buffering the radiation from nuclear power, or for building dams to generate hydrological electricity (Wackernagel et al. 1999a; 1999b).

In most case studies the estimated energy footprint accounts for half of the total calculated ecological footprint and contributes significantly to ecological deficits (van den Bergh and Verbruggen 1999). Therefore, implementing energy-saving strategies is a key factor in reducing the ecological footprint.

II.3. RESULTS

II.3.1. Solar energy flow

In Montjuïc Park, incidental solar energy has been quantified independently from its use. Data were collected from the Solar Radiation Atlas of Catalonia (ICAEN 2001) for the nearest measuring device to the Montjuïc Park (located at x: 2º 07' E, y: 41º 23' N and z: 99 meters above sea level). By estimating the surface area of Montjuïc Park at 450 ha, it is possible to calculate the mean of the annual solar radiation in the Park (Table II.2).

Table II.2. Solar radiation in Montjuïc Park.

Daily Mean Solar Radiation ($MJ/m^2/day$)	Amplitude ($MJ/m^2/day$)	Park surface (ha)	Annual solar radiation (TOE)	Mean amplitude (TOE)
15.04	9.16	450	**594,848**	**362,288**

Source: Own elaboration from ICAEN (2001) data.

Note: Daily Mean Solar Radiation indicates the daily mean solar radiation (in annual base). Amplitude refers to the mean amplitude around the Daily Mean Solar Radiation value.
One tonne of oil equivalent (TOE) ≈ 4.18 x 10^4 megajoules (MJ, IS)

II.3.2. Anthropogenic energy flow

Figure II.2 shows the amount of each source of energy used in the Park, the consumption in absolute and relative terms, and the distribution among the different subsystems.

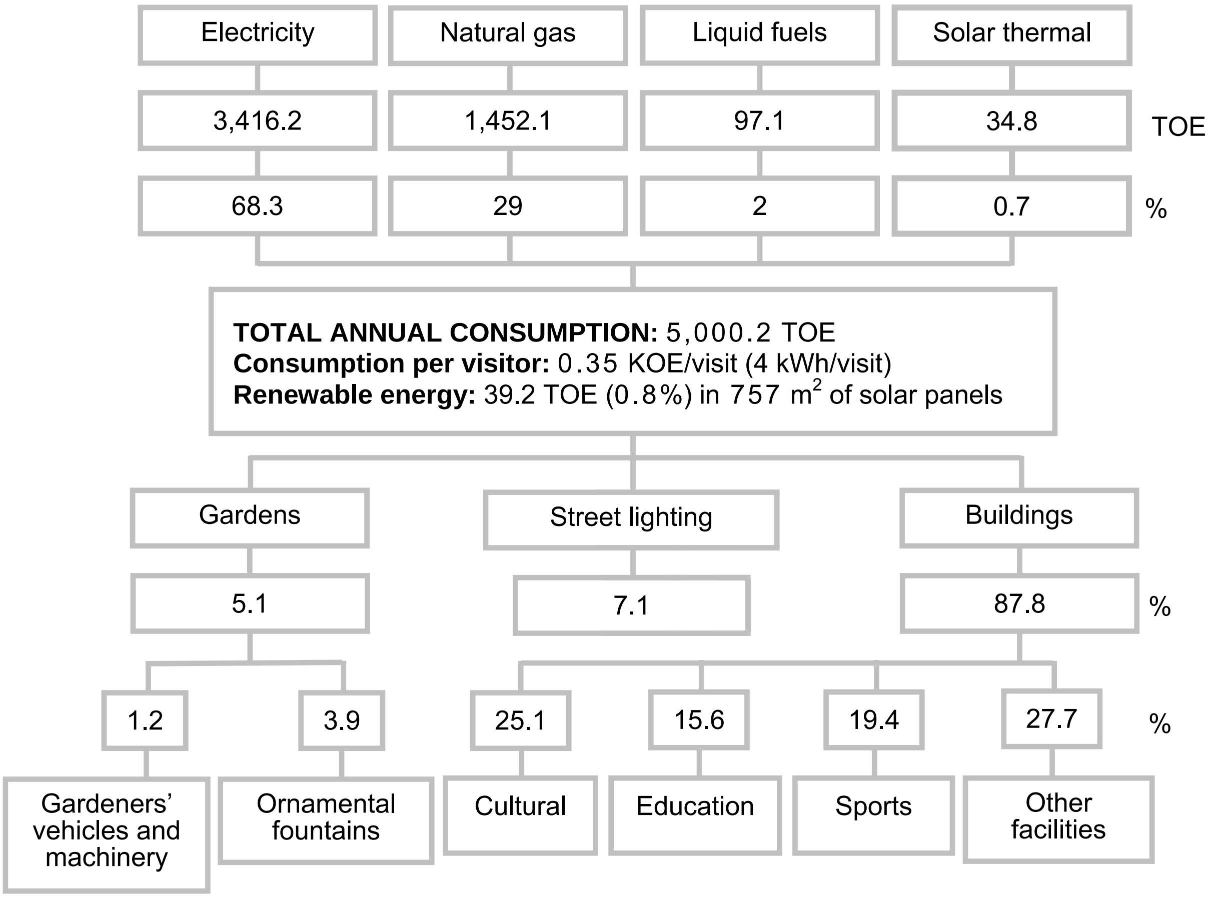

Figure II.2. Montjuïc Park technical energy consumption (in 2004).

Three key elements can be distinguished in Figure II.2:

1. Electricity consumption represents nearly 70% of the energy consumed in the Park.

2. Nearly 90% of the total consumption is used in the Buildings subsystem, wherein the cultural and "other" facilities consume more than 50% of the energy.

3. Although the Gardens subsystem does not have a high level of consumption, it is noteworthy that 75% of its consumption is due to the ornamental fountains. Nevertheless, the maintenance of the gardens is not a particularly energy-demanding subsystem; in fact, it only requires 0.027 kilograms of oil equivalent (KOE)/yr/m^2 of Park area.

In Table II.3, the energy consumption for each of the three subsystems is detailed in absolute values.

Table II.3. Energetic consumption of service facilities in the Montjuïc Park (in TOE).

	Electricity	Natural gas	LPG	Gasoline	Diesel	Solar Thermal	**Total**
Gardens Subsystem							
Gardeners' vehicles and machinery	-	-	-	11.1	48.7	-	59.8
Ornamental fountains	193.5	-	-	-	-	-	193.5
	193.5	-	-	11.1	48.7	-	**253.3**
Street Lighting							
Street lighting	323.9	-	-	-	-	-	323.9
Olympic area street lighting	27.1	-	-	-	-	-	27.1
Ornamental lighting	3.2	-	-	-	-	-	3.2
	354.2	-	-	-	-	-	**354.2**
Buildings Subsystem							
Cultural							
Museums	847	236	-	-	-	-	1,083
Theatres	149	0.4	-	-	21.7	-	171.1
	996	236.4	-	-	21.7	-	**1,254.1**
Educational							
Schools[a]	33.8	115.6	-	-	-	0.7	150.1
Special schools for the disabled	16.6	27.2	0.3	-	13	-	57.1
University centers	324	250.3	-	-	-	-	574,3
	374.4	393.1	0.3	-	13	0.7	**781.5**
Sports							
Stadiums and open air pitches	176.1	33.2	0.1	-	-	2.3	211.7
Sports center	2.7	-	-	-	2.2	-	4.9
Swimming pools	246.6	477	-	-	-	31.8	755.4
	425.4	510.2	0.1	0	2.2	34.1	**972**
Other facilities							
International trade fair	778.4	193.5	-	-	-	-	971.9
Multifunctional center	205.8	118.9	-	-	-	-	324.7
Center for art crafts, restoration, and museums	55.8	-	-	-	-	-	55.8
Funicular railway	32.7	-	-	-	-	-	32.7
	1,072.7	312.4	-	-	-	-	**1,385.1**

[a] includes nurseries, primary and secondary schools, as in many cases they are mixed in one building with only one electricity/gas meter.
Note: dashes indicate missing data or categories that are not applicable.

II.3.2.1. Comparison between Subsystems

Energy consumption in the Street lighting subsystem is 40% higher than the total consumption in the Gardens subsystem.

In the fields of education and sports, the use of natural gas is the most important type of energy (>50%), and in the cultural field and the “other facilities” electricity is the main type of energy consumed (>75%). Diesel oil for heating is used in the first three Buildings subsystem fields, but with a major presence in the cultural field, whereas in the field of sports, the use of solar thermal energy for water heating is higher. “Other facilities” is the category with the highest consumption, and that which uses the fewest types of energy.

II.3.2.2. Comparison between Services

Great variability in the amount of energy consumed has been observed among different services of the same field (up to two orders of magnitude); at the same time, considering efficiency, the values obtained inside each type of service are very different (up to two orders of magnitude), as can be seen in Table II.4. These differences in efficiency between the different facilities are likely due to the lack of market pressure on many of the entities within the service sector when compared with the industrial sector as well as the general lack of awareness of the environmental impacts of the service industries.

The disparity in the efficiency per unit surface area may be explained by the differences in the types of museums, as the electricity supply might vary across different kinds of exhibitions. In the case of schools, the differences are due to the ineffective operation of some heating systems, as a consequence of inadequate maintenance[6].

Finally, the university center with the highest energy consumption is the physical education center, the significant factor for which may be the supply of hot water for showers.

[6] This assertion is based on the authors’ personal observation of the schools in Montjuïc Park, and also on the often noted fact that many schools in Barcelona have to open their windows in winter because the heating systems cannot be controlled.

Table II.4. Energetic efficiency in Montjuïc Park services.

	TOE		KOE/visitor		KOE/m²	
	Max.	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**
Cultural						
Museums	907	4.8	2.48	0.03	70.88	0.86
Theatres	116	0.9	1.25	0.03	w.s.d.	w.s.d.
Educational						
Schools[a]	32.7	5.4	91.67[b]	21.45[b]	17.11	5.39
Special schools for the disabled	43.8	13.3	211.71[b]	138.81[b]	w.s.d.	w.s.d.
University centers	363.0	211.4	211.36[b]	63.54[b]	19.03	5.28
Sports						
Stadiums and open air pitches	199	0	5.20	0	-[c]	-
Sports center	-	4.9	w.v.d.	w.v.d.	-	
Swimming pools	522.8	52	2.50	0.43	-	-
Other Facilities						
International trade fair	-	971.9	-	0.71	-	-
Multifunctional center	-	324.7	-	0.34	-	-
Center for art crafts, restoration, and museums	-	55.8	-	0.04	-	-
Funicular railway	-	32.7	-	0.27	-	-

[a] Includes nurseries, primary schools, and secondary schools, as in many cases these are combined in one building with only one electricity/gas meter.
[b] Schools do not have visitors; this data reflects the annual consumption per student.
[c] Dashes indicate absence of data or the presence of only one facility of each kind, obviating a comparison of the maximum and minimum.
Note: w.s.d. without surface area data; w.v.d. without visitors' data.

II.4. GLOBAL ENVIRONMENTAL IMPACT

LCA has been used to evaluate the global environmental impact of the energy consumption at Montjuïc Park. One of the impact categories that has been analyzed is "global warming potential." Using data from this impact category, the Montjuïc Park energy footprint has been calculated.

II.4.1. Impact characterization results

The global environmental impact of the annual energy consumption in Montjuïc Park — taking into account the raw material extraction, production, stocking, transportation, and consumption processes for each source of energy — has been calculated using the LCA methodology.

Table II.5 shows the results for the characterization stage. Seven impact categories, some local and some global, have been chosen among the categories described by the CML 2000 methodology. Global warming potential and human toxicity are the two categories scoring the highest number of equivalent units.

The analysis methodology used in this case study, CML 2000, has been chosen according to ISO 14,042 requirements, which consider that the substances that cause an impact can only contribute to one impact category. For example, double accounting occurs when the land use category is considered, as fertilization and agrochemical application can be considered as impacts on soil biodiversity, ecotoxicity, and eutrophication. This double accounting should be avoided as recommended by ISO 14,042 (GoedKoop and Spriensma 1999).

Table II.5. Impact characterization for the Park's annual energy consumption.

Impact category	Unit	Impact	Characterization model
Abiotic depletion	tonnes Sb eq	202	Guinée et al. 2001
Global warming potential (GWP 100)	tonnes CO_2 eq	28,200	Houghton et al. 1994, 1995
Ozone layer depletion (ODP)	tonnes CFC-11 eq	0.0014	Hauschild and Wenzel 1998
Human toxicity	tonnes 1,4-DB eq	9,750	Huijbregts 2000
Photochemical oxidation	tonnes C_2H_4	13	Derwent et al. 1998; Jenkin and Hayman 1999 Hauschild and Wenzel 1998
Acidification	tonnes SO_2 eq	336	Hauschild and Wenzel 1998
Eutrophication	tonnes PO_4^{3-} eq	12	Heijungs 1992

Source: Own elaboration from SimaPro V.6.0. and the CML 2000 methodology.
Note: eq = equivalents; Sb = antimony; CO_2 = carbon dioxide; CFC-11 = chlorofluorocarbons; 1,4-DB =1,4-dibuthyl; SO_2 = sulphur dioxide; PO_4^{3-} = phosphate; C_2H_4 =ethylene.

We can infer from the data presented in Table II.5 that each user of the Montjuïc Park's services is responsible for emitting nearly 2 kg CO_2 equivalents. The contribution of each source of energy (Figure II.2) to the range of impacts is presented in Table II.6. As the impact of any one energy source varies across environmental impact categories, each source of energy lists a range, across categories, of the energy source's contribution to the overall impact of each category.

The major impact, considering all of the impact categories, is due to electricity consumption (Table II.6); therefore, any strategy for greater efficiency, energy savings, or the introduction of renewable energy to substitute or reduce the current source of electricity, will have a noticeable positive effect.

Table II.6. Consumption and range of contribution of each source of energy to the global impact, across seven environmental impact categories.

Source of energy	Consumption (%)	Range of Contribution to the overall impact (%) [a]
Electricity	68.3	53.26 – 98.51
Natural gas	29.0	1.16 – 43.04
Liquid petroleum gas	0.007	0.01 – 0.09
Gasoline	0.2	0.05 – 0.54
Diesel	1.7	0.09 – 2.17
Solar thermal	0.8	0.01 – 0.28

Source: Own elaboration from SimaPro V.6.0. and the CML 2000 methodology.

[a] Data in this column represent a range, across 7 impact categories, of an energy source's contribution to the overall impact of each category.

II.4.2. Energy footprint

For the Montjuïc Park energy footprint calculation, the results obtained for the characterization of the global warming potential impact category (Table II.5) have been used. The values are expressed in CO_2 equivalents, hence, not only are CO_2 emissions being considered, but also all the other gases that have global warming potential. In addition, the emissions considered not only belong to the combustion phase but to all the phases from extraction to combustion.

It is also necessary to identify the carbon (C) absorption ratio from net ecosystem production data. In the case of Catalonia, a study by Gracia (2004) calculates net production for a holm-oak (*Quercus ilex*) forest as 140 g of C/m^2/yr. With these data, the surface area needed — considering a holm-oak forest such as that in the study by Gracia — to absorb the equivalent CO_2 emitted by the Park's services has been calculated as 5,500 ha, which represents 12.2 times the surface area of Montjuïc Park.

II.5. DISCUSSION OF RESULTS

II.5.1. Constraints found during the study

The main constraints found during the research were related to the difficulty of dealing with the managers of 50 different service facilities. For some of these facilities, especially those with a lower level of energy consumption, the energy consumption data were not easy to compile.

II.5.2. Comparison with other systems

In Table II.7 Montjuïc's technical energy consumption is compared with the consumption in other Catalan towns and Catalonia overall.

Although there are some limitations to this comparison, as the systems compared do not have the same functions (one is only a group of services, whereas the others are cities with not only services but also residential, industrial, and mobility elements), it is a useful way to conceptualize what the energy consumed by the Park's services represents. It must be taken into account that no other detailed studies of energy consumption in multiservice systems have been identified and so it is not possible to make a comparison with similar systems.

If a visitor to the Park's service facilities is considered the equivalent of a town or city inhabitant, Table II.7 suggests that 10.5% to 16% of the overall energy consumption per person in a city is due to technical consumption in the service sector.

Table II.7. Montjuïc Park's technical energy consumption compared with other Catalan towns.

	Year	Inhabitants or visitors	Annual consumption (TOE)	Park's proportional representation (%)	TOE/ inhabitant
Montjuïc Park	2004	14,405,258[a]/year (39,467/day)	5,000.2	100.0	0.13 [d]
La Bisbal d'Empordà	2000	8,145 [b]	9,274	54.0	1.14
Viladecans	2003	59,343 [c]	64,907	8.4	1.09
Mataró	2003	111,879 [c]	119,874	4.2	1.07
Badalona	2003	214,440 [c]	266,580	1.9	1.24
Barcelona	1999	1,503,884 [b]	1,222,772	0.4	0.81
Catalonia	2000	6,343,110 [b]	13,300,000	0.04	2.10

[a] Barcelona City Council Montjuïc Division (2005).
[b] IDESCAT (2001).
[c] Diputació de Barcelona Xarxa de Ciutats i Pobles cap a la Sostenibilitat (2005).
[d] Calculation made with the daily visitors, as this value is comparable with town inhabitants.

The energy consumption of Montjuïc Park service facilities represents 0.4% of Barcelona's overall consumption. When comparing the Park's consumption with other towns, it represents more than half of the overall consumption of a town with 8,000 inhabitants.

In relative terms, the comparison is more difficult because the Park has visitors and not inhabitants. Therefore, to compare the energy consumption per person, it is necessary to use the number of daily visitors. The result is that the energy consumption needed to satisfy the service use per visitor to the park represents 16% of the energy that a Barcelona citizen consumes to satisfy the overall energy requirements of the city (housing, industry, services, and mobility).

II.5.3. Measures towards energy performance improvement

After having studied Montjuïc Park's energy consumption, in 2006 we proposed a total of 18 improvement measures to the decision makers, including the managers of Montjuïc Park and the Barcelona City Council. These proposals are noted herein, including two examples containing quantification.

II.5.3.1. Management Strategies

1. Reduce the use of and/or increase the efficiency of ornamental fountains.

2. Make energy audits in some service centers such as schools because the levels of energy consumption for similar centers are very different.

3. Promote on-foot mobility.

4. Promote car pooling.

5. Extend and improve the collective public transport service.

6. Promote cycling.

7. Use bio-diesel as the common fuel for the Park's caretakers' and gardeners' vehicles.

8. Obtain electricity from a 100% renewable origin ("green electricity"). In the Spanish case, the only commercial green electricity is a mix of wind energy (94%), mini-hydraulic (5%), and solar (1%).

In Table II.8 we present the results that would be obtained if the electricity used in the service facilities were generated with the Spanish mix of commercial green electricity.

Table II.8. Impact reduction by using Green electricity.

Impact category	Unit	Current energy mix	Green electricity mix	Impact reduction by using Green electricity
Abiotic depletion	tons Sb eq	202	43.3	158.7 (78.6%)
Global warming potential	tons CO_2 eq	28,200	5,650	22,550 (80.0%)
Ozone layer depletion	tons CFC-11 eq	1.35×10^{-3}	6.7×10^{-4}	6.8×10^{-4} (50.4%)
Human toxicity	tons 1,4-DB eq	9,750	6,320	3,430 (35.2%)
Photochemical oxidation	tons C_2H_4	13.2	1.22	11.98 (90.8%)
Acidification	tons SO_2 eq	336	12.2	323.8 (96.4%)
Eutrophication	tons PO_4^{3-} eq	12	1.24	10.76 (89.7%)

Source: Own elaboration from SimaPro V.6.0. and the CML 2000 methodology.

II.5.3.2. Infrastructure Strategies

9. Substitute mercury bulbs for ones that are more efficient. If the substitution bulbs were low pressure sodium bulbs and the number of bulbs remained the same after the substitution, the energy consumption of the Park's public streetlights network would be reduced by 54%.

10. Substitute the electromagnetic ballasts with electronic ones in the streetlights.

11. Reduce light pollution[7].

[7] Reducing the amount of light that escapes into the night sky would likely also mean a reduction in energy used.

12. Improve energy efficiency in restaurants.
13. Install self-sufficient photovoltaic streetlights connected to the electricity grid.
14. Introduce renewable energies in educational centers.
15. Install solar thermal plants in the sports centers.
16. Install solar photovoltaic power plants in sports centers.
17. Install a solar photovoltaic power plant on the roof of the trade fair building.
18. Include solar thermal energy in the processes of new construction or restoration of buildings.

II.6. CONCLUSIONS

II.6.1. Conclusions about the service sector

Energy consumption varies among different types of services, not only in the amount of energy consumed by each facility, but also in the energy profile of a facility. It must be taken into account that within each service category, there are also huge differences that can approximate two orders of magnitude. For instance, consumption in a museum differs from the consumption in a school in terms of the amount and type of energy consumed, and also within the category of museums, energy requirements are very different (e.g., we have detected museums with an annual consumption of 907 TOE and others with a consumption of 4.8 TOE). Finding performance improvement strategies for the service sector in general, due to its heterogeneity, is difficult. Learning about the sources of energy required by each type of service and which types require more energy will allow establishing specific measures for savings and efficiency for each type of service, as all of these services have different profiles of energy consumption and so require different measures.

The service sector is not as controlled and regulated by statute as is the industrial sector. This lack of environmental regulation and the perception that services have a low environmental impact contribute to the services facilities' managers' failing to control or ignoring the important contribution that they could make in achieving a reduction in energy consumption, and thus to a better environment. The service sector's contribution to the city's technical energy consumption is not at all negligible, and according to some estimation can represent 16% of the total energy consumed.

Recently the concept of industrial parks has been imitated in the creation of service parks where many different service facilities are collocated. This co-location is happening with commercial parks as well as with other kinds of public services such as medical centers, libraries, and schools. The improvements introduced so far in service sector energy management are isolated and are the result of isolated actions. There is no global initiative to the authors' knowledge, beyond the work of the United Nations Environment Programme on Product Service Systems, to apply the concepts of Industrial Ecology to the service sector that would allow the establishment of possible synergies between facilities (UNEP 2007). Such association would open up opportunities for incorporating the methods of Industrial Ecology to these service parks to improve the global environmental performance of the service sector. The service sector, as we suggest in this chapter, has at the very least a non-negligible impact on energy consumption.

II.6.2. Conclusions about the Montjuïc Park

The energy consumption of the Montjuïc Park's services is 5,000.2 TOE/yr, which represents 0.8% of the annual incidental solar energy that the Park receives. In terms of technical energy consumed per visitor, the average value is 0.35 KOE (4 kWh) per visit, which represents an emission of 2 kg CO_2 equivalents per user. The only renewable energies installed in the Montjuïc Park are solar thermal and photovoltaic, which produce nearly 1% of the total energy consumed.

The service sector in Montjuïc Park is a large and unsustainable energy consumer not only because of the amount of energy consumed, but also because the energy comes largely from nonrenewable sources. Although visitors may generally perceive the service facilities of the Park as being very sustainable, as they are located in a green area, the results obtained with the three methodologies of EFA, LCA, and energy footprint clearly show that the great energy demand and the associated impacts of the service sector in this urban area could satisfy the entire energy demands of a town of 4,000 inhabitants.

The consumption range per type of service is highly variable, and inside each field, variability is also very high. In general terms, it has been seen that the energy consumption in the garden works requires 0.027 KOE/m^2 of Park area, whereas the energy consumption per surface area unit in the Buildings subsystem is at least one order of magnitude higher. In the Buildings subsystem there are sports facilities that consume more than 5 KOE per visitor. The reason for such high consumption is that some facilities have a fixed energy consumption and the number of users is not high enough to compensate for this.

The impact categories for energy consumption in the Park with the greatest number of equivalent units are the global warming potential at 28,200 equivalent tonnes of CO_2 and human toxicity at 9,750 equivalent tonnes of 1,4-DB.

With these CO_2-equivalent emissions, the energy footprint, understood as the land surface area required to absorb the CO_2 emitted, is approximately 55 km^2, which represents 12.2 times the Park's surface area. This implies that the services sector in the Montjuïc Park is consuming some of the potential ecological services that urban parks are considered to be providing.

II.6.3. Further research

Research should focus on applying the concepts of Industrial Ecology to the service sector and finding solutions by creating synergies between different facilities to reduce the amount of energy consumed. It is necessary to continue research into energy consumption within the service sector so as to identify impacts and define appropriate strategies for improving the energy and the global environmental performance of these facilities.

The approach of this chapter could be widened by incorporating the calculations of the energy consumed by visitors and workers when traveling to and from Montjuïc Park, and by enlarging the system limits; it would be interesting to consider the reduction in the heat island effect for the area surrounding the Park.

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CHAPTER III

ENVIRONMENTAL OPTIMIZATION OF CONCRETE SIDEWALKS IN URBAN AREAS

Oliver-Solà J, Josa A, Rieradevall J, Gabarrell X (2009) Environmental optimization of concrete sidewalks in urban areas. International Journal of Life Cycle Assessment. In Press.

ABSTRACT

Background, aim, and scope: New neighborhoods and cities are built in both developing and developed countries worldwide. Given this urbanization context and current global environmental threats, the concept of sustainability will, in the long term, succeed or fail in cities. To succeed, we need to provide lifecycle-based data aimed at improving the environmental performance of new urban developments and redevelopments. This study discusses the installation criteria for three specific types of sidewalk; these criteria are currently based exclusively on economic and social factors, leading to design uniformity. This study also provides a comparative life cycle assessment (LCA) of these three types of concrete sidewalks and identifies potential redesign solutions. If sidewalk design were adapted to specific usability requirements, the environmental impact factors associated with sidewalks, and therefore cities, would be significantly optimized and reduced.

Materials and methods: Although a wide range of materials and constructive solutions are available for sidewalk paving, this study focuses on three very common concrete-based systems with different functionalities in terms of traffic, surface characteristics, and maintenance (i.e., interlocking blocks, continuous concrete layer, and slabs set on a 10-, 12-, and 15-cm-thick concrete base). These systems are analyzed from a life cycle perspective. The impact assessment method used was CML 2 Baseline 2000; input data were provided by the City of Barcelona and other local municipal councils in Catalonia, Spain as well as by local producers.

Results: In terms of main findings, this study provides a comprehensive description and inventory of the sidewalk systems under study. According to the LCA, the slab system has the highest environmental impacts; this happens to be the most widely used sidewalk type in the area studied, mainly due to aesthetic concerns and the imperatives of maintaining underground urban services. Regardless of the thickness of the concrete base, the slab system has the highest impact in all categories compared with the other two sidewalk types. However, when the slabs are set on 10 cm of concrete, performance approaches that of the continuous concrete system (with the difference ranging from 3.4% to 6.3%, depending on the impact category); this system is very convenient when maintenance work on underground urban services is required. The interlocking block system, which has the lowest structural capacity, reduces environmental impacts in all categories by 73.8% compared with the highest impact system (i.e., slabs plus a 15-cm concrete base). However, the interlocking block system is limited to areas in which vehicular traffic is prohibited. Nevertheless, there is a high potential for environmental impact reductions when this system is used in places where high structural capacity is not required. The highest environmental impacts of the various sidewalk types are associated with the use of cement (accounting for approximately 24% to nearly 77% of the total impact, depending on the impact category and the sidewalk system used); other impacts have origin in site-to-site

transportation of materials, installation, and removal of slabs and continuous concrete layers. Aggregates, which are the materials used in larger quantities in concrete, have a negligible effect on the environmental impact (less than 10% in the categories where its effect is most pronounced). In contrast, the contribution of admixtures, which are used in much smaller quantities, exceeds 10% in the abiotic depletion category.

Discussion: The redesign of sidewalks using environmental criteria and adjusting the sidewalk types to functions fulfilled can bring important benefits. Using a linear regression of the characterization results based on the weight of cement in each system, Pearson's coefficient of regression is greater than 0.99 for all impact categories. Therefore, the content of cement is a key factor in determining the environmental impacts of each sidewalk type.

Conclusions: In certain high-traffic areas, e.g., when a sidewalk is located between a roadway and a parking garage entrance or when a sidewalk must to be dug up frequently to access underground service networks (in a process known as ‘trenching”), the sidewalk must be reinforced and surface damage must be concealed. In such cases, the environmental impacts may be justified. However, sidewalks have multiple uses, and in many cases, their structural requirements are not excessively rigorous. Therefore, the systematic application of the slab system exacerbates urban environmental impacts. Restricting the use of concrete sidewalks with high structural capacity to street sections that actually require them could reduce environmental impacts by up to 73.8% in pedestrian-only areas.

Recommendations and perspectives: In light of these findings, attention should be paid to the appropriate selection of sidewalks in urban developments and redevelopments based on street function. In addition, the use of materials containing cement should be optimized, local suppliers should be selected, and sidewalks should be designed to facilitate dismantling and reutilization of their components, especially when frequent access to underground networks is required.

III.1. INTRODUCTION

III.1.1. Towards sustainable urban settlements

Understanding the metabolism of urban settlements and the characteristics of their material and energy flows is essential to understanding the many subtle interrelated factors present in cities (Bettini 1996). Based on this knowledge, the most pressing urban environmental problems, which are related to increases in inputs and management of the residual outputs, can be identified and strategies to improve urban sustainability can be developed.

Following the UNCED in Rio de Janeiro in 1992, Local Agenda 21 (LA21), as a global framework, has been widely used to describe the necessity to ensure a sustainable urban development. The tools included in this municipal environmental planning process, such as environmental diagnoses and environmental indicators, are used to identify socio-environmental issues and propose improvements. Environmental indicators are used to monitor socio-environmental trends and to evaluate the efficiency of proposed initiatives, as well as to set goals and to guide the decision-making process.

Using the LA21 content, environmental data are used to optimize the process of urban planning. However, life-cycle-related urban environmental data (including sidewalk data) are still in short supply (relevant examples are provided in Intron 1995). To manage global environmental threats, "life-cycle thinking" is needed to improve the urban design process. Therefore, access to information is crucial to the decision-making process.

Research in the area of sustainable urban infrastructure reflects the need to design and manage engineering systems in light of both environmental and socioeconomic considerations (Sahely et al. 2005). Concerning the environmental analysis, in the nineties several studies used LCA to compare among infrastructures made of different materials. A case study from that period was the Zaltbommel road bridge (Kortman and Lim 1992). This case used LCA to compare the environmental impact of two alternative bridges, made of concrete and steel, respectively. The goals of the study were to help develop a meaningful LCA system and to improve the awareness of the Public Works Department in The Netherlands. Another study from that period was conducted by the Technical Research Centre of Finland (VTT) (Häkkinen and Mäkelä 1996) and compared the environmental impact of concrete and asphalt pavements for a specific application in Nordic motorways.

III.1.2. Concrete sidewalks

Although much attention on mitigating climate change has focused on alternative fuels, vehicles, and electricity generation, better urban design represents an important yet undervalued opportunity. Fortunately, such decisions are well within the reach of local governments and leaders and can reduce long-term carbon emissions (Marshall 2008).

Within the framework of Kyoto Protocol and other global initiatives to reduce human impact on the environment, cities are a cornerstone in the implementation of strategies for resource conservation and efficiency on its use, establishing an intrinsic union between the concepts "city" and "sustainability" (Harper and Graedel 2004). It is in this context that the study of sidewalks is especially interesting, particularly because they represent a significant share of the urban landscape. For instance in Barcelona, they account for 6 km^2 (2006), or 7.2% of the total developed area. Similar values are also found in Sacramento (USA), where 5% of the developed areas are covered by sidewalks (Akbari et al. 2003.). By sidewalk we understand a pedestrian path, usually paved, running along the side of a street.

All the sidewalk systems analyzed in this study are commonly used worldwide. Data for the study were obtained from public officials and developers that operate in Barcelona and other nearby towns. However, the selected sites are comparable to locations in other European cities and regions.

The administrative criteria for installing specific types of sidewalk are usually determined by economic and social factors such as price, esthetics and ergonomics; environmental factors are not usually taken into account. A wide range of sidewalk materials and systems are used, e.g., asphalt, stone slabs, wooden bricks (in flat and dry areas, compacted earth may be used, without any additional material). However, this study focuses on concrete sidewalks, which are very common in many urban areas. In the case of Barcelona, a compact and densely populated city, concrete sidewalks account for 97% of the total sidewalk area, which in turn accounts for more than 45% of the total paved public area. In all likelihood, these statistics could be similar in other cities.

Paving with concrete is usually viewed as an environmentally and economically sustainable choice, primarily due to concrete's durability and low maintenance requirements (ACPA 2007). High durability ensures that the desirable performance characteristics and environmental advantages of concrete paving remain essentially intact for several decades. In the case of sidewalks, however, durability may be reduced due to the need to access underground distribution networks by trenching, which entails demolishing (and then reconstructing) the paved area.

Literature on paving has focused primarily on road paving. During and after the first oil crisis in the 1970s, many comparative studies were carried out on paving alternatives that consumed less energy or oil (for related discussion, see Asphalt Institute 1975; Wester 1980; Cembureau 1980; RGRA 1981; Fernández 1981). Other authors have analyzed design alternatives and issues relating to road paving maintenance and repairs (see Thenoux et al. 2007 and Chiu et al. 2008 for recent papers on energy consumption and LCAs of pavement rehabilitation).

However, scientific literature on sidewalks has focused exclusively on economic issues (e.g., price), social issues (e.g., usability, ergonomics, wheelchair users' vibration exposure) and local environmental issues (e.g., soil sealing and the heat island effect) (Asaeda and Ca 2000 and Tan and Fwa 1992). Few studies have been conducted covering a wide range of global and regional environmental impacts from a life-cycle perspective.

It should be assumed that all of the sidewalks analyzed in this study are located next to roadways and are suitable for pedestrian use. However, many urban sidewalks also have non-pedestrian uses, which may include accommodating street cleaning equipment or vehicles entering parking garages. Therefore, different sidewalk sections have different functions and, thus, different structural requirements.

In addition, certain esthetic requirements may affect sidewalk installation, e.g., if urban services (water, energy and telecommunications networks) are underground. When these networks are repaired or replaced by trenching, the pavement must be reconstructed; this process leaves "scars" that are often concealed with slabs. However, installing these networks beneath sidewalks is more convenient than installing them beneath the roadway, where trenching would disrupt traffic flows and repaving would be more costly. In other words, the sidewalk life cycle is affected by the frequency of trenching operations, in addition to the durability of various component materials and structural sections.

In the case of Barcelona, approximately 13 hectares of sidewalk is dug up every year to install or repair underground networks (Torrero 2008). This surface is equivalent to 2.2% of the total sidewalk area containing concrete-based materials (approximately 5,850,000 m^2), distributed as follows: 91.6% concrete slabs, and 8.4% continuous concrete layer (Llauradó 2008).

III.2. GOAL AND SCOPE

III.2.1. Objectives

All of the sidewalk systems analyzed in this study are suitable for pedestrian use, in addition to non-motorized traffic such as bicycles and wheelchairs. However, different sidewalk systems have different functionalities and are not structurally equivalent, as shown in Figure III.1; this study therefore does not aim to compare these systems directly, but rather attempts to quantify the potential environmental impacts of three most usually installed types of concrete-based sidewalks in the case of Barcelona and nearby cities, and that are also commonly used in many countries with subsequent variations and adaptations; to identify which type is environmentally preferable based on certain functionality; to compile an inventory of materials and processes; and to assess the potential environmental savings to be gained in matching each type of sidewalk use to the specific functionality that it fulfills. Additionally, the results obtained should provide guidelines for the redesign of these sidewalks integrating environmental criteria.

III.2.2. Functional unit

The functional unit provides a benchmark for inputs and outputs (ISO 2006). The functional unit is one square meter of sidewalk, including all pavement layers extending from the compacted soil (subgrade) to the surface (top layer), over a timeframe of 45 years. Given that sidewalks in urban contexts may have one or more of three different functions (including all three at the same time), four combinations of functions have been defined to determine which sidewalk type is environmentally optimal for each situation. The four combinations of sidewalk functions are as follows:

- o FU1: Pedestrian traffic only.
- o FU_2: Underground services + pedestrian traffic.
- o FU_3: Motorized traffic + pedestrian traffic.
- o FU_4: Motorized traffic + underground services + pedestrian traffic.

Curbs are not included in the analysis because they are assumed to be the same for all four combinations of sidewalk functions and are frequently outside the maintenance area, i.e., they are not affected by trenching.

According to developer-supplied data, a properly designed and constructed sidewalk consisting of a continuous layer of concrete or concrete slabs has a lifespan of 25-50 years; it may be less than 20 years if, for instance, low-strength concrete is used. Due to the high degree of uncertainty associated with the average lifespan, another benchmark must be used to define the timeframe for the functional unit. According to data provided by the City of Barcelona, an area equivalent to the entire sidewalk surface (including inner and outer, residential and non-residential urban areas) is reconstructed every 45 years due to trenching or maintenance. Since 45 years falls within the component materials' potential lifespan, we will use it to represent the average lifespan of a sidewalk. At the same time, by using this 45-year average, the effect of trenching during the time of use can be disregarded.

III.2.3. Description of the sidewalk systems under study

This section describes in detail the structural features of the various sidewalk systems (Figure III.1), which are named after their top layer. We also discuss optimal functionality-based solutions and describe the system boundaries and process chain under study.

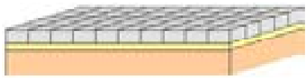
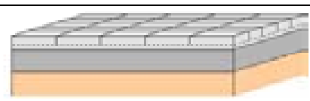
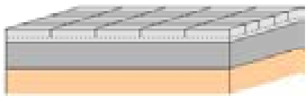
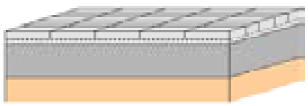
System		Layers	Layout for 1m^2 of sidewalk	FU_1	FU_2	FU_3	FU_4
B		blocks, 6cm; sand bed, 3cm; subgrade		x	x		
C		concrete, 15cm; subgrade		x		x	
S	1	slabs, 4cm; mortar, 2cm; concrete, 10cm; subgrade		x	x		
	2	slabs, 4cm; mortar, 2cm; concrete, 12cm; subgrade		x	x		
	3	slabs, 4cm; mortar, 2cm; concrete, 15cm; subgrade		x	x	x	x

Figure III.1. Structural section of systems B, C and S1-3 and technically suitable sidewalks according to its function.

Interlocking blocks. In the case of small surface areas, the subgrade is compacted using machinery such as tampers operated by a single worker. However, in exceptional circumstances when large areas must be paved, heavy equipment, such as vibrating rollers, is used. On top of the subgrade, a 3-cm layer of sand is used as a base for the concrete blocks, which typically have a compressive strength of 30 MPa. Fine aggregates (maximum size 1 mm) are poured into the joints and the blocks are compacted with a plate compactor to fit them together; this system provides for a measure of flexibility. The interlocking concrete blocks analyzed in this study measure 20 cm x 10 cm x 6 cm, and their composition is completely homogeneous. This paving system is occasionally used for plazas or pedestrian areas, but rarely for sidewalks.

Continuous concrete layer. As with the block system, in small surface areas (such as sidewalks), the subgrade is compacted using tampers. Concrete with a typical compressive strength of 20-25 MPa is poured from the mixer truck and spread, compacted and finished manually. Since the top layer of the sidewalk is made of concrete, finishing (e.g., texture, evenness) is particularly important. In this study, the top layer is 15 cm thick and highly durable (concrete producers guarantee a service life of more than 30 years).

Slabs. As with the two previous systems, the subgrade must be compacted. A concrete layer with a thickness of 10 cm, 12 cm or 15 cm with a typical compressive strength of 20-25 MPa is cast on top of the compacted soil (subgrade). The concrete is poured from the mixer truck and spread manually. The standard thickness of the concrete layer increased from 10 cm in the 1980s to 12 cm in the 1990s; a 15-cm layer is used in parking garage entrances to ensure appropriate structural performance. In keeping with this process of progressive structural reinforcement, the new trend is the standard use of a 15-cm layer.

On top of the concrete there is a 2-cm layer of dry mortar, on which the concrete slabs are laid, tapped down with a mallet and finished with a grout that seeps through the slab joints into the mortar. The slabs typically measure 20 cm x 20 cm x 4 cm. They have a double-layer structure; the upper layer has a higher compressive strength (approximately 30 MPa) and better finishing, with a combination of cement and fine and coarse aggregates.

The slab system is the most commonly used in Barcelona (and in some other nearby cities); under municipal regulations, it must be used in any new development or redevelopment for maintenance and esthetic reasons.

Slab and continuous concrete sidewalks are deconstructed with pneumatic hammers installed on backhoe loaders; block sidewalks can be deconstructed manually, since the blocks are not permanently attached to each other.

Various factors are used to determine which of the sidewalk systems described in Figure III.1 will be chosen. All of the systems analyzed are suitable for the FU_1 pedestrian-only function; however, when underground services are installed (FU_2), continuous concrete sidewalk is no longer suitable (this is an esthetic concern since there are no technical problems associated with trenching). Accommodating vehicle traffic on sidewalks (FU_3) reduces the number of suitable systems to two (C and S3), while S3 is the only system that can accommodate a combination of vehicles and underground networks (FU_4).

Taking into account the criteria described in Figure III.1, municipalities often prefer to standardize their sidewalks (also for esthetic reasons); in so doing, they ensure that all sidewalks are prepared for the multi-function scenario (S3).

The hypothesis of this study is that when design is tailored to usability requirements, the environmental impacts associated with pedestrian comfort/convenience and other related sidewalk functions (e.g., accessing underground networks or parking garages) can be significantly reduced in some cases. In other words, “one size fits all” solutions are unsuitable in many cases and carry a higher environmental cost than “tailor-made” solutions do.

The main sidewalk construction/deconstruction stages are as follows: raw material extraction, material production/processing, soil compaction, sidewalk installation, sidewalk maintenance/removal and materials transportation (raw materials, other components and final disposal) (Figure III.2). Due to the durability of sidewalk materials and uncertainties concerning disposal at the end of their life cycle, only transportation is considered in the final stage; waste treatment processes are not considered.

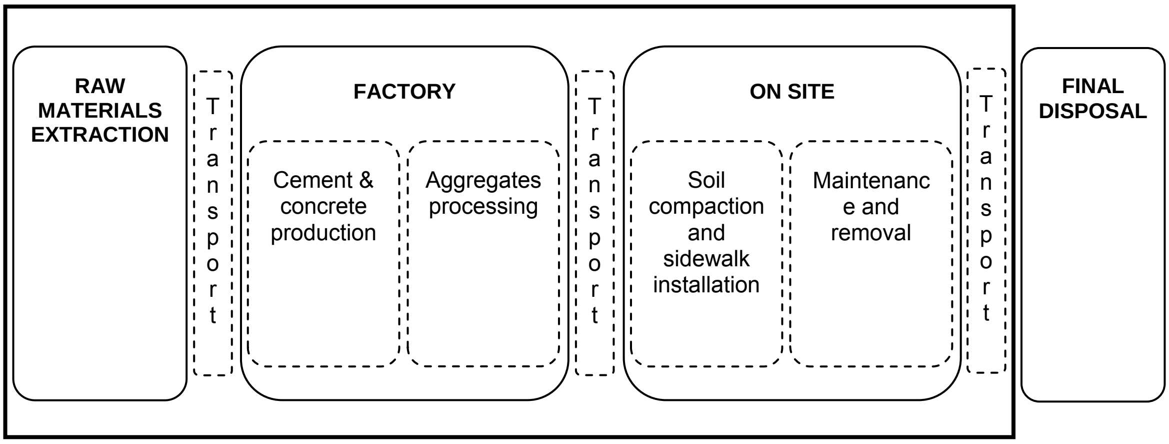


Figure III.2. System boundaries and process chain under study.

III.2.4. Data quality

The foreground system is composed of the materials (type and weight), processes and transportation distances of the various infrastructural elements that compose the sidewalk systems under study, based on the technical standards prescribed by municipalities in 2008 and the material composition data provided by local producers.

Input/output data for the concrete were compiled using the EcoConcrete LCA tool (Cembureau et al. 2003), a customized peer-reviewed MS Excel-based software program promoted by the EU Joint Project Group on the LCA of concrete, which has access to detailed inventory data provided by European concrete producers. In addition, the Ecoinvent 1.2 database (Ecoinvent 2006) was used for the sand-related processes (DE: silica sand, at plant) (Kellenberger 2004), emissions from transporting materials to the site (RER: transport, lorry 16t), transportation of concrete constituents and disposal (CH: transportation, lorry 28t) (Spielmann 2004) and diesel combustion in a diesel-electric generating set (GLO: diesel, burned in diesel-electric generating set) (Dones 2003).

The cement type used in the analysis was CEM II/A-L 32.5R Europe, which is the most appropriate for sidewalk applications in the EcoConcrete inventory. However, we are well aware that if CEM I or CEM III cement were used, the results would vary significantly, not only in terms of environmental impacts but also in terms of performance.

The results would be significantly affected by inventory uncertainties and differences between technologies if different types of materials were compared (e.g., asphalt, natural stone). But the fact that all of the sidewalk systems studied use Portland-based cement materials increases the reliability of the comparison. In addition, the durability of materials and the safety criteria in civil engineering works makes of it a conservative sector where technological changes take place slowly. As a result, inventories are considered valid for longer periods compared with other sectors.

III.2.5. Methodology

The LCA methodology is used to assess all environmental impacts associated with a product, process or activity by calculating and evaluating resource consumption and emissions (ISO 2006). Civil engineering and the built environment are high-potential fields for LCA, and research in these areas may provide useful information for the ecodesign of cities in the future.

Of the various steps in the life cycle impact assessment (LCIA) methodology (ISO 2000), only classification and characterization have been used in this study. In the classification step, each environmental burden is linked to one or more impact categories; in the characterization step, the contribution of each burden to each impact category is calculated by multiplying each burden by a characterization factor. The classification and characterization method used was CML 2 Baseline 2000 (Guinée et al. 2001). The selected midpoint impact categories and their units are as follows: abiotic depletion potential (ADP, kg Sb eq.), acidification potential (AP, kg SO_2 eq.), eutrophication potential (EP, kg PO_4^{3-} eq.), global warming potential (GWP, kg CO_2 eq.), human toxicity potential (HTP, kg 1.4-DB eq.), ozone layer depletion potential (ODP, kg CFC-11 eq.) and photochemical ozone creation potential (POCP, kg C_2H_4 eq.).

Other local impacts such as contribution to urban heat island, negative impact to soil by sealing or leaching, potential loss of biodiversity living in cities and other, are neither considered by CML 2 Baseline 2000 nor properly agreed and have not been included in the analysis.

III.3. RESULTS

III.3.1. Methodology

The transportation distances for goods and waste materials are estimates for a standard location in central Barcelona. Since most producers and waste treatment facilities are located on the outskirts of the city, the estimated travel distance is 30 km. Concrete components are transported by truck to the production plants; according to the production companies, the average distances are 75 km for cement, 40 km for aggregates and 100 km for admixtures. Table III.1 indicates the materials and energy content for one square meter of the various systems.

Table III.1. Materials contained in one square meter of the various systems.

	Layer	LC Phase	Data per functional unit			
System B	Subgrade	Compaction	12.17 MJ (gasoil)			
	Sand	Material	30 kg sand			
		Transport	To site (16 tonne truck): 30 km sand			
	Block	Material	15 kg cement 129 kg aggregate 8.21 kg tap water 0.225 kg admixture			
		Transport	Concrete components (lorry 28t): 75 km cement, 40 km aggregates, 100 km admixture To site (lorry 16t): 30 km blocks To disposal (lorry 28t): 30 km blocks			
		Installation	2.43 MJ (gasoil) (plate compactor)			
		Removal	0 MJ (manual)			
System C	Subgrade	Compaction	12.17 MJ (gasoil)			
	Concrete	Material	45 kg cement 150 kg fine aggregate 150 kg coarse aggregate 19.66 kg tap water 0.675 kg admixture			
		Transport	Components (lorry 28t): 75 km cement, 40 km aggregates, 100 km admixture To site (lorry 16t): 30 km concrete To disposal (lorry 28t): 30 km concrete			
		Installation	0 MJ (concrete mixer is included in transport)			
		Removal	34.43 MJ (gasoil)			
System S	Subgrade	Compaction	12.17 MJ (gasoil)			
	Concrete	Material		S1	S2	S3
			Cement	30 kg	36 kg	45 kg
			Fine aggregate	100 kg	120 kg	150 kg
			Coarse	100 kg	120 kg	150 kg
			Tap water	13.11 kg	15.73 kg	19.66 kg
			Admixture	0.45 kg	0.54 kg	0.67 kg
	Mortar	Material	6.6 kg cement 40 kg fine aggregate			
	Slab	Material	11 kg cement 85 kg aggregate 5.47 kg tap water 0.165 kg admixture			
	Common Processes	Transport	Concrete components (lorry 28t): 75 km cement, 40 km aggregates, 100 km admixture To site (lorry 16t): 30 km concrete, mortar and slabs To disposal (lorry 28t): 30 km concrete, mortar and slabs			
		Installation	0.34 MJ (electricity) (mixer for grout)			
		Removal	34.43 MJ (gasoil)			

III.3.2. Impact assessment of systems

The life cycle impacts for one square meter of the various systems are presented in absolute values in Table III.2 and are disaggregated in the following section (Figure III.3).

Table III.2. Characterization results for each sidewalk.

	Blocks	Concrete	Slabs 1	Slabs 2	Slabs 3
ADP (kg Sb eq.)	2.65E-01	7.39E-01	7.74E-01	8.69E-01	1.01E+00
AP (kg SO_2 eq.)	8.62E-02	2.28E-01	2.43E-01	2.66E-01	3.00E-01
EP (kg PO_4^{3-} eq.)	1.60E-02	4.16E-02	4.43E-02	4.85E-02	5.47E-02
GWP (kg CO_2 eq.)	1.97E+01	5.33E+01	5.79E+01	6.45E+01	7.43E+01
HTP (kg 1.4-DB eq.)	1.32E+00	3.33E+00	3.63E+00	4.04E+00	4.65E+00
ODP (kg CFC-11 eq.)	1.40E-06	3.32E-06	3.55E-06	3.93E-06	4.49E-06
POCP (kg C_2H_4 eq.)	8.78E-03	2.14E-02	2.27E-02	2.49E-02	2.81E-02

The highest-impact sidewalk system, slabs, is the most widely used in the area of study mainly due to esthetic and maintenance concerns.

Independent of the thickness of the concrete base, the slab system has the highest impacts in all categories. However, the slab system plus 10 cm of concrete performs similarly to the continuous concrete system, with differences between them being less than 6.5% in all impact categories.

The interlocking block system has the lowest environmental impacts by far, with impacts reduced by approximately 70% in all impact categories compared to the highest-impact type (S3). In light of this finding, block sidewalks may be the best choice in urban environments. However, they are not suitable for occasional vehicle circulation (as shown in Figure III.1) and may have functional and maintenance problems, depending on the use conditions.

Table III.3 shows that based on characterization results and functional limitations, the best environmental choice in areas without vehicular traffic (FU_1 and FU_2) would be blocks; in areas with vehicular traffic but without underground networks (FU_3), the best environmental choice would be a continuous concrete layer; and, in areas with both requirements (FU_4), the best environmental choice would be slabs plus 15 cm of concrete base. Although the latter is the highest-impact system, it is the only suitable choice in technical and esthetic terms.

Table III.3. Environmentally optimal sidewalk and impact reduction with respect to S3.

	Environmentally optimal sidewalk	Impact reduction with respect to Slabs 3
FU_1: Pedestrian traffic only	Blocks	68.7-73.8%
FU_2: Underground services + pedestrian traffic	Blocks	68.7-73.8%
FU_3: Motorized traffic + pedestrian traffic	Concrete	26.0-26.9%
FU_4: Motorized traffic + underground services + pedestrian traffic	Slabs 3	0%

III.3.3. Impact assessment of materials and processes

When the results are disaggregated by material type (Figure III.3), it becomes clear that the highest-impact material is cement (contributing from approximately 24% to nearly 77% of the total impact, depending on the impact category and system). Cement has the highest and the lowest contribution in the GWP and POCP categories, respectively.

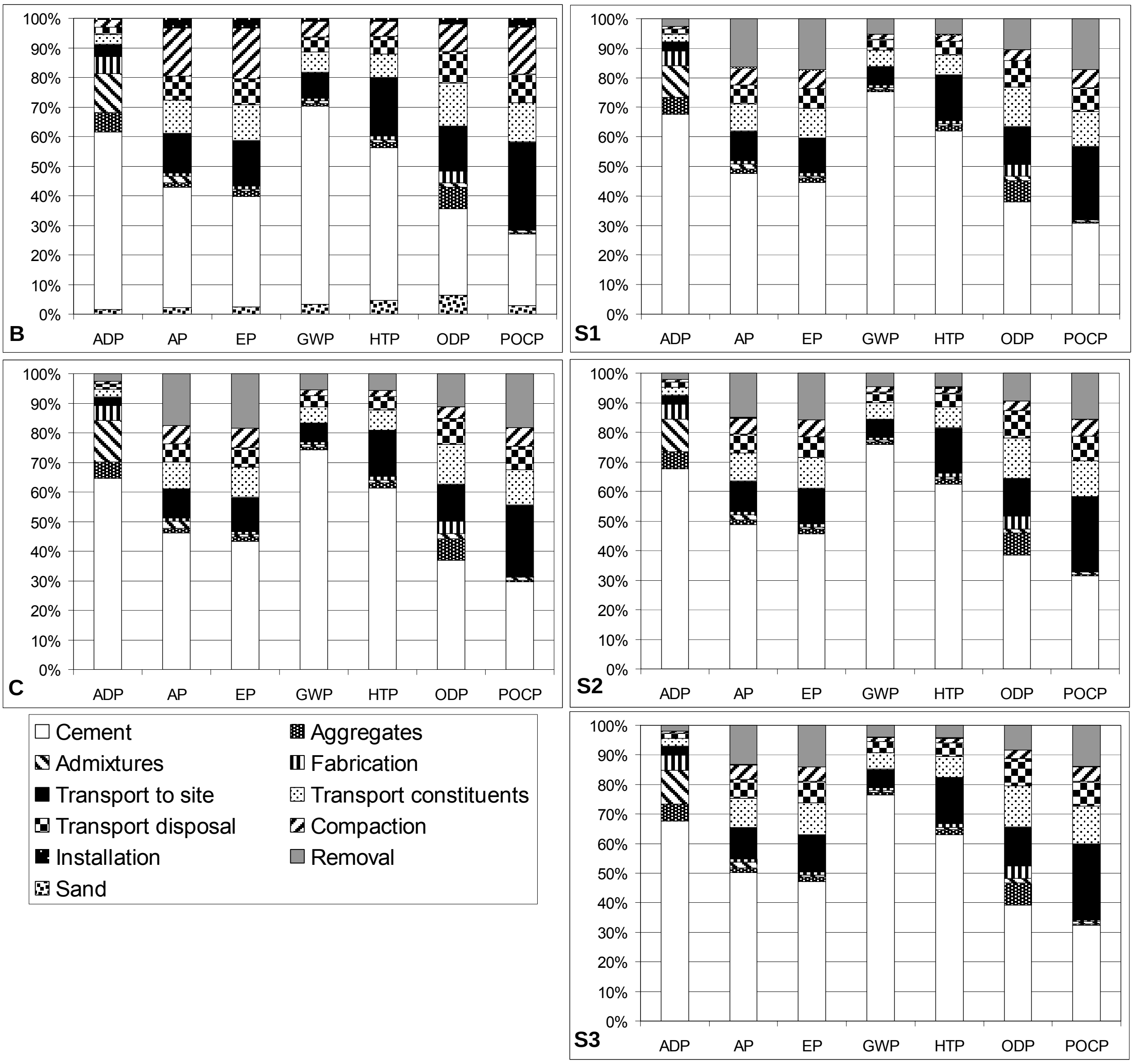


Figure III.3. Contribution to each impact category of the various materials and processes involved in each system (water is not included due to its low contribution). From top to bottom in the left column B and C, and in the right column S1, S2 and S3.

The slab and continuous concrete layer systems perform similarly in relative terms. In these systems, cement content and transportation are the highest-impact processes, followed by materials removal. In the block system, the most relevant processes are also cement content and transportation, although the relative distribution varies slightly as the relative contribution of transportation increases with respect to that of cement; compaction also appears to be environmentally relevant.

Machinery use is less extensive in the block system than in the other systems, primarily because materials can be removed manually. However, this is not reflected in Figure III.3 because the relative contribution of compaction in the block system is high.

Aggregate is used in larger quantities but contributes little to the impact (less than 10% in ADP and ODP, where it contributes the most). This means that efforts to use recycled aggregates would have a negligible effect on reducing the environmental impact of sidewalks. On the other hand, admixtures which are used in very low quantities contribute more than 10% in ADP, probably due to the raw materials used to produce the chemicals in the admixtures.

The impact of transportation is also relatively high, especially in the POCP impact category for all sidewalk types and in ODP for interlocking block sidewalks, where the impact is higher for transportation than for cement. The transportation factor with the largest contribution is the transportation of elements and materials from factory to site.

Finally, the removal or demolition stage is relevant in the case of the slab and continuous concrete layer systems (especially in the AP, EP and POCP impact categories) since the machinery used (pneumatic hammers installed on backhoe loaders) consumes large amounts of energy. In slab systems, the environmental cost of demolishing paved sidewalks ranges from a minimum of 1.9% in subsystem S3 to a maximum of 17.3% in subsystem S1, depending on the impact category. In the continuous concrete layer system, demolition's contribution to emissions ranges from 2.6% to 18.4% in ADP and EP, respectively.

III.4. DISCUSSION

Apart from the global and regional environmental impacts, other local impact categories, such as urban heat island contribution or soil sealing and leaching, could have also been suitable for analyzing environmental impacts of sidewalks. However, given that all the studied systems use the same type (but different quantities) of materials; local impacts are expected to be similar among them.

As previously described, the environmental impact associated to each sidewalk can be reduced up to 68.7-73.8% in the block system with respect to the slabs with a 15 cm concrete base. So, the redesign of sidewalks using environmental criteria and adjusting the sidewalk types to functions fulfilled can bring important benefits. Regarding the sidewalk functions, this means that when different functions are combined in the same street section (e.g., FU_2 and FU_4), different sidewalk systems should be combined depending on the functions of each individual section. Moreover, combining various sidewalk alternatives with different surface appearances in the same urban area may present difficulties.

Esthetic requirements for sidewalks may also entail relevant differences on environmental impact. For instance, use slab sidewalk with 15 cm concrete base rather than a continuous concrete layer in order to obtain a better finishing and concealment of trench marks increases the environmental impact by 26.0%-26.9% with no gain in technical functionality.

Concerning the values for the GWP category obtained for the concrete sidewalks in this study, similar values were presented by Flower and Sanjayan (2007), who found that Portland cement accounted for 74%-81% of total CO_2 emissions in commercially-produced concrete mixes. Cement is used in many different system components (e.g., slabs, concrete bricks, mortar and concrete; see Table III.1), while clinker is the cement component that contributes the most to the total final impact (as a result of the chemical reactions in the clinker kiln, the fuel combustion during clinker production and the energy consumed throughout the whole production process) (Josa et al. 2004); clinker is also one of the main sources of distortion in the LCIA of the cement inventories (Josa et al. 2007).

Based on a linear regression of the characterization results in Table III.2 with the weight of cement in each system, Pearson's coefficient of regression is greater than 0.99 in all impact categories. Therefore, cement content is a key factor in determining the environmental impact of each sidewalk.

The results obtained concerning the processes with a higher contribution to the final impact associated with the slabs and continuous concrete systems (cement content and transportation); are supported by Schuurmans et al. (2005), who defend that cement content and truck transportation are the main contributing factors as regards concrete's environmental impacts.

In connection with cement content, data was obtained from real doses in each sidewalk system. However, for transport from factory to site, average distances had to be estimated. Moreover, if the distances were increased or decreased, it would affect all the analyzed systems in a similar way. This draws the conclusion that, although the absolute impact values could be influenced by different assumptions in the distances, the relative results obtained in this chapter are accurate and can be generalized.

III.5. CONCLUSIONS

During the fieldwork, we observed a trend toward uniformity of sidewalk types aimed at facilitating installation and maintenance and ensuring the consistent appearance of all city sidewalks, with no consideration for environmental concerns. However, "one size fits all" solutions entail a significant increase (68.7%-73.8% for FU_1 and FU_2 and 26.0%-26.9% for FU_3) in the environmental impacts associated with sidewalks. For this reason, the technical functionality criteria are especially important.

The use of block sidewalk should be prioritized in all sections that do not require structural reinforcement, i.e., because vehicles are not driven on the sidewalks. Efforts should be focused on prohibiting automobiles in pedestrian areas, or at least minimizing their use, since this factor is the main contributor to environmental impacts.

Based on our findings, the main contributor to environmental impacts for the various sidewalk types is cement use (GWP is the impact category in which cement contributes the most, B: 67.09%, C: 74.38%, S1: 75.25%, S2: 75.78%, S3: 76.40%; POCP is the category in which cement contributes the least, B: 24.08%, C: 29.71%, S1: 30.68%, S2: 31.44%, S3: 32.36%). Based on previous studies, we know that clinker is the main contributor to cement impact. In light of these results, techniques should be developed and implemented to reduce environmental impacts at the clinker manufacturing stage and, if possible, to use other types of cement with more additions and less clinker.

Other materials, such as aggregates, are used in large quantities but are low-impact. For this reason, strategies like using recycled aggregates would have a negligible effect on reducing the overall environmental impact. However, there is no reason not to recycle aggregates if rubble or materials from other construction sites are available.

III.6. RECOMMENDATIONS AND PERSPECTIVES

As regards ecodesign and green public procurement, it is essential that sidewalks are adapted to their required function(s), thereby avoiding the current oversizing of many sidewalk sections and reducing the environmental impacts within the public space. Secondly, the use of certain materials, especially those containing cement, should be optimized. Thirdly, local suppliers should be used wherever possible. Although the final users may have little knowledge of the background processes as regards materials and sources, transportation distance is easily determined. Since source-to-site transportation is the most environmentally relevant transportation factor, supplier proximity should also be taken into consideration. Finally, sidewalks should be designed to facilitate dismantling and reutilization, especially when access to underground networks is required.

As regards the latter point, future studies should consider the possibility of expanding sidewalk systems to include underground service galleries. This would facilitate underground network access and repairs and yield substantial social gains. However, the environmental gains would not be quite so apparent due to the large quantities of concrete that could be required to build the galleries; this topic warrants a deeper life cycle analysis.

III.7. ADDENDUM

This addendum outlines the content and preliminary results of a paper in elaboration that determines the potential saving of GHG emissions that could be achieved in an urban scenario adjusting the sidewalk characteristics to the functional requirements, based on the results of the LCA of concrete sidewalks previously shown.

The relevance of this section is the implementation of a GHG mitigation strategy on a neighborhood scale based on coupling environmental quantification tools like LCA with urban planning processes. This process can be led by two strategies:

1. Refurbishment: Substitute the current “one size fits all” solution with sidewalks tailored to the specific structural (if possible also aesthetic) requirements of each street section.

2. Redesign: Redefine the urban uses to make possible the generalized use of these sidewalks with a lower contribution to GHG emissions during their life cycle.

III.7.1. Description of the urban scenario where the analyzed sidewalks are applied

Many different urban shapes and forms can be found in different cities or even inside each of them (regular or curved grids; districts from medieval, Arabic, baroque or industrial eras; garden cities, etc.); however for calculation purposes a regular grid typical of European 19th century city planning has been chosen as a reference.

The urban scenario under analysis is based on compact blocks (Figure III.4). The selected block has 10,000 m^2 for residential uses (although part of it may be used by public spaces), 1,664 m^2 for sidewalks and also 2,736 m^2 for roads.

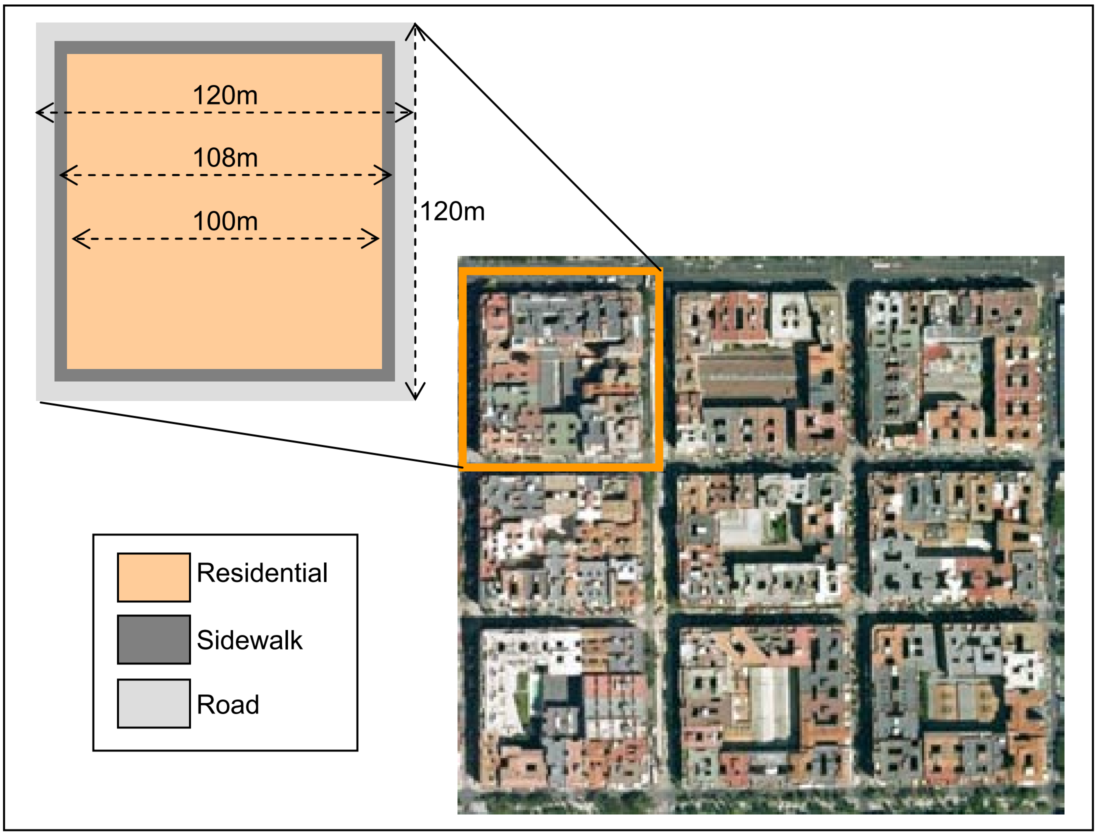


Figure III.4. Contextualization of the analyzed compact block within a broader urban area.

In the analyzed urban scenario nearly one third of the urban surface is public space, and sidewalks represent 11.6% of this urban pattern. Within public space nearly 37.8% of the surface is occupied by sidewalks.

III.7.2. GHG savings in neighborhoods through the optimization of concrete sidewalks

According to the types of sidewalks that are currently installed and the backpack of GHG emissions associated to each of them (Table III.2), the contribution to the global warming potential originated in a sidewalk surface can be quantified for three scenarios where the block fulfills the same function (Table III.4):

a) **"One size fits all".** This scenario consists of a generalized application of the slab system with a 15 cm subgrade of concrete. This system has a high structural resistance thanks to the thick subgrade. In addition, when the underground networks have to be repaired or replaced by trenching, the pavement must be reconstructed; this process leaves "scars" that in this scenario can be concealed with slabs.

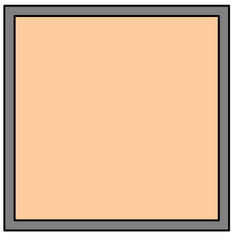
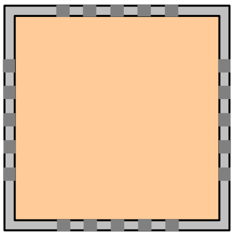
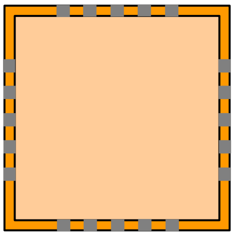
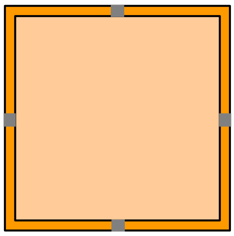
b) **Refurbishment:**

1) **Maintaining the same aesthetic appearance.** This scenario maintains the sidewalks' aesthetic appearance but optimizes the sidewalk typology to the existing functions. All the sidewalk area is paved with slabs but the subgrade is reinforced only in these street sections that require such reinforcement, i.e. garage entrances.

2) **With changes in the aesthetic appearance.** In this scenario 74% of the surface is covered by interlocking blocks; which implies an aesthetic change. However, the fact that slabs are still in use in front of garage entrances may be useful to attract the attention of pedestrians whenever they are passing by these places.

c) **Redesign.** This scenario implies changes in the urban planning that restrict the number of garage entrances allowed in each street section. It represents an evolution from the second refurbishment scenario that could be applied in new neighborhoods. This scenario maximizes the use of interlocking block sidewalks without changing the urban function, or the block uses, although it requires a common garage entrance for the whole street section.

Table III.4. Sidewalk scenarios, suitable uses, surface and associates GHG emissions.

	"One size fits all"	Refurbishment 1	Refurbishment 2	Redesign
Block				
Pedestrian traffic	✓	✓	✓	✓
Motorized traffic	✓	Restricted to garage entrances (20)	Restricted to garage entrances (20)	Restricted to garage entrances (4)
Underground networks	✓	✓	✓	✓
Surface for motorized traffic	1,664 m^2 S3	500 m^2 S3	500 m^2 S3	100 m^2 S3
Surface for pedestrian uses		1,164 m^2 S1	1,164 m^2 B	1,564 m^2 B
Associated kg CO_2-eq.	123,635.2	104,545.6	60,080.8	38,240.8
GHG footprint (ha)	24.1	20.4	11.7	7.4

Note: Garage entrances are considered to be 5 meters wide.

Results in Table III.4 reflect that slight and feasible changes in the sidewalk configuration can lead to up to a 69.1% saving in GHG emissions from one scenario to another. In absolute values, the potential GHG savings per block are of 85 tonnes of CO_2 equivalent.

In the case of a Mediterranean forest, a study by Gracia (2004) calculates net production for a holm-oak (*Quercus ilex*) forest as 140 g of C/m^2/yr. With this data, the surface area needed—considering a holm-oak forest such as that in the study by Gracia—to absorb the equivalent GHG avoided by optimizing the concrete sidewalks to its function, between the most extreme scenarios 16.7 hectares per block has been calculated.

One of the strengths of working on a neighborhood level is that most measures have a multiplying effect. Considering a Mediterranean city of 100,000 inhabitants (with an average density of 35,000 inhabitants/km^2), the proposed measure of optimizing the concrete sidewalk application could represent a saving of 24,286 tonnes of CO_2 equivalent, which would require 4,731 hectares of Mediterranean forest to be absorbed.

As shown in Table III.4, intermediate solutions are also feasible with the subsequent more limited reductions of GHG emissions. Moreover, ecostrategies in the public space give room for a gradual application depending on the technical viability or political will.

III.7.3. Addendum conclusions

The results presented in this addendum are especially relevant because they reveal that environmental data provided by environmental quantification tools like LCA coupled with urban planning processes can lead to an effective reduction in GHG emissions. Furthermore, sidewalks represent approximately 40% of the public space in a city and local governments may have a direct incidence on them.

The results show that the reduction in GHG emissions associated with the optimization of concrete sidewalks to pedestrian uses has a high potential; 15.4 to 69.1% reduction depending on the degree of change introduced.

In analogy with the ecodesign of products, processes and services, where environmental data is taken into consideration and used by designers, architects or engineers in their work in order to produce better products from the sustainability perspective, the urban planning process using environmental data in the decision making process becomes a process of ecodesign on a broader scale.

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CHAPTER IV

ENVIRONMENTAL IMPACTS OF NATURAL GAS DISTRIBUTION NETWORKS WITHIN URBAN NEIGHBORHOODS

Oliver-Solà J, Gabarrell X, Rieradevall J (2009) Environmental impacts of natural gas distribution networks within urban neighborhoods. Applied Energy 86(10): 1915-1924.

ABSTRACT

This study uses the life cycle assessment methodology to analyze the type and origin of environmental impacts related to natural gas distribution networks in high and low density neighborhoods, and compares the environmental performance of two infrastructures in low density neighborhoods: a standard natural gas grid and a discontinuous system based on propane tanks. The results show that the impact per dwelling in the environmental categories studied is between 1.9 and 4.8 times higher in a low density neighborhood, depending on the impact category. Besides, in high density areas the main impact originates from components and materials related to the buildings and dwellings, whereas in low density areas the main impact originates on the neighborhood network. Given this last result, the advisability of substituting the neighborhood network by a discontinuous system based on propane tanks has been evaluated, obtaining as a result that when a single neighborhood pipe, longer than 1 km, is required to reach one user, it is environmentally preferable for all the studied environmental categories to use the propane tank system.

IV.1. INTRODUCTION

In a global context, the world population is on the increase and with it the urban population, meaning that a large number of new cities and neighborhoods are being built all around the world. All these new urban areas require service infrastructures, one of which may be natural gas (methane) distribution networks.

Some literature revises the heat and cooling consumption using different technologies, such as buried pipe systems (e.g. Hollmuller and Lachal 2001) or district cooling in new urban developments (e.g. Chow et al. 2004), but frequently the main focus has been on monitoring the efficiency differences between technologies or economic costs. Additionally, Theodosiou et al. (2005; 2007) have studied the impact of energy consumption for covering the needs of a typical apartment building; but still little attention has been paid to the environmental impact of local energy distribution networks and their relationship with urban density parameters.

Distribution networks have appealed to some authors, however; Carvalho and Ferreira (2004), for example, analyzed power distribution networks, although without considering environmental impacts. Their focus was to find the best possible trade-off between investment costs, energy losses costs, and reliability costs.

Yamaguchi et al. (2007) used an interesting Industrial Ecology approach, with concepts such as clustering, applied to building stock pattern management. But in this case, only an inventory of CO_2 emissions was used rather than impact categories. The present chapter addresses the environmental impacts of local natural gas distribution networks from a life-cycle perspective and considers six impact categories, which provide strength on the results.

Until now, LCA has not been widely applied to natural gas urban distribution networks, although this methodology has been used to evaluate the environmental advantages of a given fuel in comparison to others. For instance, Riva et al. (2006) determined that natural gas is environmentally better than the other fossil fuels in the final use stage, and achieves even better results if complete fuel cycles, from production to final consumption, are taken into account.

This study calculates the environmental impact associated to the infrastructure of an urban network for distributing natural gas and complements studies on the impacts of natural gas consumption by focusing on distribution system inside a neighborhood. In densely built urban areas the same length of neighborhood network can be used by more consumers than in areas with a low building density. The high ratio of consumers per unit length makes the networks easier to maintain from an economic perspective and has a lower impact per service from an environmental perspective.

This study is different from other studies of similar infrastructure because doesn't focus on a specific component (e.g. pipes) but on the complete system within a neighborhood for distributing gas. It facilitates our understanding of which parts of an urban natural gas grid are the main contributors to the overall environmental impact and what level of urban density can be considered environmentally adequate for the installation of a distribution network rather than a discontinuous system with propane tanks. Local aspects such as topography or soil characteristics haven't been considered in order to facilitate the adaptation of the results to other neighborhoods. If the regional gas pipeline and other very locally dependant data were taken into consideration the results would be more precise for the case study, but at the same time would not as clearly show differences between different neighborhood gas distribution systems. As the aim of the study is to provide environmental data for guiding urban planning, not national planning, elements that are external to the neighborhood are not considered here.

Figure IV.1 describes the steps of natural gas supply in Spain (Dones et al. 2004), and points out the neighborhood system (in gray in the figure), which is the one that is investigated in this study.

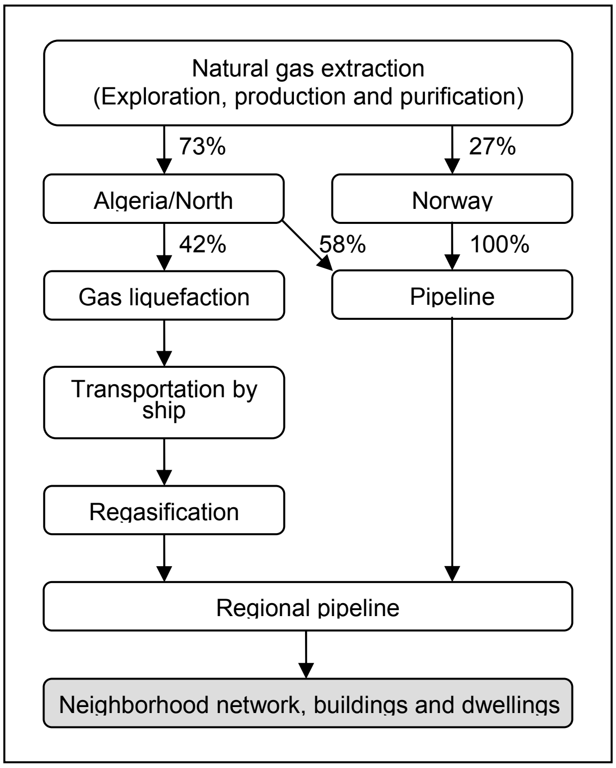

Figure IV.1. Diagram of the different steps of the natural gas supply in Spain.
Source: Dones et al. 2004.
Note: in grey, the subsystem under study in this chapter.

In many European countries there is an extensive natural gas pipeline infrastructure. According to Eurostat (1998) most recent data, for 1998, Spain ranked sixth on the natural gas pipeline length, with 30,131 kilometers, in a ranking leaded by the United Kingdom, Germany and Italy with 421,000, 347,700 and 197,100 kilometers respectively. However, according to national data, in 2004 the total length of natural gas grid in Spain had already surpassed 52,000 kilometers, it had about six million domestic and commercial customers, and 1,500 out of 8,000 villages had access to the grid (Fundación Vida Sostenible 2007).

IV.2. SYSTEM DESCRIPTION

The studied system includes two main technologies applied to two urban neighborhoods with the densities defined in Table IV.1, resulting in three scenarios.

Table IV.1. Characteristics of the three scenarios.

Technologies	Urban density	Neighborhood distribution (meters)	Buildings (number)	Dwellings per building (number)
Gas grid	High	100	10	24
	Low	100	4	1
Propane tank	Low	10,000	4	1

The first and second scenarios are a standard grid for distributing natural gas which impact is analyzed for high and low density neighborhoods. The third scenario is based on a discontinuous system for distributing propane, applied only in low density neighborhoods where there isn't any natural gas grid in the neighborhood. Although the compared scenarios use different types of fuel this does not change the use of the gas in a way that makes the two systems incomparable. Probably, one reason for the change on the type of fuel is the higher calorific power of propane, which implies a lower volume of tanks and tankers.

IV.2.1. Gas grid scenario

The system boundaries are the limits of a street of 100 meters within the neighborhood itself. The environmental impact of the gas grid is analyzed in two different urban densities, which allows us to verify whether different urban structures determine different environmental impacts and also whether the source of impacts within the system remains in the same elements (components and materials) or not.

Energy infrastructures are partly located in the public domain and it is therefore possible to use the same amount of network for just a few individuals and for hundreds of people. Their use depends heavily on the shape and density of the urban area.

In both density scenarios the gas grid has the same elements, but in different quantities. The only exception is the length of the downpipe which is shorter in the low density scenario (1 meter instead of 10 per dwelling) because the one-floor buildings require a shorter pipe.

It is taken for granted that the regional natural gas pipeline reaches the neighborhood boundary. Figure IV.2 gives detailed information of one segment of the system, including the neighborhood network, one building and one dwelling.

IV.2.2. Propane tank scenario

In low density, as well as isolated areas, it is less likely to find a gas grid, and customers may be supplied with a discontinuous system based on propane tanks located in each house. In the case of Spain, the installation of propane tanks is fairly common in places where there isn't any natural gas grid. There are several options for using propane tanks, but the system studied considers tanks of 2,450 liters – according to gas companies, the most commonly used for domestic purposes in Spain – installed at each consumer's house place.

The propane tanks are refilled according to consumption, which may vary greatly between consumers and regions. However, the average number of yearly refills for residential houses is around five (Repsol Gas 2007).

In the comparison performed, this means that instead of installing a neighborhood gas network, the propane is supplied by a truck five times per year. The truck covers a distance of 10 km from a terminal where propane is stored to the final consumer assuming that it refills the tanks of all the houses in the same trip. This distance is assumed to be valid in metropolitan areas, where propane is stored in gas stations. To be methodologically comparable with the neighborhood grid scenario, the truck emissions for the two way trips as well as the proportional part of the truck production are considered for the impact calculation.

Although the neighborhood network is eliminated, it is considered that all other systems in the building and dwelling subsystems are the same as in the low density scenario.

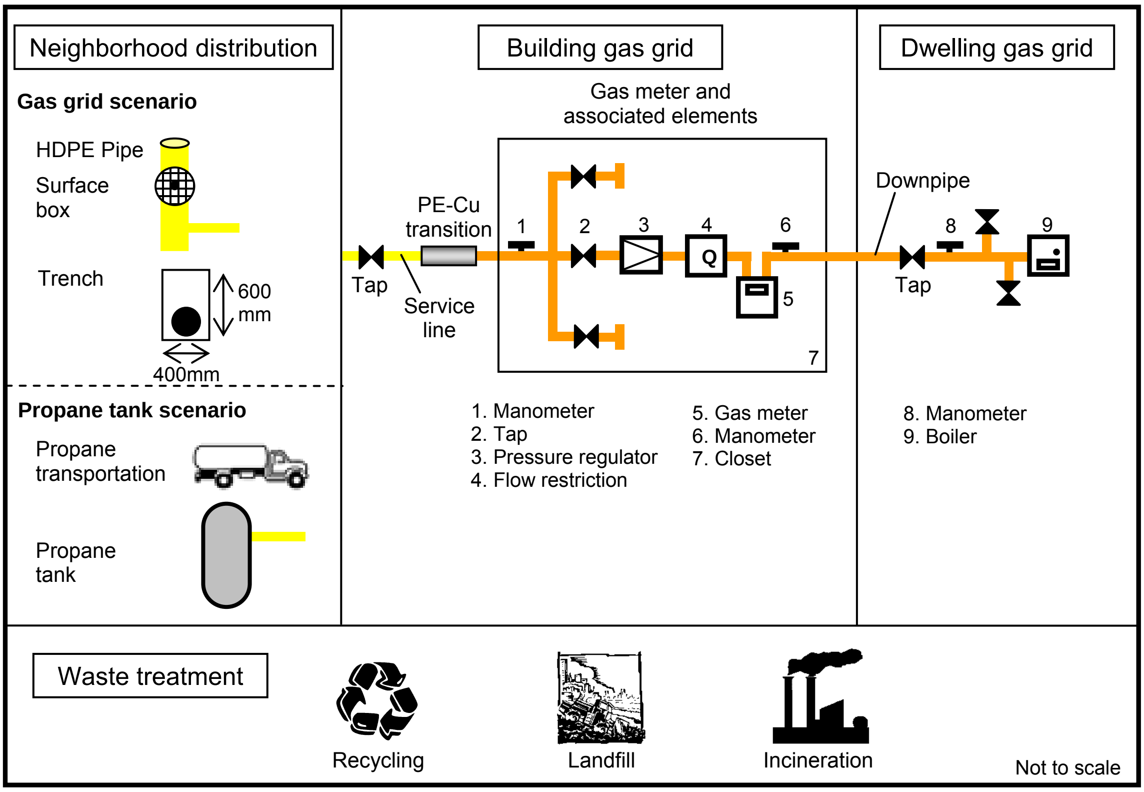

Figure IV.2. Subsystems of the scenarios analyzed.

IV.3. GOAL AND SCOPE

IV.3.1. Objectives

This study attempts to quantify the potential environmental impact of a standard neighborhood and in-house distribution gas network; to identify which subsystem and elements are the most environmentally relevant; to compile an inventory of materials and processes; and to provide guidelines for the ecoredesign of these networks.

IV.3.2. Functional unit

The functional unit is a system to distribute either natural gas or propane (continuous or discontinuous grids) for satisfying the domestic requirements of standard families for space heating and sanitary hot water within a local urban neighborhood during 50 years.

Two different urban densities have been considered for the local neighborhood network, as well as a discontinuous system for the low density scenario, resulting in three scenarios described in Table IV.1.

IV.3.3. Data sources

The foreground system, that is the inventory of materials and weights of the different infrastructural components involved in a standard natural gas network, as well as the energy consumed in the trench works, are obtained through the *Metabase ITeC* (2009), a database that provides information of generic building elements and products. In addition, all the scenarios used have been checked and approved by engineers of multinational natural gas companies.

The background system consists on the materials, packaging materials, minor waste during installation, energy consumed in digging the trenches for the neighborhood grid and for the installation of the tank, transportation, necessary maintenance and replacement of compounds over 50 years and also the impacts related to the treatment of materials at the end of their working life. The potential use of the recycled materials in another product is not taken into account, and so, neither the avoided impacts.

The Ecoinvent 1.2 inventories (Doka 2003; Althaus et al. 2004; Hischier 2004; Kellenberger et al. 2004; Spielmann et al. 2004) have been used for evaluating the emissions related with the materials and energy. In these few cases when data sets for specific materials were not available in the Ecoinvent inventories, the inventory data was obtained from the PE Europe database associated with the software *GaBi 4* (IKP University of Stuttgart and PE Europe GmbH 2003).

Concerning transportation of materials for all scenarios only the local transport from a regional storage to site has been considered, and data was obtained from PE Europe database. An average distance of 25 kilometers has been chosen as an appropriate approximation in a metropolitan area. The selected truck processes are *Truck/7.5t total cap./4.7t payload/local*.

IV.3.4. Impact assessment

The impact categories analyzed are AP, EP, GWP, HTP, ODP and ADP. All categories are widely used and accepted within the LCA practitioners.

IV.3.5. Methodology

The LCA is a useful and practical tool for guiding planning processes with environmental criteria and it facilitates our understanding of environmental impact on urban infrastructures.

The methodology for conducting a LCA of products, goods and/or services is described in ISO standards. The analytic tools of LCI and LCIA included in LCA – which is governed by the ISO 14,041 (1998) and ISO 14,042 (2000) standards – have been used to evaluate the global environmental impact of the natural gas distribution network in urban systems of different densities in comparison with a discontinuous system based on propane tanks. Inventory results are characterized using the CML 2 Baseline 2000 (Guinée et al. 2001) indices, but not normalized or weighted.

This study takes into account the materials, installation works, maintenance of components, transportation and waste treatment of the infrastructures required to distribute either natural gas or propane (continuous or discontinuous grids) in urban areas. One stage was deliberately omitted: the use phase; that is gas (either methane or propane) consumption in the dwellings for obtaining thermal comfort and other uses, such as cooking.

IV.4. INVENTORY

IV.4.1. Materials and average lifespan

In Tables IV.2 - IV.5 are presented the inventory of components and materials included in the analysis for the neighborhood, building, dwelling and propane tank subsystems, respectively; and Table IV.6 shows their average lifespan. Minor maintenance processes like painting, cleaning or insignificant repairs have not been considered in the analysis. The *trench works* in Table IV.2, include the materials and the energy used for excavating.

Table IV.2. Components and materials for the neighborhood network subsystem.

Component	Material	Process	Quantity in the component	Quantity in the scenario
Pipe (1 meter)	HDPE	RER: polyethylene, HDPE, granulate	4.09 kg	100 meters
Surface box (1 unit)	Water	RER: tap water, at user	228.48 kg	1 unit
	Sand	CH: sand, at mine	2,078.84 kg	
	Limestone	CH: gypsum plaster board, at plant	135.51 kg	
	Cement	CH: cement, unspecified, at plant	431.91 kg	
	Cast iron	RER: cast iron, at plant	165.40 kg	
	Ceramic brick	RER: brick, at plant	1,789.74 kg	
	Electricity	ES: electricity, low voltage, production ES, at grid	7.76 MJ	
Trench works (1 meter)	Pavement	CH: cement, unspecified, at plant	21.40 kg	100 meters
	Concrete	DE: concrete block, at plant	32.09 kg	
	Aggregates	CH: sand, at mine	403.09 kg	
	Diesel	GLO: diesel, burned in building machine	34.53 MJ	

Table IV.3. Components and materials for the building subsystem.

Component	Material	Process	Quantity in the component	Quantity in the scenario
PE-Cu transition (1 unit)	Galvanized steel	DE: Steel sheet galvanized PE [1]	0.044 kg	10/4 units
	Rubber adhesive	RER: synthetic rubber, at plant	0.0072 kg	
	Copper	RER: copper, at regional storage	0.018 kg	
Service line (1 unit)	Galvanized steel	DE: Steel sheet galvanized PE [1]	0.003 kg	200/80 meters
	Copper	RER: copper, at regional storage	1.924 kg	
	Priming	DE: Previous coat (synthetic resin) PE [1]	0.11 kg	
	Wood (p)	CH: disposal, building, waste wood, untreated, to final disposal	0.0021 kg	
	Metal (p)	RER: copper, at regional storage	0.78 kg	
	Plastic (p)	RER: polyethylene, LDPE, granulate, at plant	2.65E-05 kg	
	Copper (w)	RER: copper, at regional storage	0.036 kg	
Tap (1 unit)	Bronze	CH: bronze, at plant	4.45 kg	10/4 units
	Synthetic rubber	RER: silicone product, at plant	0.045 kg	
	Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	2.37E-05 kg	
Gas meters and associated elements (1 unit)	Brass	CH: brass, at plant	17.85 kg	240/4 units
	PVC	RER: polyvinylchloride, at regional storage	1.62 kg	
	Cast iron	RER: cast iron, at plant	1.9 kg	
	Glass fiber	RER: glass fibre reinforced plastic, polyester resin, hand lay-up, at plant	6.3 kg	
	Synthetic rubber	RER: silicone product, at plant	0.0068 kg	
	Bronze	CH: bronze, at plant	0.67 kg	
Closet (1 unit)	Galvanized steel	DE: Steel sheet galvanized PE [1]	149 kg	20/0.33 units
	Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	11.33 kg	

(p) packaging, (w) waste
[1] PE Europe database
The values for "Quantity in the scenario" are given for high density and low density (read like h.d./l.d.)

Table IV.4. Components and materials for the dwelling subsystem.

Component	Material	Process	Quantity in the component	Quantity in the scenario
Downpipe (1 meter)	Steel	RER: steel, low-alloyed, at plant	0.0022 kg	2,400/4 meters
	Copper	RER: copper, at regional storage	0.834 kg	
	Priming	DE: Previous coat (synthetic resin) PE [1]	0.071 kg	
	Wood (p)	CH: disposal, building, waste wood, untreated, to final disposal	0.0014 kg	
	Metal (p)	RER: copper, at regional storage	0.52 kg	
	Plastic (p)	RER: polyethylene, LDPE, granulate, at plant	1.76E-05 kg	
	Copper retails (w)	RER: copper, at regional storage	0.016 kg	
Tap (1 unit)	Bronze	CH: bronze, at plant	0.67 kg	240/4 units
	Synthetic rubber	RER: silicone product, at plant	0.0068 kg	
	Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	2.37E-05 kg	
Manometer (1 unit)	Brass	CH: brass, at plant	0.15 kg	240/4 units
	PVC	RER: polyvinylchloride, at regional storage	0.1 kg	
Boiler (1 unit)	Steel	RER: steel, low-alloyed, at plant	18.9 kg	240/4 units
	Stainless steel	DE: Stainless steel sheet PE	8.4 kg	
	Copper	RER: copper, at regional storage	8.4 kg	
	Glass fiber	RER: glass fibre reinforced plastic, polyester resin, hand lay-up, at plant	4.0 kg	
	PVC	RER: polyvinylchloride, at regional storage	6.3 kg	

(p) packaging, (w) waste
[1] PE Europe database
The values for “Quantity in the scenario” are given for high density and low density (read like h.d./l.d.)

Table IV.5. Materials for a propane tank of 2,450 liters.

Component	Material	Process	Quantity in the component	Quantity in the scenario
Propane tank (1 unit)	Steel	RER: steel, low-alloyed, at plant	618.77 kg	4 units
	Brass	CH: brass, at plant	2.35 kg	
	PVC	RER: polyvinylchloride, at regional storage	0.25 kg	
	Epoxy resin	RER: epoxy resin, liquid, at plant	11.24 kg	
	Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	1.42 kg	
	Diesel (Installation)	GLO: diesel, burned in building machine	936 MJ	
Propane distribution (250 two-way trips)		RER: operation, lorry 16t	31.385 MJ	5,000 km
Truck (0.005 unit)		RER: lorry 16t	0.005 units	0.005 units

(p) packaging

In order to determine the average lifespan of the network components, two experts were consulted, providing very heterogeneous data as a result (Table IV.6). This variability in the data may be a consequence of the short time that has passed since the components currently being used in natural gas distribution came into use; and also the different technologies and maintenance operations used in different networks (Lilly et al. 2007).

Table IV.6. Average lifespan of natural gas grid components according to two experts.

	Average lifespan of the components	
Gas grid scenario	Expert 1[1]	Expert 2[2]
Neighborhood network		
HDPE pipe	50 years	15 years
Surface box	50 years	15 years
Building		
Service line	50 years	15 years
PE-Cu transition	50 years	15 years
Gas meter	50 years	15 years
Tap	50 years	15 years
Dwelling		
Downpipe	50 years	15 years
Gas boiler	15 - 20 years	10 – 15 years
Propane tank scenario		
Propane tank		
Whole infrastructure	50 years (Repsol Gas 2007)	
Truck (km)	1,000,000 km (Volvo Truck Corporation 2004)	

[1] with maintenance most components can last for many years before changes in technology make them obsolete. In these cases, 50 years have been considered.
[2] without maintenance.

Data from expert 1 was used for the analysis and data from expert 2 was used for the sensitivity analysis. The end results are the sum of the impacts of all components but where the impact from the gas boiler is scaled by 50/15, and the truck that carries the propane is scaled according to the average distance travelled by a truck in all its life span: about 1,000,000 km (Volvo Truck Corporation 2004).

IV.4.2. Wastes and waste treatment

Although there is no clear data on the exact treatment that each material receives, Table IV.7 presents the more common treatments applied to each group of materials, as well as the quantity for each of them, resulting from the combination of values given in Tables IV.2 - IV.5 and the parameters of each scenario. The Ecoinvent processes have been manipulated in order to avoid considering the avoided impact due to the recycling of materials.

Table IV.7. Quantity of materials that are treated for each scenario and waste treatment considered for each material.

Material	Gas grid scenario, high density	Gas grid scenario, low density	Propane tank scenario	Treatment	Process
HDPE	408.97 kg	408.97 kg	-	recycling	Recycling mixed plastics/RER
Water	228.48 kg	228.48 kg	-	not considered	-
Sand	38,136.40 kg	38,136.40 kg	-	landfill	Disposal, limestone residue, 5% water to inert material landfill/CH
Limestone	135.51 kg	135.51 kg	-	landfill	Disposal, inert waste, 5% water, to inert material landfill/CH
Cement	431.91 kg	431.91 kg	-	landfill	Disposal, building, cement (in concrete) and mortar, to final disposal/CH
Cast iron	621.40 kg	347.80 kg	182.40 kg	recycling	Recycling steel and iron/RER
Ceramic brick	1,789.74 kg	1,789.74 kg	-	landfill	Disposal, building, brick, to final disposal/CH
Pavement	3,840.00 kg	3,840.00 kg	-	landfill	Disposal, inert waste, 5% water, to inert material landfill/CH
Concrete	5,760.00 kg	5,760.00 kg	-	landfill	Disposal, inert waste, 5% water, to inert material landfill/CH
Steel	24,826.32 kg	1,556.50 kg	2,889.17 kg	recycling	Recycling steel and iron/RER
Synthetic rubber	3.79 kg	0.89 kg	0.89 kg	recycling	Recycling mixed plastics/RER
Copper	10,556.18 kg	386.07 kg	336.75 kg	recycling	Recycling steel and iron/RER
Priming	192.40 kg	11.64 kg	9.08 kg	landfill	Disposal, building, emulsion paint on walls, to final disposal/CH
Wood	3.78 kg	0.22 kg	0.17 kg	incineration	Disposal, building, waste wood, untreated, to final disposal/CH
LDPE	0.05 kg	-	-	recycling	Recycling mixed plastics/RER
Bronze	366.10 kg	84.80 kg	84.80 kg	recycling	Recycling steel and iron/RER
Cardboard	226.61 kg	90.64 kg	9.46 kg	recycling	Recycling cardboard/RER
Brass	4,320.00 kg	1,714.20 kg	1,723.60 kg	recycling	Recycling steel and iron/RER
PVC	5,452.80 kg	239.92 kg	240.92 kg	recycling	Recycling PVC/RER
Glass fiber	4,712.00 kg	658.13 kg	658.13 kg	landfill	Disposal, building, mineral plaster, to final disposal/CH
Epoxy resin	-	-	44.96 kg	landfill	Disposal, building, polyurethane sealing , to final disposal/CH

IV.5. RESULTS AND DISCUSSION

This section presents the results of the LCA for the gas grid in high and low density neighborhoods and for propane tank scenarios in low density neighborhoods. Additionally, a sensitivity analysis is performed using the average lifespan provided by expert 2 to analyze how this variability can affect the results. Finally, the neighborhood pipe distance that equals the impact for the propane tanks system is calculated.

IV.5.1. Subsystems analysis for the gas grid scenario

The results are first presented for each of the subsytems of the high density scenario (from IV.5.1.1. to IV.5.1.3.) and after together for the complete high density (IV.5.1.4.) and low density (IV.5.1.5) scenario.

IV.5.1.1. Neighborhood network

Table IV.8. Characterization results for each element of the neighborhood network subsystem. Data for 100 m of grid.

Impact category	HDPE tube	surface box	trench	Total
AP (kg SO_2 eq.)	8.47E+00 (35.4%)	3.56E+00 (14.9%)	1.19E+01 (49.7%)	**2.39E+01**
EP (kg PO_4^{2-} eq.)	5.56E-01 (17.3%)	6.12E-01 (19.1%)	2.04E+00 (63.6%)	**3.21E+00**
GWP (kg CO_2 eq.)	7.75E+02 (12.3%)	1.16E+03 (18.5%)	4.35E+03 (69.2%)	**6.29E+03**
HTP (kg 1.4-DB eq.)	2.76E+01 (5.4%)	2.17E+02 (42.5%)	2.67E+02 (52.1%)	**5.11E+02**
ODP (kg CFC-11 eq.)	2.44E-07 (0.1%)	6.03E-05 (24.8%)	1.82E-04 (75.1%)	**2.43E-04**
ADP (kg Sb eq.)	1.42E+01 (45.7%)	5.17E+00 (16.7%)	1.17E+01 (37.6%)	**3.10E+01**

In Table IV.8 we see that the excavation and refilling of the trench have an impact greater than 50% in the EP, GWP, HTP and ODP categories. With regard to the category AP, the trench and the material of the HDPE tube have similar impacts (about 40%) and finally, for the ADP category, what contributes most to the impact is the pipe. The surface box is never the component with a greater impact in any impact category. However, its impact is non-negligible.

The contribution of the trench comes mainly from the use of cement and concrete. Bricks and cast iron are the most impacting materials used in the surface box.

IV.5.1.2. Building subsystem

Table IV.9. Characterization results for each element of the building subsystem in the high density scenario. Data for one building.

Impact category	PE-Cu Transition	service line	gas meter & assoc. elem.	closet	gas tap	Total
AP (kg SO_2 eq.)	2.46E-03 (0.0%)	6.69E+00 (6.5%)	9.57E+01 (92.4%)	1.13E+00 (1.1%)	9.36E-02 (0.1%)	**1.04E+02**
EP (kg PO_4^{2-} eq.)	1.04E-04 (0.0%)	2.42E-01 (17.3%)	1.05E+00 (75.5%)	9.67E-02 (6.9%)	3.69E-03 (0.3%)	**1.40E+00**
GWP (kg CO_2 eq.)	1.27E-01 (0.0%)	1.04E+02 (3.5%)	2.39E+03 (79.7%)	5.01E+02 (16.7%)	1.84E+00 (0.1%)	**3.00E+03**
HTP (kg 1.4-DB eq.)	1.59E+00 (0.0%)	4.80E+03 (64.5%)	2.56E+03 (34.4%)	2.50E+01 (0.3%)	5.64E+01 (0.8%)	**7.45E+03**
ODP (kg CFC-11 eq.)	1.42E-08 (0.0%)	7.25E-06 (1.0%)	6.80E-04 (92.2%)	5.02E-05 (6.8%)	1.34E-07 (0.0%)	**7.37E-04**
ADP (kg Sb eq.)	8.15E-04 (0.0%)	7.08E-01 (3.1%)	2.04E+01 (88.3%)	1.98E+00 (8.6%)	1.35E-02 (0.1%)	**2.31E+01**

Gas meters and associated elements are the major contributors to the total impact of the building subsystem (Table IV.9), mainly due to the pressure regulator (due to the glass fiber and the brass) and the gas meter (due to the brass).

IV.5.1.3. Dwellings subsystem

Table IV.10. Characterization results for each element of the dwelling subsystem in the high density scenario. Data for one dwelling.

Impact category	downpipe	gas tap	pressure meter	boiler	Total
AP (kg SO_2 eq.)	1.67E+00 (25.7%)	9.35E-02 (1.4%)	3.31E-02 (0.5%)	4.70E+00 (72.3%)	**6.50E+00**
EP (kg PO_4^{2-} eq.)	6.04E-02 (11.0%)	3.68E-03 (0.7%)	3.54E-04 (0.1%)	4.86E-01 (88.3%)	**5.50E-01**
GWP (kg CO_2 eq.)	2.61E+01 (8.3%)	1.82E+00 (0.6%)	7.25E-01 (0.2%)	2.84E+02 (90.8%)	**3.13E+02**
HTP (kg 1.4-DB eq.)	1.20E+03 (32.2%)	5.64E+01 (1.5%)	4.21E-01 (0.0%)	2.47E+03 (66.3%)	**3.73E+03**
ODP (kg CFC-11 eq.)	1.85E-06 (9.1%)	1.20E-07 (0.6%)	1.37E-07 (0.7%)	1.81E-05 (89.6%)	**2.02E-05**
ADP (kg Sb eq.)	1.78E-01 (11.8%)	1.34E-02 (0.9%)	6.17E-03 (0.4%)	1.31E+00 (86.9%)	**1.51E+00**

The component with the highest impact in all impact categories in the dwellings subsystem is the boiler, followed by the downpipe (Table IV.10). The impact of both elements is mainly due to the use of copper.

IV.5.1.4. Total impact of a high density neighborhood gas grid scenario

Data in Table IV.11 is for 100 meters of neighborhood network, 10 buildings, 240 dwellings and waste treatment of the materials involved.

Table IV.11. Characterization results for the complete high density gas grid scenario.

Impact category	Neighborhood	Buildings	Dwellings	Waste treatment	Total
AP (kg SO_2 eq.)	2.39E+01 (0.9%)	1.04E+03 (39.0%)	1.56E+03 (58.8%)	3.28E+01 (1.2%)	**2.65E+03**
EP (kg PO_4^{2-} eq.)	3.21E+00 (2.1%)	1.40E+01 (9.0%)	1.32E+02 (85.5%)	5.15E+00 (3.3%)	**1.54E+02**
GWP (kg CO_2 eq.)	6.29E+03 (5.4%)	3.00E+04 (26.0%)	7.51E+04 (65.1%)	4.03E+03 (3.5%)	**1.15E+05**
HTP (kg 1.4-DB eq.)	5.11E+02 (0.1%)	7.45E+04 (7.7%)	8.95E+05 (92.0%)	2.58E+03 (0.3%)	**9.72E+05**
ODP (kg CFC-11 eq.)	2.43E-04 (1.9%)	7.37E-03 (57.0%)	4.85E-03 (37.5%)	4.65E-04 (3.6%)	**1.29E-02**
ADP (kg Sb eq.)	3.10E+01 (4.7%)	2.31E+02 (35.3%)	3.61E+02 (55.2%)	3.08E+01 (4.7%)	**6.54E+02**

Table IV.11 shows the proportional impact attributable to each of the three subsystems included in the high density scenario, plus the waste treatment. Due to the high density of the analyzed scenario, the neighborhood grid is the one with the smallest impact in all impact categories (always below 5.2% contribution).

If the subsystems were to be segregated into the elements that compose them, the gas meters, the boiler and the downpipe are those which have the greatest impact in the modeled scenario. This is due to the fact that these elements are used individually by all end consumers, whereas there is only one neighborhood network, which is shared by all users.

The contribution of waste treatment to overall impact is low (a maximum of 4.7% in the case of ADP) and similar to the one of the neighborhood subsystem.

IV.5.1.5. Total impact of a low density neighborhood gas grid scenario

Table IV.12 presents data for 100 meters of neighborhood network, 4 detached houses, 4 dwellings and waste treatment of the materials involved.

Table IV.12. Characterization results for the complete low density gas grid scenario.

Impact category	Neighborhood	Buildings	Dwellings	Waste treatment	Total
AP (kg SO_2 eq.)	2.39E+01 (24.8%)	4.33E+01 (44.9%)	2.00E+01 (20.7%)	9.24E+00 (9.9%)	**9.64E+01**
EP (kg PO_4^{2-} eq.)	3.21E+00 (40.5%)	1.17E+00 (14.8%)	1.98E+00 (25.0%)	1.56E+00 (19.7%)	**7.93E+00**
GWP (kg CO_2 eq.)	6.29E+03 (68.2%)	9.05E+02 (9.8%)	1.16E+03 (12.6%)	8.66E+02 (9.4%)	**9.21E+03**
HTP (kg 1.4-DB eq.)	5.11E+02 (1.6%)	1.99E+04 (62.9%)	1.06E+04 (33.5%)	6.00E+02 (1.9%)	**3.16E+04**
ODP (kg CFC-11 eq.)	2.43E-04 (35.3%)	1.51E-04 (22.0%)	7.42E-05 (10.8%)	2.19E-04 (31.9%)	**6.87E-04**
ADP (kg Sb eq.)	3.10E+01 (60.6%)	6.62E+00 (12.9%)	5.38E+00 (10.5%)	8.16E+00 (16.0%)	**5.12E+01**

In low density neighborhoods the impact is much more distributed among the different subsystems than in the high density scenario. However, the neighborhood network is the subsystem with a greater impact in four impact categories (EP, GWP, ODP and ADP). This introduces the idea that in low density neighborhoods there is a certain length of neighborhood network that has a greater impact than other alternative systems for providing the same service. This theoretical length is calculated in section IV.5.5.

IV.5.2. Propane tank scenario

Table IV.13 provides the impact of one propane tank operating during 50 years, considering the materials involved, diesel consumption for supplying propane five times per year (10 kilometers each time) and truck production. The impact of propane transport represented in Table IV.13 accounts for 250 two-way trips of 10 km (the impact of the trip is the same for one or four neighbors as the truck has to travel anyway).

Table IV.13. Characterization results for each element of the propane tank subsystem.

Impact category	Tank						Transport		Total
	brass	cardboard	epoxy	Installat.	PVC	steel	truck prod.	Propane transport.	
AP (kg SO_2 eq.)	2.31E-01 (0.9%)	3.41E-03 (0.0%)	4.95E-01 (1.9%)	8.38E-01 (3.3%)	4.24E-03 (0.0%)	5.21E+00 (20.3%)	4.50E-01 (1.8%)	1.84E+01 (71.8%)	**2.56E+01**
EP (kg PO_4^{2-} eq.)	9.50E-03 (0.2%)	5.67E-04 (0.0%)	7.48E-02 (1.3%)	1.71E-01 (3.0%)	4.13E-04 (0.0%)	1.38E+00 (24.3%)	9.70E-02 (1.7%)	3.92E+00 (69.4%)	**5.65E+00**
GWP (kg CO_2 eq.)	5.14E+00 (0.1%)	5.66E-01 (0.0%)	7.51E+01 (1.9%)	8.49E+01 (2.1%)	5.41E-01 (0.0%)	1.01E+03 (25.4%)	8.80E+01 (2.2%)	2.72E+03 (68.2%)	**3.99E+03**
HTP (kg 1.4-DB eq.)	1.50E+02 (5.6%)	4.60E-02 (0.0%)	5.69E+00 (0.2%)	6.61E+00 (0.2%)	4.86E-02 (0.0%)	2.07E+03 (76.7%)	4.87E+01 (1.8%)	4.19E+02 (15.5%)	**2.70E+03**
ODP (kg CFC-11 eq.)	3.26E-07 (0.1%)	1.15E-07 (0.0%)	2.04E-08 (0.0%)	1.06E-05 (2.6%)	9.48E-10 (0.0%)	5.06E-05 (12.4%)	6.89E-06 (1.7%)	3.39E-04 (83.2%)	**4.08E-04**
ADP (kg Sb eq.)	3.46E-02 (0.1%)	4.20E-03 (0.0%)	6.79E-01 (2.5%)	5.71E-01 (2.1%)	6.02E-03 (0.0%)	6.89E+00 (25.8%)	6.78E-01 (2.5%)	1.78E+01 (66.8%)	**2.67E+01**

The transport of propane and the steel of the tank are the two elements that determine the impact of this subsystem. Together they two represent more than 92% of the environmental impact in all impact categories for the propane tank subsystem.

The impacts for 4 propane tanks, 4 building and dwelling grids in a low density neighborhood, and the impact of waste treatment of the materials involved are given in Table IV.14. The waste treatment processes selected for the environmental analysis of propane tank waste are given in Table IV.7.

Table IV.14. Characterization results for the complete propane tank scenario.

Impact category	Propane tank (transp. incld.)	Buildings	Dwellings	Waste treatment	Total
AP (kg SO_2 eq.)	2.56E+01 (28%)	4.33E+01 (47.3%)	2.00E+01 (21.9%)	2.55E+00 (2.8%)	**9.15E+01**
EP (kg PO_4^{2-} eq.)	5.65E+00 (61.0%)	1.17E+00 (12.6%)	1.98E+00 (21.4%)	4.67E-01 (5.0%)	**9.27E+00**
GWP (kg CO_2 eq.)	3.99E+03 (62.8%)	9.05E+02 (14.2%)	1.16E+03 (18.3%)	2.97E+02 (4.7%)	**6.35E+03**
HTP (kg 1.4-DB eq.)	2.70E+03 (8.1%)	1.99E+04 (59.5%)	1.06E+04 (31.7%)	2.30E+02 (0.7%)	**3.34E+04**
ODP (kg CFC-11 eq.)	4.08E-04 (61.7%)	1.51E-04 (22.8%)	7.42E-05 (11.2%)	2.85E-05 (4.3%)	**6.62E-04**
ADP (kg Sb eq.)	2.67E+01 (65.4%)	6.62E+00 (16.2%)	5.38E+00 (13.2%)	2.12E+00 (5.2%)	**4.08E+01**

The contribution of the propane tank subsystem to the total impact of the complete propane tank scenario is above 60% in four impact categories (EP, GWP, ODP and ADP). For AP and HTP the main source of impact is in the buildings subsystem, mainly due to the service line and gas meters. Besides, the impact associated with the waste treatment of propane tank materials is very low (5.2% in ADP is the maximum).

IV.5.3. Results put into perspective

The results obtained are briefly put in perspective by comparing them with the proportional part of regional gas pipeline attributable to each user. According to the data for Spain given in the introduction (52,000 km of gas pipeline per 6,000,000 users), each costumer roughly uses 8.6 meters of regional pipeline.

The environmental impacts from the construction of one kilometer of off shore natural gas pipeline are taken from the Ecoinvent process *GLO: pipeline, natural gas, long distance, high capacity, offshore*) (Faist Emmengger et al. 2003).

Table IV.15. Comparison of the environmental impacts of 8.6 m of regional gas pipeline with the proportional part per user of a neighborhood and in-house network.

Impact category	8.6 meters regional pipeline	Gas grid scenario high density (per user)	Gas grid scenario low density (per user)	Propane tank scenario (per user)
AP (kg SO_2 eq.)	5.97E+01 (100.0%)	1.10E+01 (18.5%)	2.41E+01 (40.4%)	2.29E+01 (38.3%)
EP (kg PO_4^{2-} eq.)	1.65E+01 (100.0%)	6.42E-01 (3.9%)	1.98E+00 (12.0%)	2.32E+00 (14.0%)
GWP (kg CO_2 eq.)	1.15E+04 (100.0%)	4.79E+02 (4.2%)	2.30E+03 (20.0%)	1.59E+03 (13.8%)
HTP (kg 1.4-DB eq.)	2.75E+03 (100.0%)	4.05E+03 (147.2%)	7.90E+03 (287.1%)	8.35E+03 (303.4%)
ODP (kg CFC-11 eq.)	8.77E-04 (100.0%)	5.38E-05 (6.1%)	1.72E-04 (19.6%)	1.66E-04 (18.9%)
ADP (kg Sb eq.)	6.97E+01 (100.0%)	2.73E+00 (3.9%)	1.28E+01 (18.4%)	1.02E+01 (14.6%)

Note: Results obtained for the scenarios are divided by the number of final users (240 for the high density and 4 for the low density scenarios), and are compared with the impact for 8.6 meters of offshore natural gas pipeline. Percentages indicate the relative importance of each scenario in relation to 8.6 meters of offshore natural gas pipeline.

Table IV.15 shows that the neighborhood and in-house distribution gas network have a non negligible contribution to the total environmental impact from the gas distribution system. This point out the importance of how the neighborhood network is designed and built, and thus the importance of the study described in this chapter.

IV.5.4. Sensitivity analysis; average lifespan of gas grid components

So far we have presented the results for high and low density neighborhoods. But given the fact that infrastructure experts cannot be sure of the average lifespan of each of the components, a sensitivity analysis has been performed by extending the analysis to the data given by expert 2 (Table IV.6).

As it has been presented, when urban density is modified the relative distribution of impacts among subsystems has a great variability. However, modifying the average lifespan of the components has very little effect on the relative distribution of the results (Figure IV.3). Moving horizontally in Figure IV.3 we can see that there are slight changes on the distribution of impacts, whereas there are significant changes if we move vertically through the figure. It is especially remarkable the shift on the most dominant subsystem, dwellings in the high density and neighborhood in the low density.

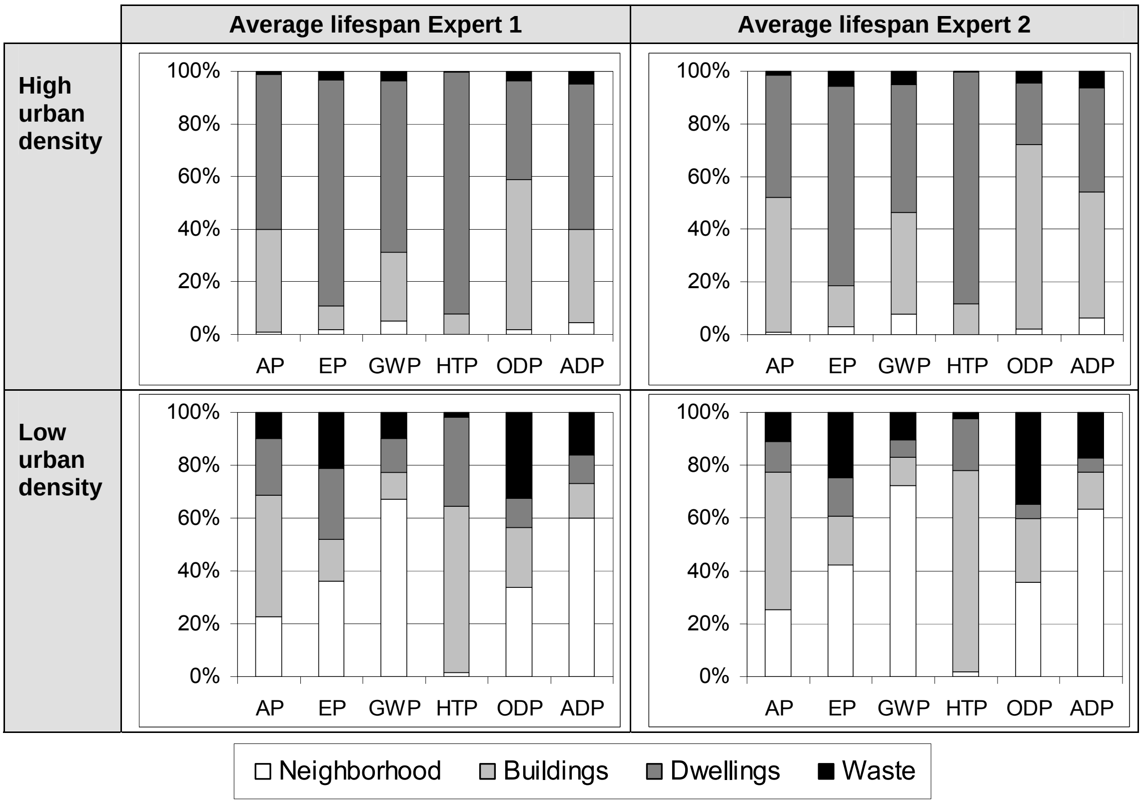

Figure IV.3. Relative contribution (%) of each subsystem to global environmental impact according to urban density and the average lifespan of materials.

According to the high urban density and long average lifespan scenarios, we find that, depending on the category, the impact of a natural gas grid per house is between 1.9 and 4.8 times higher in a detached house located in a low density area than in a dwelling located in a high density area (Table IV.16). The GWP and ADP impact categories are the ones more affected by the urban density reduction, increasing their impact by more than a factor 4.

Table IV.16. Ratio of impact per living unit (low-density scenario/high density scenario).

Neighborhood	Buildings	Dwellings	Waste treatment	Total
60.0	1.2 – 16.0	0.7 – 0.9	12.9 – 28.2	1.9 – 4.8

The total impact of the neighborhood network is the same in both scenarios, but as there are fewer houses in the low density scenario, the impact corresponding to each is 60 times higher.

In the building category, there are certain elements such as PE-Cu transition and service line which are shared among the different users in the case of housing blocks, reducing their relative impact.

In the dwelling subsystem the impact of a single-family building is lower than that of a dwelling in a housing block. This is due to the fact that a lower average distance has been considered from the gas meter to end consumption, i.e. the downpipe is shorter.

IV.5.5. Comparison of the natural gas distribution network and isolated infrastructure using propane tanks

Given that in low density areas the neighborhood subsystem is the most environmentally relevant, the environmental advisability of its substitution by a discontinuous system based on propane tanks has been evaluated.

This section compares the impact of the neighborhood subsystem for the gas grid scenario (Table IV.8) and the propane tank scenarios (Table IV.14). The aim is to calculate the neighborhood pipe distance that equals the impact for the propane tanks system, in order to provide information on whether to install or not a new natural gas grid or keep using discontinuous systems based on tanks, i.e. there is a certain distance from which the grid has more impact than a propane tank, and so it is environmentally preferable not to install it. If an isolated house requires more than 60 meters of neighborhood network for itself, the environmental balance for the ODP becomes favorable for the installation of propane tanks, and the same happens progressively with the GWP (69 m), ADP (92 m), AP (88 m) and EP (162 m). The last impact category to be compensated would be HTP, and for this a neighborhood grid of 1 kilometer would be required. This high value is due to the impact of the steel involved in the propane tanks.

As the differences between impact categories are of two orders of magnitude the results highlight the importance of working with several impact categories, instead of self-limiting the results to CO_2 emissions, for instance.

IV.6. CONCLUSIONS

The amount of environmental impact originated by natural gas grids in urban neighborhoods depends on the urban density. The environmental impact of the neighborhood and in-house grid per living unit is between 1.9 to 4.8 times higher in a single-family house located in a low density area than in a dwelling located in a housing block in a high density area. The impact categories that are more affected by a decrease on urban density are GWP and ADP.

In addition, the location of the main sources of environmental impact is also determined by the urban density. In this sense in high density neighborhoods the impact comes from the building and dwelling subsystems (more than 94% of the impact in all impact categories), while in low density neighborhoods the impact comes mainly from the neighborhood subsystem (main contributor in EP, GWP, ODP and ADP impact categories). Within each subsystem there are several elements which make different contributions to the overall impact. For instance, in the high density scenario, the critical components (>40% impact contribution in at least five impact categories) are the trench works and refilling, the gas meter and associated elements and the boiler, while the most irrelevant ones (<1% impact contribution in all impact categories), which are placed in the building and dwelling subsystems, are the PE-Cu transition, the building tap and the pressure meters in the dwellings.

In low density areas the neighborhood pipe distance that equals the impact for the propane tanks system for all impact categories is of 1 kilometer. This means that if an isolated single user requires more than 1,000 meters of neighborhood pipe it's environmentally preferable to use a propane tank system. This result is true for those environmental impacts considered in this study.

The results obtained in this study may be of interest for municipal decision makers and engineers responsible for the design of natural gas grids, as the results clearly show in which cases installing a grid is environmentally advisable or not. In addition, having identified which components are the main responsible for the environmental impact of gas grids in urban neighborhoods provides clues for the eco-design of natural gas grids in order to reduce the environmental impact of these infrastructures.

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CHAPTER V

ENVIRONMENTAL IMPACTS OF THE INFRASTRUCTURE FOR DISTRICT HEATING IN URBAN NEIGHBORHOODS

Oliver-Solà J, Gabarrell X, Rieradevall J (2009) Environmental impacts of the infrastructure for district heating in urban neighborhoods. Energy Policy, Under revision since December 2008.

ABSTRACT

District heating is a technology for distributing centrally produced heat for space heating and sanitary hot water generation for residential and commercial uses. The objectives are to identify which subsystems and components of a district heating grid are the main contributors to the overall impact of the infrastructure; and provide environmentally oriented design strategies for the future eco-redesign of these kinds of infrastructures. This paper performs a Life Cycle Assessment (LCA) to determine the environmental impacts of a district heating infrastructure in an urban neighbourhood context. The analysis covers seven subsystems (power plant, main grid, auxiliary components of the main grid, trench works, service pipes, buildings and dwellings) and twelve standard components. The results for the subsystems show that the sources of impact are not particularly located in the main grid (less than 7.1% contribution in all impact categories), which is the focus of attention in the literature, but in the power plants and dwelling components. These two subsystems together contribute from 40% to 92% to the overall impact depending on the impact categories. Concerning the components, only a reduced number are responsible for the majority of the environmental impact. This facilitates identifying effective strategies for the redesign of the infrastructure.

V.1.INTRODUCTION

District heating is a technology for distributing centrally produced heat for space heating and sanitary hot water generation for residential and commercial uses. Heat is distributed to the consumers through a network of district heating pipes using water as the transport medium. The market for district heating is primarily based on apartment blocks in dense areas. As Gustavsson and Karlsson (2003) have noted, the development of district heating in single–family houses is restricted by distribution costs and heat distribution losses.

Domestic heat demand for about 6% of the population in the 15 member countries of the European Union in 1999 is covered by district heating (Euroheat & Power Unichal 2003). However, there are significant regional variations. In countries with cold climates, such as the Scandinavian countries, Poland and Estonia, district heating technology in urban areas has been used for many years and its use is widespread (Froning 2003). More specifically, in Sweden about 40% of the space heating market is affected by district heating (Euroheat & Power 2001). However, in southern European countries, where mild climates prevail, this technology is still fairly new.

Despite the milder weather, which implies shorter usage periods, governments support combined heat and power (CHP) plants and district heating by subsidies for investments, fuels, preferential feed-in tariffs and connection rights (Agrell and Bogetoft 2005). Comparatively high-energy efficiency in district heating projects, often combined with use of renewable fuels, makes the technologies especially attractive in order to reduce emissions of greenhouse gases (Bowitz and Trong 2001) and other benefits like fewer chimneys and better air quality in dwelling areas. With this objective, in 2002 the Commission of the European Communities proposed a directive on the promotion of combined heat and power (Commission of the European Communities 2002) because cogeneration of electricity and heat makes possible a more efficient utilization of fuel than electricity production alone. District heating is the way to make use of the collected heat in the cogeneration scheme.

In southern Europe some new urban developments that aim to achieve a better environmental performance choose district heating as an efficient option in the use of energy. In Catalonia (Spain) there is a successful experience of district heating for about 700 dwellings with centrally produced heat from biomass in the municipality of Molins de Rei (Barcelona). Most of the technical local data for this study has been gathered from this site. However research evaluating the environmental impacts related to this kind of infrastructure from a life cycle perspective is in its early stages.

Some of the most detailed LCA of district heating pipes (pipe production (Fröling et al. 2004) and network construction (Fröling and Svanstrom 2005)) including the use phase (Persson et al. 2006; Perzon et al. 2007) has been done by researchers at the Department of Chemical and Biological Engineering at Chalmers University of Technology. However, this excellent work does not study a complete district heating grid within a neighborhood, including all the components from the CHP plant to the heat exchangers, which is the aim of the current chapter.

Additional research has been carried out on fuels for district heating rather than infrastructure research. Many different heat sources can be used to supply district heating networks with hot water. The most common fuels for district heating in Europe are natural gas and coal, but oil and renewables are also commonly used. Waste heat from industrial processes can also be utilized, as well as heat from waste incineration, geothermal heat and solar heat (Persson et al. 2006).

Eriksson et al. (2007) performed a LCA comparing district heating based on waste incineration with combustion of biomass or natural gas. Their results indicated that combustion of natural gas in CHP plants is an alternative of interest if marginal electricity has a high fossil content. However, gas generally performs worse than bio-fuels. In addition, as Persson et al. (2006) point out, another advantage of central heat generation in large plants is that it makes possible the arrangement of highly efficient burning and flue gas treatment.

Regarding efficient technological options other than district heating, Pehnt (2008) states that the advantages of micro cogeneration (cogeneration based on small conversion units in a single building) with regards to green house gases are comparable to district heating with CHP. More focused on district heating, Gustavsson and Karlsson (2003) compare district heating using CHP with local fuel-based and electric heating systems for detached houses. The heat pump and district heating systems are found to be most energy efficient, followed by the local fuel-based systems. Furthermore, district heating, natural gas fired boiler systems and heat pump systems exhibited the lowest costs.

V.2.GOAL AND SCOPE

V.2.1. Objectives

There are several systems for providing heat to a neighborhood. The two most extensively used in cities of developed countries – besides electricity – are either providing heat using a district heating scheme or distributing the fuel, mostly natural gas (methane), which provides heat after combustion in a domestic boiler. This chapter aims to perform a LCA to determine the environmental impacts within a local neighborhood context of a district heating infrastructure, from the central CHP plant to the heat exchangers in the dwellings.

Currently, we only know the environmental impact of isolated elements of a district heating infrastructure. We do not have a global vision that shows which system, subsystem or component has a greater impact. In addition, the urban population is increasing every year, which makes the building of new urban infrastructures necessary. Knowing the sources of environmental impact for these infrastructures may help to redesign them from an environmental perspective and reduce their environmental impact.

The results obtained should:

- Obtain inventory data of subsystems not studied in former papers on district heating networks.

- Answer which subsystems and components of a district heating grid are the main contributors to the overall environmental impact of the infrastructure.
- Provide environmentally oriented design strategies for the future eco-redesign of these kinds of infrastructures. This is in line with what was also asked for in the conclusions of Bardouille and Koubsky (2000).
- Determine whether building density is a determining factor for the environmental impact per dwelling in a district heating infrastructure.
- Put the impact of a district heating infrastructure into perspective by comparing it with the one for a standard infrastructure used for distributing natural gas (Oliver-Solà et al. 2009), which after combustion is a source of heat for domestic uses.

The results obtained in this study may be of interest to energy companies constructing and designing district heating infrastructures, as well as to public officials and decision makers trying to integrate environmental criteria into the municipal planning process of new and existing neighborhoods.

V.2.2. Functional unit

The functional unit is the basis that enables alternative goods, or services, to be compared and analyzed. In this case, the functional unit is the neighborhood infrastructure that serves to provide heat for satisfying the domestic requirements for space heating and sanitary hot water of a standard family in 240 dwellings[8] within a local urban neighborhood for 50 years.

This functional unit does not directly reflect the function of the district heating infrastructure (i.e. heat distribution), as it refers only to the infrastructure for distributing heat, not the energy consumption, nor the heat losses during the use phase. This use is not considered.

V.2.3. Description of the systems under study

The district heating infrastructure has been studied in a section of urban neighborhood corresponding to one hundred meters of street with ten blocks of 24 dwellings each.

The scenario boundaries are the limits of the defined neighborhood. The chapter differentiates between three systems: neighborhood, building and dwelling (Figure V.1).

In turn, each system contains subsystems. There are seven subsystems in the scenario distributed as follows:

- Neighborhood: power plant, main grid, components of the main grid, and trench works.
- Buildings: service pipes and components in the buildings.
- Dwelling: components in the dwellings.

[8] Assuming that these dwellings are the main residence for this standard family.

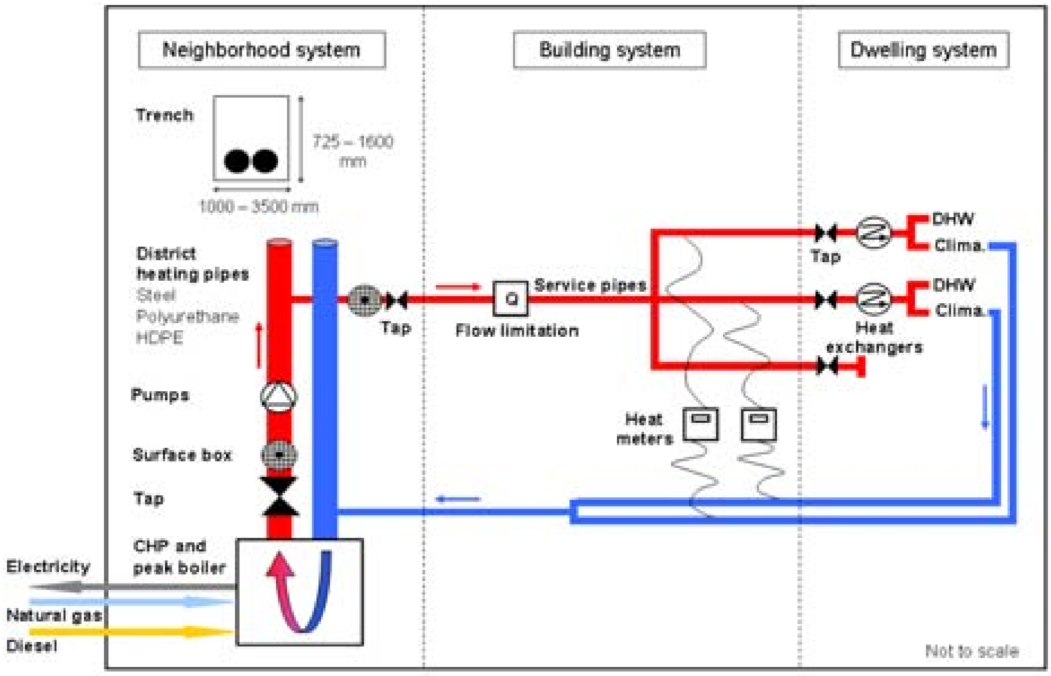


Figure V.1. Schematic diagram of the systems and components that compose a district heating infrastructure.

Note: DHW: Domestic Hot Water; Clima.: Climatization

Each subsystem, in turn, is composed of different components. In the neighborhood system there are 100 meters of flow and 100 meters of return pipes, eleven surface boxes and taps (one every 100 meters of street and one in the connection with each building) and two pumps. In the buildings system there are 3,912 meters of service pipes, ten flow limiting devices (one per building), and 240 heat meters (one per dwelling). Finally, in the dwelling subsystem, each dwelling has a heat exchanger and a tap (240 in the total scenario).

Under consideration were: materials, installation works and maintenance of components for 50 years of operation.

The district heating pipes under study consist of a steel tube insulated with foamed polyurethane to avoid large heat losses from the networks. A polyethylene casing protects the foam layer from damage, water intrusion and thermal ageing due to gas diffusion.

Like infrastructure for many urban services, the district heating pipe system is buried under streets and sidewalks. The necessary excavation and construction work is also considered in this chapter. As presented in Figure V.1, the trench measures are in a variable range of 725 - 1600 mm of depth and 1000 - 3500 mm width. Average measures have been used for calculation purposes.

V.2.4. Data source

In order to compile the materials and weights of the different infrastructural components that commonly make up the district heating infrastructure in a Spanish context, the database *Metabase ITeC* (2008) has been used. At the same time, all the scenarios have been approved by a local expert engineer in district heating systems.

Data for power plants and the dimensions of the district heating pipes was adapted from a real project for a 2,000 dwelling unit neighborhood (VIMED 2007). In that project, heat was produced in a CHP installation (1 MW_e) producing both heat and electricity from natural gas as well as a peak boiler (6 MW_{th}), producing only heat from diesel fuel. The peak boiler was used to supply heat during the moments of higher demand, which account for 25% of the annual heat produced in the system. The neighborhood under analysis in this chapter is considered to be inserted in this broader urban area, therefore, only the proportional part of CHP plant and peak boiler have been considered (240 dwellings in the chapters' scenario/ 2,000 dwellings in the project = 0.12).

With regard to pipes, the length of the neighborhood pipes is defined by the scenario under study (100 meters each way) and the average diameter is 100 mm, and for the service pipes an average length of 391.2 meters per building is assumed, with the average diameter being around 50 mm.

Taking the above mentioned inventory of materials involved in the infrastructures as a foreground system (detailed in Tables V.1 to V.3), the background system consists in the raw material extraction, production, stocking and transportation, as well as energy consumed in digging the trenches for the main grid (Figure V.2).

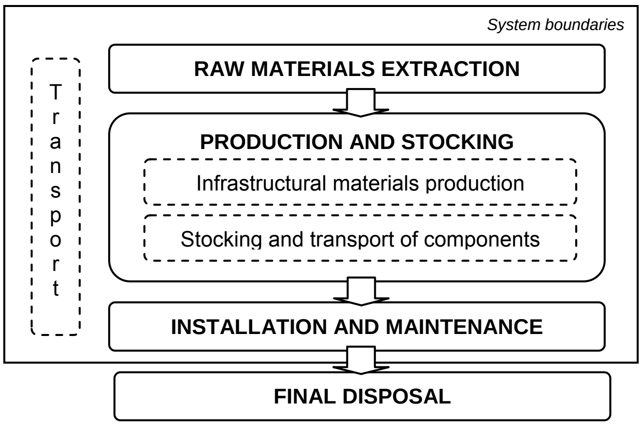


Figure V.2. System boundaries and process chain under study.

The Ecoinvent 1.2 inventories of building products (Kellenberger et al. 2004), waste treatment services (Doka 2003), metals (Althaus et al. 2004), packaging and graphical paper (Hischier 2004), transport services (Spielmann et al. 2004) and energy systems (Dones et al. 2004) have been used for evaluating the emissions related to materials and energy. In the few cases where an inventory process was not available in the Ecoinvent inventories, the material was chosen from the PE Europe database associated with the software *GaBi 4* (IKP University of Stuttgart and PE Europe GmbH 2003). In all cases these processes have been clearly identified in Tables V.1 to V.3.

Due to the novelty and the low number of district heating infrastructures in southern Europe there is a lack of average data on the origin of the different materials involved in the district heating infrastructure. Therefore, only local transportation has been considered. Data was obtained from the process *Truck/7.5t total cap./4.7t payload/local* of PE Europe database and an average distance of 25 kilometers has been chosen as an appropriate approximation in a metropolitan area. The impact of transportation is not presented in a disaggregated way, but accounted for in the values of impacts for each of the materials and components.

Waste treatment is not included in the analysis because currently, to the best of the authors' knowledge, no district heating has been dismantled in Spain. And so the lack of local experience on waste treatment of district heating infrastructures and the long durability of these infrastructures makes it impossible at this time to determine which treatment processes will be followed in the future, which components will be reused, or which designs allow or facilitate recycling and which do not. Nevertheless, as the majority of components are made from metal, the inclusion of end of life treatments (i.e. recycling) in the system certainly could make a relevant difference in the results.

V.2.5. Methodology

The LCA methodology permits the assessment of all environmental impacts associated with a product, process or activity by accounting and evaluating resource consumption and emissions (ISO 2006). Civil engineering and the built environment are fields of great potential for LCA, and research in these areas may provide useful information for the eco-design of the cities of the future.

Of all the steps included in the Life Cycle Impact Assessment (LCIA) methodology (ISO 2000), only the classification and characterization steps have been conducted here. In the classification step, each environmental burden is linked to one or more impact categories. In the characterization step, the contribution of each burden to each impact category is calculated by multiplying each burden by a characterization factor (Guinée 2001). The classification and characterization method used was CML 2 Baseline 2000 (Guinée 2001), and the LCA software *Gabi 4* (IKP University of Stuttgart and PE Europe GmbH, 2003). The impact categories analyzed and their units are acidification (AP, kg SO_2 eq.), eutrophication (EP, kg PO_4^{3-} eq.), global warming (GWP, kg CO_2 eq.), human toxicity (HTP, kg 1.4-DB eq.), ozone layer depletion (ODP, kg CFC-11 eq.) and abiotic depletion (ADP, kg Sb eq.).

V.3. RESULTS

The results are presented in two sections. Section V.3.1 presents the inventory data and section V.3.2 the impact assessment.

V.3.1. Inventory data

Tables V.1 to V.3 describe the materials, processes and weights, referenced in lineal meters or units, of each component of the district heating infrastructure for the neighborhood, buildings and dwellings systems. At the same time, in the last column on the right, the amount of each component required in the studied scenario is presented. The CHP plant and peak boiler are not specifically modeled but taken from a background database and scaled on the basis of dwellings served.

The energy values in Table V.1 for surface box and trench works correspond to the energy needed for installation and excavation respectively.

a) Neighborhood system

Table V.1. Components and materials for the neighborhood system.

Sub-system	Component	Material	Process	Quantity in the component	Quantity in the scenario
Power plant	CHP plant[1] (1 unit)	Cogen unit 1MWe	RER: cogen unit 1MWe, common components for heat+electricity	Aggregated data from Ecoinvent 1.2	0.12 units
	Peak boiler[1] (1 unit)	Diesel, heat generating set 6MWth	RER: diesel-electric generating set production 10MW	Aggregated data from Ecoinvent 1.2	0.12 units
Trench works	Trench works (1 meter)	Pavement	CH: cement, unspecified, at plant	3.84E+01 kg	100 meters
		Concrete	DE: concrete block, at plant	5.76E+01 kg	
		Aggregates	CH: sand, at mine	3.61E+02 kg	
		Diesel	GLO: diesel, burned in building machine	3.45E+01 MJ	
Main grid	District heating pipes (1 meter)	Steel	RER: steel, low-alloyed, at plant	1.17E+01 kg	200 meters
		Foamed polyurethane	RER: polyurethane, rigid foam, at plant	2.06E+00 kg	
		HDPE	RER: polyethylene, HDPE, granulate, at plant	2.35E+00 kg	
Components of the main grid	Surface box (1 unit)	Water	RER: tap water, at user	2.28E+02 kg	11 units
		Sand	CH: sand, at mine	2.08E+03 kg	
		Limestone	CH: gypsum plaster board, at plant	1.36E+02 kg	
		Cement	CH: cement, unspecified, at plant	4.39E+01 kg	
		Cast iron	RER: cast iron, at plant	1.65E+02 kg	
		Ceramic brick	RER: brick, at plant	1.79E+03 kg	
		Electricity	ES: electricity, low voltage, production ES, at grid	7.76 MJ kg	
	Tap (1 unit)	Bronze	CH: bronze, at plant	6.70E-01 kg	11 units
		Synthetic rubber	RER: silicone product, at plant	6.80E-03 kg	
		Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	2.37E-05 kg	
	Pump (1 unit)	Stainless steel	DE: Stainless steel sheet PE[2]	1.51E+01 kg	2 units
		Cast iron	RER: cast iron, at plant	1.36E+02 kg	

[1] Data for these components was taken from the Ecoinvent 1.2 database. No material disaggregation could be done. Quantity in the scenario was calculated from real data (1 unit per 2,000 dwellings was extrapolated to 0.12 units per 240 dwellings).

[2] Data from PE Europe database

(p) packaging

b) Building system

Table V.2. Components and materials for the building system.

Sub-system	Component	Material	Process	Quantity in the component	Quantity in the scenario
Service pipes	Service pipes (1 meter)	Steel	RER: steel, low-alloyed, at plant	3.64E+00 kg	3,912 meters
		Foamed polyurethane	RER: polyurethane, rigid foam, at plant	8.20E-01 kg	
		HDPE	RER: polyethylene, HDPE, granulate, at plant	1.03E+00 kg	
Components in the buildings	Flow limiting (1 unit)	Brass	CH: brass, at plant	3.00E-01 kg	10 units
	Heat meter (1 unit)	Aluminum anodized	RER: sheet rolling, aluminium	7.00E-01 kg	240 units
		PVC	RER: polyvinylchloride, at regional storage	1.00E-01 kg	
		ABS	RER: acrylonitrile-butadiene-styrene copolymer, ABS, at plant	2.00E-01 kg	

c) Dwelling system

Table V.3. Components and materials for the dwelling system.

Sub-system	Component	Material	Process	Quantity in the component	Quantity in the scenario
Components in the dwellings	Heat exchangers (1 unit)	Galvanized steel	DE: Steel sheet galvanized PE [1]	2.27E+01 kg	240 units
		Stainless steel	DE: Stainless steel sheet PE [1]	2.70E+00 kg	
		Copper	RER: copper, at regional storage	2.16E+01 kg	
		Foamed polyurethane	RER: polyurethane, rigid foam, at plant	2.70E+00 kg	
		PVC	RER: polyvinylchloride, at regional storage	4.32E+00 kg	
		Wood (p)	CH: disposal, building, waste wood, untreated, to final disposal	8.00E+00 kg	
		LDPE (p)	RER: packaging film, LDPE, at plant	1.15E+00 kg	
		Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	3.07E+00 kg	
	Tap (1 unit)	Bronze	CH: bronze, at plant	6.70E-01 kg	240 units
		Synthetic rubber	RER: silicone product, at plant	6.80E-03 kg	
		Cardboard (p)	CH: disposal, packaging cardboard, 19.6% water, to inert material landfill	2.37E-05 kg	

[1] Data from PE Europe database

(p) packaging

V.3.1.1. Average life of components

According to Perret (1995) and adaptations of his work, the average life of components for district heating infrastructures is twenty years for power plants, district heating pipes and trench works; fifteen years for surface boxes, flow limiting devices, heat meters and heat exchangers; and ten years for pumps and taps.

Although many construction materials and products can be perfectly operable for more than 30 years there is a lot of uncertainty and lack of reliable data on lifespan of components. However, the majority of material producers and suppliers don't guarantee their products for more than ten years. This is mainly because insurance companies rarely issue insurance for more than this time period.

V.3.2. Impact assessment per systems, subsystems and components

Systems

Each system has a different contribution to the total impact depending on the considered impact categories; but it is the neighborhood system that is the main contributor in four impact categories (EP, GWP, ODP, ADP) and the dwelling system in the other two (AP, HTP) (Table V.4). With the exception of the ADP category, due to the large amount of materials required for the secondary district heating grid, the building system has a less relevant contribution.

Table V.4. Distribution of the environmental impacts in each system of the complete district heating infrastructure in the defined scenario.

System	AP (%)	EP (%)	GWP (%)	HTP (%)	ODP (%)	ADP (%)
Neighborhood	33.3	49.4	59.5	26.1	65.1	44.8
Building	17.0	26.0	23.0	5.4	12.7	35.5
Dwelling	49.6	24.5	17.5	68.4	22.2	19.6

Subsystems

Breaking down the system division into subsystems (Figure V.3), it can be seen that the power plant (CHP plant and peak boiler), and especially the dwelling components (basically, the heat exchanger), are those components with the greatest impact. Individually, they are always above 17% of the global impact, and together they are responsible for a contribution of between 40% and 92% of the global impact depending on the impact categories. However, it is also worth stressing that the service pipes have an important impact contribution (more than 15% in three impact categories) because of its great length, especially if compared with the main grid.

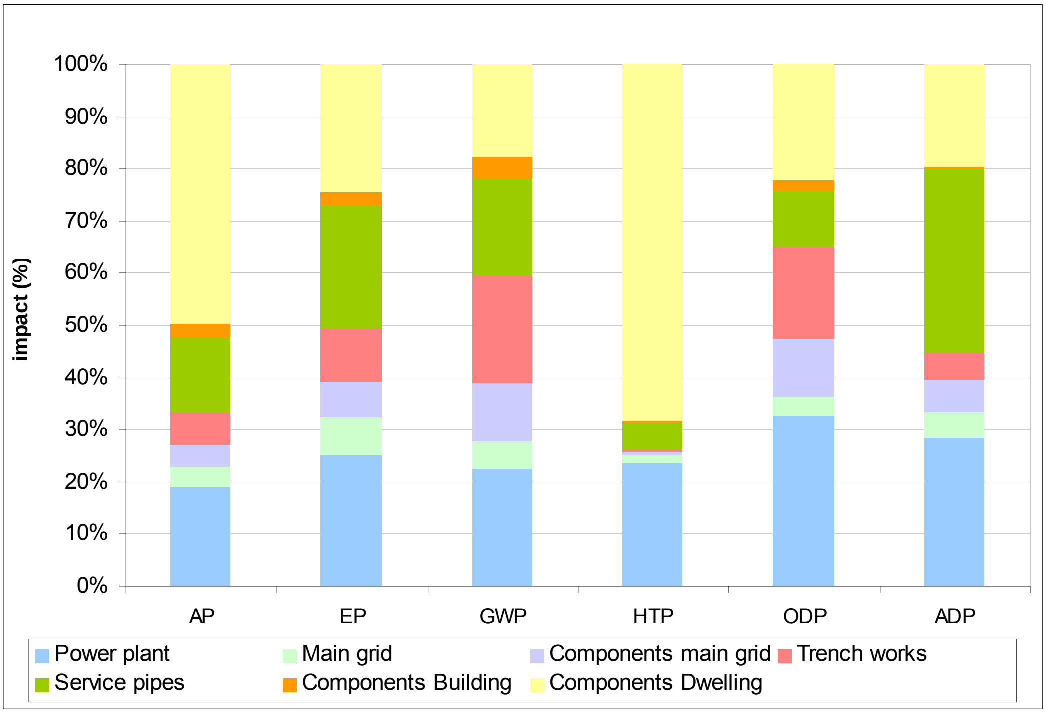


Figure V.3. Relative distribution of environmental impacts per impact category and subsystems.

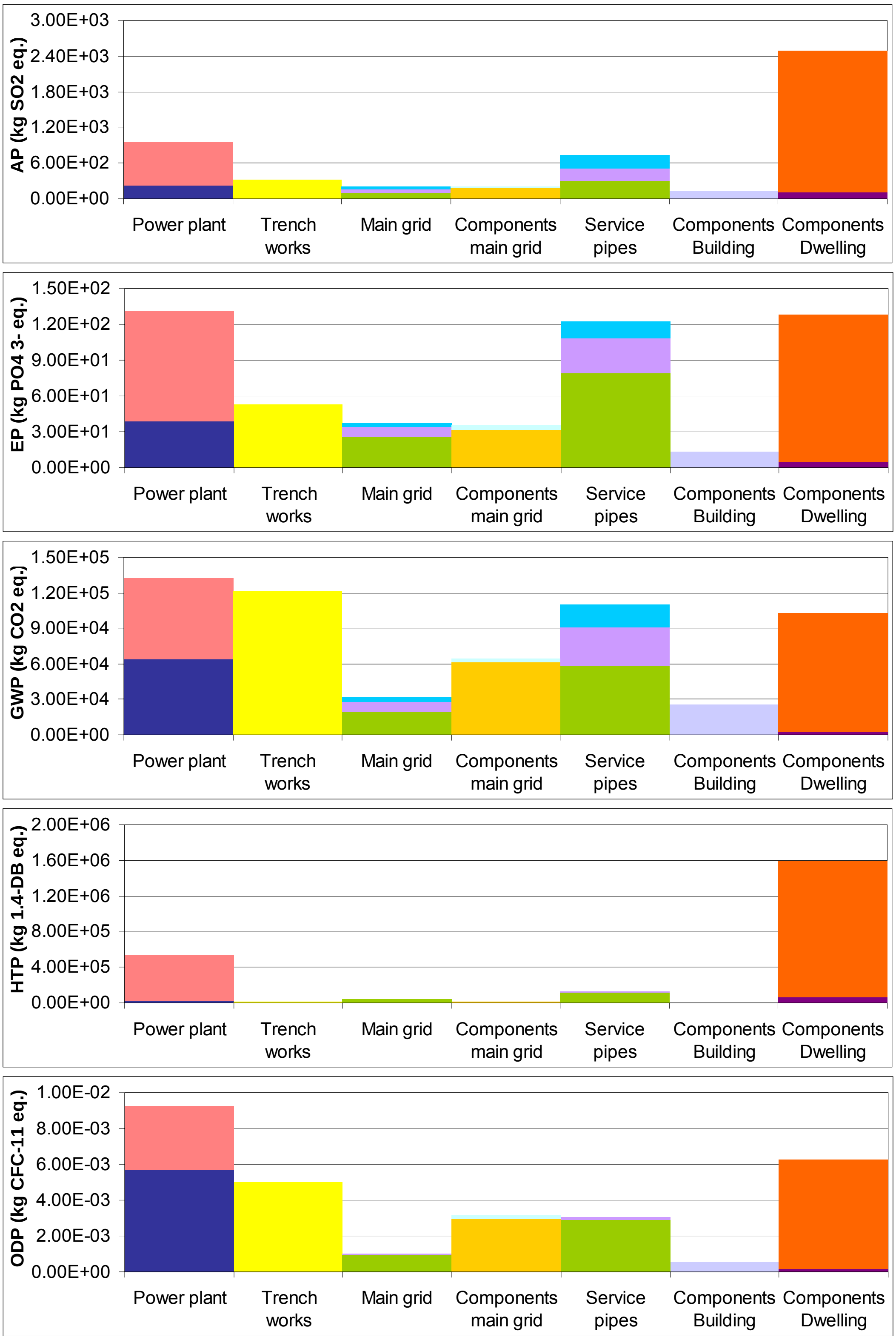
These results lead to the conclusion that increasing the building density wouldn't help to diminish the environmental impact per dwelling of a district heating infrastructure because the components with most impact are proportional to the number of dwellings. The power plants and the heat exchangers do not behave like the pipes in the neighborhood system, whose impact is shared among all the users. Rather, each dwelling has a heat exchanger and the power plant would need to be upgraded in order for it to produce heat for more dwellings.

Components

Figure V.4 shows the distribution of the environmental load among the components of each subsystem for each of the six impact categories analyzed. Due to the low quantity of materials in the district heating pipes, this subsystem is also divided into sub-materials.

Within the power plant subsystem, a minimum of 38.5% (ODP impact category) and a maximum of 95.5% (HTP impact category) of the impact originate in the peak boiler. On the other hand, within the dwelling components, more than 95.5% of the impact is attributable to the heat exchangers; the use of copper is the main source of impact in this component. With regards to the district heating pipes, between 43.2 – 97.4% of the impact is attributable to steel, while in the service pipes, the contribution is 36.1 – 96.6%, being in both cases the maximum contribution in the HTP category and the lowest in the ADP category. These results obtained for the pipes are supported by the ones obtained by Fröling et al. (2004), for the three impact categories that coincide in both analysis.

Among the components of the main grid, the surface box is responsible for a minimum impact of 87.6% in EP and a maximum of 95.2% in GWP. The trench works are especially relevant in the GWP category (20.6% contribution), as it was also identified by Fröling and Svanstrom (2005) (although in a slightly different scenario).



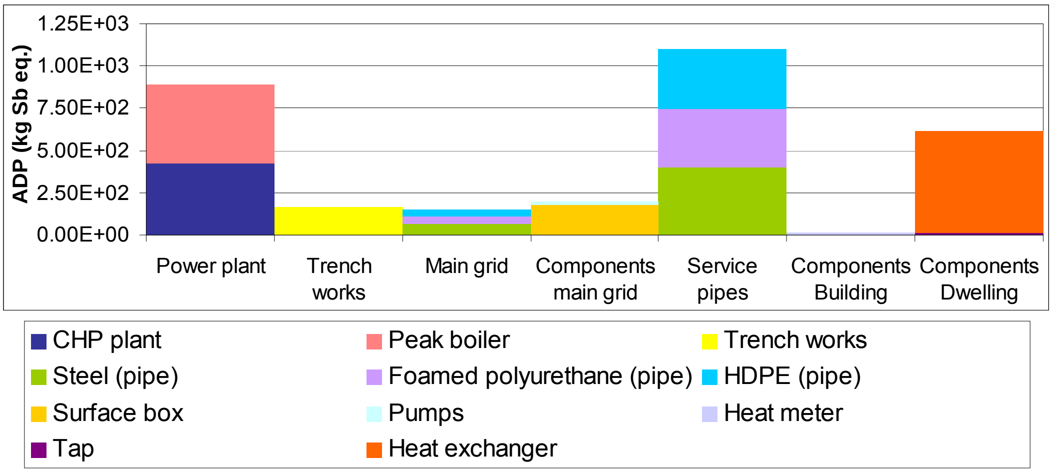


Figure V.4. Contribution of each component to the global impact per subsystem. The components with a contribution below 1% to their subsystem have been removed from the figure.

Studying the relative impact of components with respect to the total impact of the infrastructure, the components that make a contribution greater than 15% in at least one category are trench works (20.6% in GWP, 17.7% in ODP), CHP plants (20.2% in ODP), peak boilers (17.9% in EP, 22.3% in HTP and 25% in ADP), steel from the service pipes (25.2% in EP) and heat exchangers (47.4% in AP, 23.7% in EP, 17.1% in GWP, 65.5% in HTP, 21.6% in ODP and 19.1% in ADP).

As a consequence of the results presented above, a reduced number of components are responsible for the majority of the environmental impact.

V.4. RESULTS PUT INTO PERSPECTIVE

In this section the results obtained for the district heating infrastructure are put into perspective by comparing them with the ones obtained by the same authors for a natural gas grid in the same urban scenario (Oliver-Solà et al. 2009).

Both infrastructures are used to provide the same thermal service to a neighborhood. The natural gas grid provides fuel to the dwellings, which is combusted in domestic boilers to provide useful heat. However, in the case of the district heating with a CHP plant scenario, in addition to heat supply there is also electricity production. The aim of this comparison is not to compare completely functionally equivalent infrastructures, but to put into perspective and compare the environmental impacts of two infrastructures that largely share the same function.

This comparison is especially relevant for municipal planners that have to choose how to supply heat to a new or refurbished neighborhood.

The average life for the natural gas grid components is also taken from Perret (1995). This is twenty years for copper pipe, PE-copper transition, closets and trench works; fifteen years for surface boxes, gas meters and pressure meters; and ten years for taps and gas boilers.

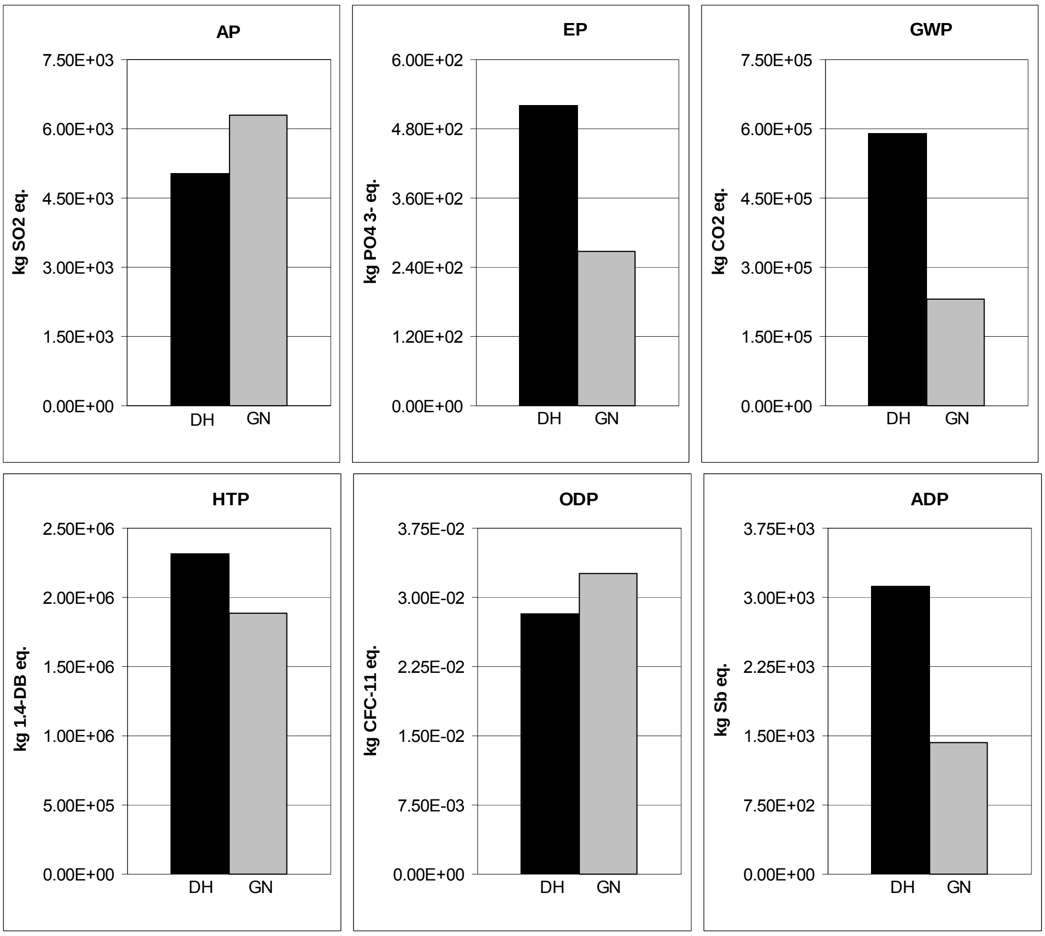


Figure V.5. Characterization contribution of district heating (DH) and natural gas (NG) infrastructures to each impact category.

Figure V.5 shows that using the same data reference for the average life of components, the infrastructure for district heating has more than a 40% higher impact than the infrastructure for the supply of natural gas in three impact categories (EP, GWP, ADP). In the other three (AP, HTP, ODP) it has an impact similar to natural gas, with differences of less than 20%.

As presented in Figure V.4 in the AP category, the impact for the district heating is mainly focused in the heat exchangers, while in the natural gas system the main sources of impact for this category are in the gas meters, boilers and downpipes.

In the EP category the main source of impact for the natural gas system are the boilers, while for the district heating the heat exchangers are the components that contribute the most, although there are additional components that contribute significantly to impact, including the power plant, trench works, pipes, surface boxes and heat meters.

For GWP the impact of district heating is more than double the impact for the natural gas infrastructure. This result is explained by the deeper and wider trenches used by the district heating infrastructure and the fact that the heat exchangers alone have the same contribution as the boilers in the natural gas system, which are the main contributors in that system.

Two components monopolize the impact in the HTP category for the district heating infrastructure, the peak boiler and the heat exchangers. On the other hand, in the natural gas infrastructure, boilers and copper pipes are the contributors to the impact.

The brass and polyester resin used in the gas meters are the main contributors to the ODP impact category for the natural gas infrastructure. However, the contribution in absolute value is very low compared to the other categories.

And finally, the district heating infrastructure doubles the impact of natural gas infrastructure in the ADP category because of the important contribution of the power plant, trench works, surface boxes, service lines and heat exchangers.

V.5. CONCLUSIONS

The LCA of a district heating infrastructure in a street section of 100 meters, with ten blocks of 24 dwellings each, shows that even though the main source of environmental impact is not always associated with the same system of the district heating infrastructure (neighborhood, buildings or dwellings), it is the neighborhood system that is the main contributor in four impact categories (49.4% in EP, 59.5% in GWP, 65.1% in ODP, 44.8% in ADP) and the dwelling system in the other two (49.6% in AP, 68.4% in HTP). The building system has a less relevant contribution with the only exception being the ADP category (due to the large amount of materials required for the secondary district heating grid).

While breaking down the system division into subsystems, it was observed that the source of environmental impact in a district heating infrastructure within a neighborhood is located in a reduced number of subsystems. The four subsystems with a major contribution to the total impact are the power plant (from 18.9 up to 32.8% contribution depending on the impact categories), trench works (20.6% and 17.7% contribution in GWP and ODP impact categories, respectively), service pipes (35.2% in ADP, 23.5% in EP and 18.7% in GWP) and dwelling components (from 17.5 to 68.4% contribution depending on the impact categories).

With regards to the components, the following components make a contribution greater than 15% with respect to the total impact of the infrastructure in at least one category: trench works (20.6% in GWP, 17.7% in ODP), CHP plants (20.2% in ODP), peak boilers (17.9% in EP, 22.3% in HTP and 25% in ADP), steel from the service pipes (25.2% in EP) and heat exchangers (47.4% in AP, 23.7% in EP, 17.1% in GWP, 65.5% in HTP, 21.6% in ODP and 19.1% in ADP).

From these results it can be observed that the subsystems and components with a higher contribution are proportional to the number of dwellings, and not shared among users as it occurs, for example, with the main grid.

Additional conclusions concerning further research and eco-design are: first, given that heat exchangers are one of the components with a higher contribution to the total environmental impact, a shift from the thermo model considered in this analysis to a plate heat exchanger, could potentially reduce the environmental impact of the infrastructure.

Second, given that the impact of trenching represents more than 20% in the GWP impact category, the potential environmental saving achieved by strategies like the co-utilization of trenches for different service networks, or service galleries, which are multifunctional and can host several infrastructures, should be the object of a more in-depth analysis.

Third and last, any eco-design strategy that varies from the current components should be checked while considering all the life cycle phases in order to avoid negative problem shifting. For instance, from an infrastructural point of view, the content of foamed polyurethane could be reduced, but this decision would contribute to increasing heat losses in the use phase, and so, this would off-set any environmental savings from the measure

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CHAPTER VI

GENERAL CONCLUSIONS AND FURTHER RESEARCH

VI.1. GENERAL CONCLUSIONS

All chapters from II to V, which present research results, have had their own specific discussion, extended conclusions and have outlined future research lines to be followed. Therefore, this chapter draws the general conclusions and recommendations, based on the information and results obtained in the previous parts of the environmental analysis of the service sector and urban infrastructures, and compiles only the most relevant conclusions presented in each chapter.

The general conclusions are focused on giving an educated answer to the general objectives presented in chapter I.5.2.

VI.1.1. Industrial Ecology as a discipline for the analysis and design of sustainable urban settlements

Industrial Ecology has its origins in the analysis of industrial activities and society, and the tracking of substance flows. However, the same approach applied to urban systems, studying the metabolism of the cities, neighborhoods, economic sectors or infrastructures, provides clarifying data about the metabolism of urban systems; identifies the environmental flaws and improvement opportunities of our urban systems and becomes the first step for guiding ecodesign processes on an infrastructural or neighborhood scale. General conclusions could be summarized by the following points:

VI.1.1.1. Industrial Ecology

- Industrial Ecology's scope and tools have proved to be useful for analyzing the service sector's metabolism and the environmental impact of civil engineering infrastructures on the public space of cities.
- The results obtained in this thesis could be used as entry data for the redesign and optimization of these services and infrastructures, reproducing the ecodesign methodology on bigger scales in order to improve cities from an environmental perspective. In short, the results can be applied in the design of Eco-Neighborhoods.

VI.1.1.2. LCA in urban settlements

- It is possible to extend the use of LCA, initially designed for the analysis of products or processes, to the analysis of civil works in the urban environment.
- LCA makes the integration of environmental tools in urban planning easier.
- The main advantages of the application of LCA to civil works are that it enables determination of the materials, components, processes and subsystems that are responsible for a major contribution to the overall environmental impact of the infrastructure. Besides, the environmental impact can be quantified using different

impact categories, which turned out to be innovative for a sector that is used to focusing almost exclusively on CO_2 emissions.

- However, the analysis of complex systems like civil works entails difficulties for defining functional units that fit within the ISO 14,04X series. One reason is that civil infrastructures may have multiple and simultaneous uses (in the case of sidewalks up to four functional units had to be defined). Another reason is that, like in the case of energy distribution networks, the analysis has to be focused on a highly specific and well defined infrastructure, regardless of the function of delivering gas or heat that it fulfills.

VI.1.1.3. Service sector metabolism

- Energy consumption varies among different types of services, not only in the amount of energy consumed by each facility, but also in the energy profile of a facility. The fact must be taken into account that within each service category, there are also huge differences that can approximate two orders of magnitude.
- The lack of environmental regulation and the perception that services have a low environmental impact contribute to services facilities' managers' failing to control or ignoring the important contribution that they could make to achieving a reduction in energy consumption, and thus to a better environment.

VI.1.1.4. Concrete sidewalks

- The main contributor, considering a life-cycle perspective, to the environmental impacts of the analyzed concrete sidewalk types is cement (contributing from approximately 24% to nearly 77% of the total impact, depending on the impact category and system). Cement has the highest and the lowest contribution in the GWP and POCP categories, respectively.
- As clinker is the main contributor to cement environmental impact, techniques should be developed and implemented to reduce environmental impacts at the clinker manufacturing stage and, if possible, to use other types of cement with more additions and less clinker.
- Other materials, such as aggregates, are used in large quantities but are low-impact (less than 10% in ADP and ODP, where it contributes the most). For this reason, strategies such as using recycled aggregates would have a negligible effect on reducing the overall environmental impact.
- “One size fits all” solutions are useful for facilitating installation and maintenance. However, they entail a significant increase (up to 73.8%) in the environmental impacts associated with sidewalks.

- As regards ecodesign and green public procurement, it is essential for sidewalks to be adapted to their required function(s), thereby avoiding the current oversizing of many sidewalk sections and reducing the environmental impacts within the public space.

VI.1.1.5. Natural gas distribution networks

- The environmental impact of the neighborhood and in-house natural gas grid per living unit is between 1.9 to 4.8 (for HTP and GWP respectively) times higher in a single-family house located in a low density area than in a dwelling located in a housing block in a high density area.
- In high density neighborhoods the impact comes from the building and dwelling subsystems (more than 94% of the impact in all impact categories), while in low density neighborhoods the origin of the impact is more diffuse, but with a significant increase in the neighborhood subsystem (between 1.6 – 68.2% contribution for HTP and GWP, respectively).
- In the high density scenario, the critical components (>40% impact contribution in at least five out of six impact categories) are trench work and refilling, gas meters and associated elements and boilers.
- In low density areas the neighborhood pipe distance that equals the impact for a discontinuous system based on propane tanks and truck transportation for all impact categories is of 1 kilometer.
- There is very little information available about the average lifespan of materials and components. This lack of crucial information is a barrier for the proper analysis of these infrastructures.

VI.1.1.6. District heating distribution networks

- The four subsystems that contribute more than 15% in at least two impact categories are power plants (from a minimum contribution of 18.9% for AP up to a maximum of 32.8% for ODP), trench work (20.6% and 17.7% contribution in GWP and ODP impact categories, respectively), service pipes (35.2% in ADP, 23.5% in EP and 18.7% in GWP) and dwelling components (from a minimum contribution of 17.5% for GWP up to a maximum of 68.4% for HTP).
- The impact of trenching represents more than 20% in the GWP impact category.
- The following components make a contribution greater than 15% with respect to the total impact of the infrastructure in at least one category: trench works (20.6% in GWP, 17.7% in ODP), CHP plants (20.2% in ODP), peak boilers (17.9% in EP, 22.3% in HTP and 25% in ADP), steel from the service pipes (25.2% in EP) and heat exchangers (47.4% in AP, 23.7% in EP, 17.1% in GWP, 65.5% in HTP, 21.6% in ODP and 19.1% in ADP).

- A proposal for improvement would be the co-utilization of trenches for different service networks, or service galleries, and this should be the object of a more in-depth analysis.

VI.1.1.7. Repercussions of this research on the planning, construction and use of sustainable cities

- The results obtained in the analysis of energy consumption in the service sector are useful for formulating environmental policies in this urban subsystem.
- The symbiosis concept has been successfully applied in industrial states, however it is still inexistent in service states. Service activities could be gathered into clusters in order to take advantage of their combined improvement potentials (for example, collective transport systems, garden waste used as combustion fuels for heating purposes …).
- Although much attention to mitigating climate change and other environmental impacts has focused on direct energy consumption, better urban design represents an important yet undervalued opportunity. It would be advisable to use environmental quantification tools to guide the urban planning processes from their initial stages.
- Concerning the environmental impact of cities, the material use in infrastructures is highly relevant. There is a need to develop good practice guidelines or legislation concerning the minimum environmental requirements for the public space of cities, which is already being done with residential buildings.
- To facilitate the incorporation of environmental principles in neighborhood, services and infrastructure design is important because many of the problems encountered on the macro-city scale are in fact cumulative consequences of poor planning at the micro-neighborhood level. In addition, most of these decisions are well within the reach of local governments and leaders and can reduce long-term carbon emissions.
- New ISO standards on sustainability in building construction and new planning experiences in eco-neighborhoods will create an inflexion point for the design of future infrastructures and neighborhoods, where the creation of interdisciplinary teams, the inclusion of environmental data in the discussion process and the environmental optimization of infrastructural solutions will be crucial.
- The quantitative environmental assessment of civil engineering works provides guidelines for a green public investment in infrastructures. Public contracts with building companies should include environmental clauses in order to internalize the environmental costs as much as possible by means of selecting the best designs for fulfilling the desired functions.

The usefulness of the quantitative environmental data provided by this thesis was clear during the planning process of the Eco-Neighborhood of Vallbona (Barcelona) (Figure VI.1). Thanks to the research done on concrete sidewalks (chapter III), the whole sidewalk surface of the new Eco-Neighborhood will be optimized according to the results obtained.

At the same time, during this planning process it became clear that further research should focus on methods for optimizing the combination of environmental and planning tools, in the sense that sometimes a rigorous quantitative environmental assessment may require long periods of work while the decision making process is undertaken in a matter of few weeks.

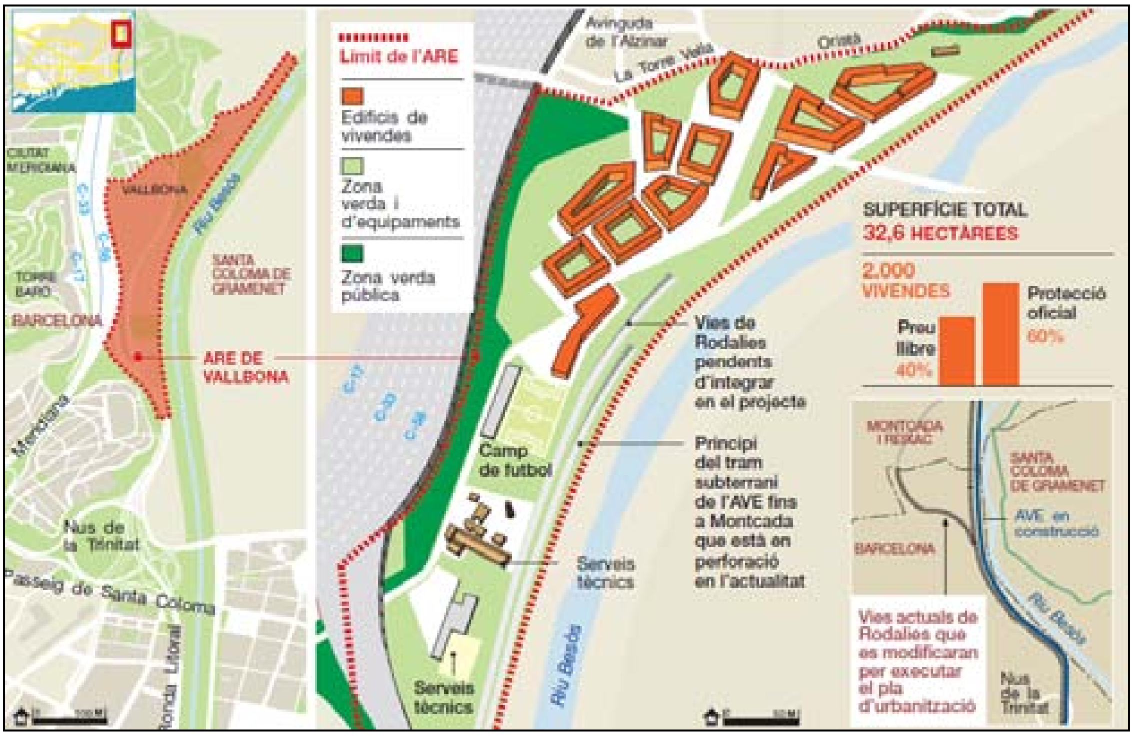

Figure VI.1. Sketch of the proposal for an Eco-Neighborhood in Vallbona (Barcelona).
Source: El Periódico de Catalunya (12/3/2009)

VI.2. FURTHER RESEARCH

This section compiles some of the most general lines of research that could be followed according to the general conclusions presented above.

VI.2.1. Methodology

- Establish a framework to develop the ecodesign methodology applied to scales larger than those of products or processes.
- Use the environmental data provided by this thesis for natural gas and district heating distribution networks, as well as for concrete sidewalks, in their redesign processes.
- Integrate the results of environmental impact of urban infrastructures with Geographic Information Systems (GIS) in order to chart the environmental impact on the urban public space.
- Initiate the development of practical projects in the service sector using symbiotic approaches between facilities.

VI.2.2. Extend the number and types of analyzed systems

- Extend the research to other urban subsystems using Industrial Ecology tools, for instance:
    - Facilities
        - Other service facilities
        - Residential buildings
    - Superficial level
        - Sidewalks of other materials
        - Roads
        - Green urban areas
    - Underground infrastructures
        - Water distribution networks (drinkable, rainwater, gray water)
        - Electricity distribution networks
        - Waste pneumatic transport system

REFERENCES TO CHAPTER VI

El Periódico de Catalunya (12/3/2009) L'ecobarri de Vallbona, sense data d'inici, tindrà 2.000 vivendes [The Eco-Neighborhood of Vallbona, without a date for beginning, will have 2.000 dwellings] http://www.elperiodico.cat/ <Accessed April 2009>