Working on strategies towards urban sustainability

Ramon Farreny Gaya

Doctoral thesis

Supervisors:
Dr. Xavier Gabarrell Durany
Dr. Joan Rieradevall Pons

A thesis submitted in fulfilment of the requirements for the Doctoral degree in Environmental Sciences and Technology

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Universitat Autònoma de Barcelona (UAB)

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icta Institut de Ciència i Tecnologia Ambientals • UAB

UAB Universitat Autònoma de Barcelona

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By

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When you see clouds gathering, prepare to catch rainwater

African proverb, Gola Tribe

The present thesis entitled 'Working on strategies towards urban sustainability' has been carried out at the Institute of Environmental Science and Technology (ICTA) at *Universitat Autònoma de Barcelona* (UAB) under the supervision of Dr. Xavier Gabarrell and Dr. Joan Rieradevall, both from the ICTA and the Department of Chemical Engineering at the UAB.

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Contents

	Page
Figures	**I**
Tables	**V**
List of acronyms, abbreviations and notation	**VII**
Acknowledgments	**IX**
Summary	**XI**
Preface	**XIII**
Part I. INTRODUCTION AND FRAMEWORK	**1**
1. Introduction	**3**
1.1. Urban settlements as a cornerstone for sustainability	5
1.1.1. The sustainability concept	5
1.1.2. Cities and the environment	8
1.1.3. The sustainable city: concept and strategies	14
1.2. Energy and water flows in urban areas	16
1.2.1. Energy and urban settlements	16
1.2.2. Water and urban settlements	19
1.2.3. Interrelations between water and energy	23
1.3. Overview of the industrial ecology framework	24
1.4. Motivation of the dissertation	26
1.5. Objectives of the dissertation	29
2. Methodology	**31**
2.1. Systems of study	33
2.2. Methodological aspects	39
2.3. Sustainability assessment tools	41
2.3.1. Material and Energy Flow Accounting and Analysis	41
2.3.2. Life Cycle Assessment	43
2.3.3. Economic asessment	45
2.3.4. Sustainability indicators	47
2.3.5. Ecodesign	48
2.4. Field and laboratory works	52
2.4.1. Experimental setup	52
2.4.2. Quantity assessment	53
2.4.3. Quality assessment. Analytical techniques	54
References for Part I	**57**

PART II. THE ECODESIGN OF URBAN SETTLEMENTS **65**

3. Transition towards sustainable cities: opportunities, constraints and strategies in planning. A neighbourhood ecodesign case study in Barcelona (Spain) **67**

3.1. Introduction 69

3.2. Case study area: the neighbourhood of Vallbona (Barcelona, Spain) 70

3.3. Methodology. Ecodesign and planning process. 71

3.4. Results and discussion 73

3.4.1. Territorial determining factors 74

3.4.2. Financial determining factors 76

3.4.3. Technical and methodological determining factors 78

3.4.4. Political determining factors 79

3.4.5. Legal determining factors 80

3.4.6. Social-cultural determining factors 82

3.5. Conclusions 83

3.6. Addendum to chapter 3. The proposal for Vallbona 85

3.6.1. Concepts 85

3.6.2. Goals and strategic actions 85

3.6.3. Indicators 86

3.6.4. Layouts of the proposal 88

References for Part II **91**

Part III. ENERGY FLOWS AND INDICATORS IN URBAN AREAS **97**

4. Energy intensity and greenhouse gas emission of a purchase in the retail park service sector: An integrative approach 99

4.1. Introduction 101

4.2. Case study area 104

4.3. Methods and approaches 105

4.3.1. Energetic metabolism description and assessment 105

4.3.2. Strategy proposal and sensibility analysis 111

4.4. Results 112

4.4.1. Energetic metabolism of the service system object of study 112

4.4.2. Sensibility analysis 113

4.5. Discussion 115

4.6. Conclusions 116

References for Part III **119**

Part IV. WATER FLOWS AND INDICATORS IN URBAN AREAS. A FOCUS ON RAINWATER HARVESTING **123**

5. Indicators for sustainable water management in urban systems: case studies of retail parks in Spain and Brazil **125**

5.1. Introduction 127
5.2. Case study areas 127
5.2.1. Spanish case study 128
5.2.2. Brazilian case study 128
5.3. Methodology 129
5.3.1. Water Input and Use Accounting 129
5.3.2. Water intensity of a purchase 131
5.3.3. Potential water self-sufficiency 131
5.4. Results 132
5.4.1. Retail park water metabolism 132
5.4.2. Water Intensity of a purchase 133
5.4.3. Potential Water Self-Sufficiency 133
5.5. Discussion 134
5.6. Conclusions 136

6. Roof selection for rainwater harvesting: quantity and quality assessment **137**

6.1. Introduction 139
6.1.1. Quantity 139
6.1.2. Quality 139
6.2. Material and methods 141
6.2.1. Case study area 141
6.2.2. Experimental design 142
6.2.3. Quantity assessment 142
6.2.4. Quality assessment 144
6.3. Results and discussion 145
6.3.1. Quantity assessment 145
6.3.2. Quality assessment 147
6.4. Conclusions 152

7. Cost-efficiency of rainwater harvesting strategies in dense Mediterranean neighbourhoods **155**
7.1. Introduction 157
7.2. Material and methods 159
7.2.1. Dense Mediterranean neighbourhood case study 159
7.2.2. Methods and approaches 160
7.3. Results 165
7.4. Discussion 169
7.5. Conclusions 171

References for Part IV **173**

Part V. TRANSFER OF KNOWLEDGE **181**

8. Towards a transition **183**
8.1. Acting at an early stage of the design of urban systems and monitoring the performance along their life cycle 200
8.2. Interdisciplinary team and sufficient understanding of the local context 204
8.3. Mixed land uses, high-density of the built-up area and self-sufficiency 206
8.4. Availability of data and criteria for urban ecodesign 213
8.4.1. What is the rainwater harvesting potential of a system? 213
8.4.2. What is the preferable scale of implementation of rainwater harvesting systems? 214

References for Part V **215**

Part VI. GENERAL CONCLUSIONS AND FUTURE ACTIONS **217**

9. Conclusions **219**
9.1. Energetic metabolism of a commercial service neighbourhood 221
9.2. Water metabolism of a commercial service neighbourhood and rainwater harvesting 222
9.3. Roof selection for rainwater harvesting: quantitative and qualitative assessment 223
9.4. Cost-efficiency of rainwater harvesting strategies in dense neighbourhoods 224
9.5. Opportunities and constraints in the design of neighbourhoods 225
9.6. Transfer of knowledge 226

10. Future actions **227**
10.1. Retail metabolism and indicators 229
10.2. (Rain)water management in urban areas 230
10.3. Ecodesign of neighbourhoods 232

Figures

		page
FIGURE A	Flow chart showing the dissertation map (structure of the dissertation).	XVIII
FIGURE 1.1	The three spheres of sustainable development. Only when all of them are fulfilled can we discuss sustainability.	6
FIGURE 1.2	Representation of the role of cities in terms of land occupation, population concentration, consumption of resources and GHG emissions.	10
FIGURE 1.3	The metabolism of a city can be compared to a large animal grazing in its pasture. Just like the beast, the city consumes resources, and all this energy and matter eventually passes through to the environment again.	11
FIGURE 1.4	The urban metabolism of Brussels, Belgium in the early 1970s.	13
FIGURE 1.5	Linear vs circular. Modern cities in many rich countries have a linear metabolism –taking resources and discarding wastes without much concern about environmental impacts. Sustainable cities, by contrast, need to mimic the circular metabolism of natural systems.	14
FIGURE 1.6	Energy and water flows within the city are conditioned by the characteristics of the urban system.	16
FIGURE 1.7	Urban planning directly affects the energy demand of urban systems.	17
FIGURE 1.8	Transport energy vs. urban density for a selection of major cities.	18
FIGURE 1.9	Change in water balance from land development.	20
FIGURE 1.10	Water flows in a typical neighbourhood.	21
FIGURE 1.11	Flows in traditional planning (left side) and in closed-loops planning (right side).	25
FIGURE 1.12	Focus and approach of each goal of the dissertation.	29
FIGURE 2.1	Main characteristics of the Vallbona neighbourhood case study.	34
FIGURE 2.2	Main characteristics of the Sant Boi retail park case study.	35
FIGURE 2.3	Main characteristics of the São Carlos retail park case study.	36
FIGURE 2.4	Main characteristics of the set of roofs in UAB campus case study.	37
FIGURE 2.5	Main characteristics of the Primer de Maig neighbourhood case study.	38
FIGURE 2.6	Overview of the methods used in Parts II, III and IV of the dissertation.	40
FIGURE 2.7	Scope of MEFA framework.	41
FIGURE 2.8	LCA framework.	45
FIGURE 2.9	Stages of the life cycle of an urban settlement.	48
FIGURE 2.10	Diagram of ecodesign methodology applied on urban systems.	49
FIGURE 2.11	Set of roofs in the UAB campus where the experimental design was installed.	52

FIGURE 2.12	Rainwater tanks installed in the set of roofs in UAB campus (from left to right: rainwater tanks in CT, M, P and FG roofs).	53
FIGURE 2.13	Location of the roofs and the weather stations around the UAB campus.	54
FIGURE 3.1	Location of Vallbona. The aerial photograph shows the limits of the future neighbourhood.	71
FIGURE 3.2	Diagram of the ecodesign and planning methodology applied at the neighbourhood scale in Vallbona case study (Barcelona, Spain).	72
FIGURE 3.3	Aerial view of the neighbourhood location in Vallbona (Barcelona, Spain).	88
FIGURE 3.4	Sketch of the proposal for a sustainable neighbourhood in Vallbona (Barcelona).	89
FIGURE 3.5	Vallbona (Barcelona, Spain) planning proposal.	89
FIGURE 4.1	Location of the RP in the metropolitan area of Barcelona. Compact urban areas (mostly residential), major roads and distance isolines are shown.	105
FIGURE 4.2	Energetic metabolism description and assessment methodology.	106
FIGURE 4.3	Retail park object of study. Representation of the energy consumption subsystems in the RP object of study (direct and indirect energy use). The sectors in white colour are in construction in year 2006.	107
FIGURE 4.4	GWP profile under the strategies described. The broken line represents the benchmark greenhouse gas emission of the retail park object of study.	114
FIGURE 5.1	Spanish case study RP. The line shows the limits of the system.	128
FIGURE 5.2	Brazilian case study RP. The line shows the limits of the system.	129
FIGURE 6.1	Diagram of the experimental design.	142
FIGURE 6.2	Regression model for roof runoff and rainfall height. Regression equations and corrected R^2 are also shown. Each point represents a monitored rain event.	145
FIGURE 6.3	Box plot diagram of rooftop runoff water quality for each roof.	151
FIGURE 7.1	(a) Location of the area of study in Europe; (b) aerial photograph of the city of Granollers; (c) aerial photograph of the neighbourhood; (d) land cover map.	160
FIGURE 7.2	Methodology for the design of infrastructures and calculation of performance of indicators.	162
FIGURE 7.3	NPV function depending on the pipe water price.	168
FIGURE 8.1	The four methodological key ideas should be integrated in the ecodesign methodology.	185
FIGURE 8.2	Interrelationships between the chapters, key messages and ecoinnovation projects.	186
FIGURE 8.3	Main characteristics of the 'Greater Helsinki Vision 2050' project.	188
FIGURE 8.4	'Greater Helsinki Vision 2050' project (Figure).	189
FIGURE 8.5	Main characteristics of the 'BSost' project.	190
FIGURE 8.6	'BSost' project (Figures).	191

FIGURE 8.7	Main characteristics of the 'RWH Mediterranean neighbourhood' project.	192
FIGURE 8.8	'RWH Mediterranean neighbourhood' project (Figure).	193
FIGURE 8.9	Main characteristics of the 'EcoPuntVerd' project.	194
FIGURE 8.10	'EcoPuntVerd' project (Figure).	195
FIGURE 8.11	Main characteristics of the 'EcoBarriSocial' project.	196
FIGURE 8.12	'EcoBarriSocial' project (Figure).	197
FIGURE 8.13	Main characteristics of the 'Energy and water flows in museums' project.	198
FIGURE 8.14	'Energy and water flows in museums' project (Figure).	199
FIGURE 8.15	Regression model between energy and water for the selection of museums.	203
FIGURE 8.16	Mixed land uses, integrating the four central nodes, allows synergies within urban systems.	206
FIGURE 8.17	Render drawing of the Sant Andreu proposal. A dense occupation of the built area (on the left) makes possible to have vast areas for agricultural purposes (on the right).	208
FIGURE 8.18	Food flows in the design of the Sant Andreu neighbourhood. Vegetables and fruit would be produced in the open-air and in greenhouses on top of the buildings. Vegetable and fruit self-sufficiency is estimated at 100 and 45 %, respectively.	209
FIGURE 8.19	Organic waste and energy flows in the design of the Sant Andreu neighbourhood. Organic wastes would be composted and used in the green and agricultural areas. Geothermal energy would be the main supply, complemented with solar photovoltaic and solar thermal energy. Energy self-sufficiency is estimated at 89%. Compost self-sufficiency is estimated at 53%.	210
FIGURE 8.20	Water flows in the design of the Sant Andreu neighbourhood. Rainwater would be collected from roofs and paved areas, and used for outdoor and indoor purposes. Groundwater would be used to supply domestic needs. Greywater systems would be installed in all households. Water self-sufficiency is estimated at 100%.	211
FIGURE 10.1	General diagram for the future actions after this dissertation.	228

Tables

		page
TABLE 2.1	Systems of study in the dissertation.	33
TABLE 2.2	Physical-chemical parameters that have been analysed in the samples of stormwater rooftop runoff.	55
TABLE 3.1	Determining factors in the design and planning of sustainable neighbourhoods.	74
TABLE 3.2	Summary of goals, strategic actions and indicators for the Vallbona neighbourhood.	87
TABLE 4.1	Summary of vehicle energy efficiencies and conversion factors for transportation operation.	109
TABLE 4.2	General data about the retail park object of study.	112
TABLE 4.3	EFA and GWP in the RP object of study, including energy consumed as electricity and other fuels for the year 2006.	113
TABLE 4.4	Results for proposed energy and GHG emission intensity indicators applied to the retail park service sector for the year 2006.	113
TABLE 4.5	Sensibility analysis results. The strategies are compared with the reference service system object of study (the variation of energy consumption is displayed in brackets as a percentage). The scenario in which the strategies can be applied is shown.	114
TABLE 5.1	Land cover analysis carried out in the two case studies for 2006 using TNTmips software and local cartographic sources.	132
TABLE 5.2	Water input and use accounting results for the two case studies in 2006.	133
TABLE 5.3	PWSS indicator applied to the two case studies considering two catchment areas alternatives: roof only, and both roof & PCGS, and two rainfall periods (average 30-year rainfall and 2006 rainfall).	133
TABLE 6.1	Review of RC estimates.	140
TABLE 6.2	Characteristics of the roof catchments.	141
TABLE 6.3	Rain events considered in the determination of the RC and the samples for quality analysis.	143
TABLE 6.4	Rooftop runoff quality results and review of literature results.	148
TABLE 6.5	Spearman Rho correlation coefficients between the water quality parameters for the whole set of roofs.	150
TABLE 7.1	Review of the research on the economic feasibility of RWH systems.	158
TABLE 7.2	Definition of RWH strategies.	160

TABLE 7.3 Performance indicators and other variables for each strategy. 165

TABLE 7.4 Elements included in the design of the infrastructures for RWH. The dash indicates that this item does not apply for the strategy. 166

TABLE 7.5 Capital costs of the infrastructures for RWH. 167

TABLE 7.6 Financial results for the RWH strategies. The shadowed cells show the positive NPV. 168

List of acronyms, abbreviations and notation

ADWP	Antecedent Dry Weather Period
Cl^-	Chlorides
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent emissions
CO_3^{2-}	Carbonates
CT roof	Clay Tiles roof
DEA	Data Envelopment Analysis
EC	Electrical Conductivity
EFA	Energy flow Accounting and Analysis
EMC	Event Mean Concentration
EU	European Union
FG roof	Flat Gravel roof
FLW	Field and Laboratory Works
GHG	Greenhouse Gases
GIS	Geographical Information Systems
GWP	Global Warming Potential
H_2CO_3	Carbon acid
HCO_3^-	Bicarbonates
ICLEI	International Council for Local Environmental Initiatives
IE	Industrial Ecology
ISO	International Organization for Standardization
IUWM	Integrated Urban Water Management
KOE	Kilograms of Oil Equivalent
LCA	Life Cycle Assessment
LCCA	Life Cycle Costing Assessment
M roof	Metal roof
MEFA	Material and Energy Flow Accounting
MFA	Material Flow Accounting and Analysis
MIVES	Integrated Value Model for a Sustainability Assessment
NH_4^+	Ammonium
NO_2^-	Nitrites

NO_3^-	Nitrates
NPV	Net Present Value
P roof	Plastic roof
PCGS	Paved Covers at Ground Surface
PO_4^{3-}	Phosphates
PP	Payback period
PWSS	Potential Water Self-Sufficiency
RC	Runoff Coefficient
RP	Retail Park
RWH	Rainwater Harvesting
SETAC	Society for Environmental Toxicology and Chemistry
SO_4^{2-}	Sulphates
SPSS	Statistical Package for the Social Sciences
SRA	Strategic Residential Area
SUDS	Sustainable Urban Drainage Systems
TAN	Total Ammonium Nitrogen
TC	Total Carbon
TIC	Total Inorganic Carbon
TOC	Total Organic Carbon
TOE	Tons of Oil Equivalent
TSS	Total Suspended Solids
UAB	Universitat Autònoma de Barcelona
UN	United Nations
WCP	Waste Collection Point
WHP	Water Harvesting Potential
WIP	Water Intensity of a Purchase
WIUA	Water Input and Use Accounting
WUF	World Urban Forum

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Summary

Global sustainability is an issue of urban sustainability since cities have become the primary human habitat. Urban settlements represent only 2.7% of the world's land area. However, the world's cities use over 75% of the world's resources, and they are responsible for 80% of greenhouse gas emissions. For this reason, it is necessary to define concepts and strategies in order to reduce the city's use of natural resources and production of wastes while simultaneously improving its livability, so it can better fit within the capacities of the local, regional and global ecosystems in a framework of social equity and welfare.

This dissertation is based on the application of several tools and approaches, many of them derived from the discipline of industrial ecology, to the urban environment and, in particular, to neighbourhoods. Industrial ecology is based on the analogy between natural and industrial systems, and consists of a systematic and integrated way by which an industrial system (i.e. a city, a region) is viewed not in isolation from its surrounding systems, but in concert with them.

Ecodesign presents itself as one of the key tools in the move towards more sustainable settlements. Its application in a new neighbourhood in Barcelona has presented the opportunity to discuss and implement several concepts essential to urban sustainability (i.e. urban metabolism, self-sufficiency of resources, land use mixticity, multifunctionality, compactness). Besides, several opportunities and constraints in the process of urban ecodesign have been identified.

Then, the concepts of urban metabolism and self-sufficiency are explored in more detail in the following chapters. Thus, an assessment of the energy and water flows in two commercial neighbourhoods (retail parks) is presented. From this, a set of environmental indicators for monitoring is obtained. Besides, the role of urban form in energy consumption and in the urban water cycle is discussed.

The research on urban water flows arises two specific questions regarding rainwater harvesting strategies, which are dealt with in two specific chapters. The first one is about the potential of rainwater harvesting of different kind of roofs (both in quality and quantity terms); and the second one is about the economic performance of rainwater harvesting systems in dense neighbourhoods.

In addition, several practical examples of the application of some of the concepts, strategies and tools arisen along the research are presented. This results in a set of key methodological ideas that are expected to facilitate a transition towards urban sustainability. These ideas are the importance of acting at an early stage of the design, the need to monitor and assess the performance of the neighbourhood along its life cycle, the requirement of an interdisciplinary team with sufficient understanding of the local context, the incorporation of several essential concepts in the design of neighbourhoods and cities in general (land use mixticity, high-density of the built-up area, urban metabolism and self-sufficiency) and access to information and criteria for urban ecodesign. The consideration of this set of ideas will be useful in the move towards urban sustainability.

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 October 2006 to November 2010 (including the period of the Master in Environmental Studies).

This dissertation is the result of a multidisciplinary approach that aims to develop strategies and tools that could aid in the transition towards urban sustainability, paying particular attention to energy and water.

The dissertation is mainly based on the following published or in review papers in peer-reviewed indexed journals:

- Farreny R, Gabarrell X, Rieradevall J (2008) Energy intensity and greenhouse gas emission of a purchase in the retail park service sector: An integrative approach. *Energy Policy* 36:1957-1968.
- Farreny R, Rieradevall J, Barbassa AP, Teixeira B, Gabarrell X. Indicators for sustainable water management in urban systems: case studies of retail parks in Spain and Brazil. Accepted with revisions in *Water and Environment Journal.*
- Farreny R, Oliver-Solà J, Montlleó M, Escribà E, Gabarrell X, Rieradevall J. Transition Towards Sustainable Cities: Opportunities, Constraints and Strategies in Planning. A Neighbourhood Ecodesign Case Study in Barcelona (Spain). Accepted with revisions in *Environment and Planning A.*
- Farreny R, Guisasola A, Morales-Pinzón T, Tayà C, Rieradevall J, Gabarrell X. Roof selection for rainwater harvesting: quantity and quality assessment. Submitted on September 2010 to *Water Research.*
- Farreny R, Gabarrell X, Rieradevall J. Cost-efficiency of Rainwater Harvesting Strategies in Dense Mediterranean Neighbourhoods. Submitted on September 2010 to *Resources, Conservation and Recycling.*

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- Angrill S, Farreny R, Gasol CM, Viñolas B, Morales T, Gabarrell X, Josa A, Rieradevall J (2010) Eco-efficiency of Rainwater Harvesting in the Design of Mediterranean Neighborhoods. Poster and oral communication. *International Conference on EcoBalance*. Tokyo (Japan).
- Sanyé E, Oliver-Solà J, Gasol CM, Farreny R, Martínez J, Rieradevall J, Gabarrell X (2010) Comparative environmental analysis of a food purchase at a municipal market and a hypermarket in a retail park. Poster. *VII international conference on life cycle assessment in the agri-food sector*. Bari (Italy).

- Farreny R, Oliver-Solà J, Rieradevall J, Gabarrell X, Escribà E, Montelló M (2010) The ecodesign and planning of sustainable neighbourhoods: the case study of Vallbona (Barcelona). Oral Communication. *Sustainable Building Conference SB10,* Madrid (Spain).
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- Rieradevall J, Gabarrell X, Farreny R, Oliver-Solà J (2009) Environmental optimization of urban public space through LCA. Oral Communication. *III International Conference on Life Cycle Assessment (CILCA 2009),* Pucón (Chile).
- Farreny R, Gabarrell X, Rieradevall J (2008) Energy flow indicators in cities: the retail park service sector. Oral Communication. *ConAccount. Accounting for the urban metabolism*. Prague (Czech Republic).
- Grau L, Pich-Aguilera F, Batlle T, Botton J, Terrisse A, Thorson O, Cot E, Gabarrell X, Rieradevall J, Oliver-Solà J, Farreny R, Batlle E, Riera P, Portabella G, Martinez P, Moskalenko M (2008) Sustainable District in Barcelona. Oral Communication. *Sustainable Building conference SB08*, Melbourne (Australia).
- Rieradevall J, Gabarrell X, Vicent T, Villalba G, Farreny R, Frakgou M, Oliver-Solà J, Sendra C, Borrós M, García-Lozano R (2008) Herramientas ambientales para el diseño de ciudades sostenibles. Oral Communication. *Congreso Internacional de Ingeniería Civil*, San José (Costa Rica).
- Gabarrell X, Frangkou M, Rieradevall J, Farreny R, Villalba G, Sendra C, Vicent T, Oliver-Solà J (2008). Strategies for a More Sustainable Urban Environment Based on Integrated Self-Sufficiency Indices and Life Cycle Assessment. Oral Communication. *7th International Ecocity Conference, Ecocity World Summit 2008*, San Francisco (USA).

Besides, during the dissertation period the opportunity has been given to work in other projects, from which the following papers in peer-reviewed journals (accepted or in review) and book chapters have been written:

- Farreny R, Oliver-Solà J, Rieradevall J, Gabarrell X (2009) Energy Conservation and Efficiency in the Service Sector. In 'Energy and Buildings: Efficiency, Air Quality and Conservation'. Ed. JB Utrick. Nova Science Publishers. ISBN: 978-1-60741-049-2. pp. 421-431.
- Gasol CM, Farreny R, Gabarrell X, Rieradevall J (2008) Life cycle assessment comparison among different reuse intensities for industrial wooden containers. *International Journal of Life Cycle Assessment*, 13:421-431.
- Farreny R, Oliver-Solà J, Lamers M, Amelung B, Gabarrell X, Rieradevall J, Boada M, Benayas J (2010) Carbon dioxide emissions of Antarctic tourism. Accepted with revisions in *Antarctic Science.*
- Escuder-Bonilla S, Roca-Martí M, Farreny R, Oliver-Solà J, Gabarrell X, Rieradevall J. The ecology of cultural services. Energy and water flows in museums. Submitted on February 2010 to *Journal of Cleaner Production.*

Structure of the dissertation

The structure of the dissertation is organised into six main parts and ten chapters. For clarity, the structure of the thesis is further outlined in Figure A. This flow chart can be used throughout the reading of this manuscript as a *dissertation map*.

Part I. Introduction and framework

Part I is composed of two chapters. **Chapter 1** sets out an introduction to the topic of urban sustainability and explains the importance of urban settlements in the achievement of this. Furthermore, it presents the concept of urban metabolism and highlights its role in understanding how urban settlements interact with the environment. In particular, the importance of energy and water flows is presented, since urbanisation processes and the eventual urban form condition them. Next, industrial ecology is presented as a discipline that may be helpful in the assessment of the sustainability of urban settlements and to define the pathway to achieve this. Finally, the motivation of this dissertation is presented, and the objectives are enumerated. **Chapter 2** presents the systems of study considered throughout the research and describes the methodology applied, which is divided into sustainability assessment tools and field and laboratory works.

Part II. The ecodesign of urban settlements

Part II is, in terms of scope, the broadest piece of research in the dissertation. It is composed of one chapter. **Chapter 3** [*Transition towards sustainable cities: opportunities, constraints and strategies in the planning of sustainable neighbourhoods. A case study in Barcelona*] sets the context for the research, by providing an example of ecodesign and planning of a real neighbourhood. From this case study, a set of opportunities and constraints in the transition towards sustainable cities has been identified. Among these, the lack of environmental data and criteria for the city ecodesign is highlighted. For this reason, the following chapters carry out an in-depth study of several aspects related to the energy and water vectors. Chapter 3 includes an addendum in which the ecodesigned planning proposal for the case study neighbourhood is briefly described.

Part III. Energy flows and indicators in urban areas

Part III focuses on the flows of energy in urban systems. It is composed of one chapter. **Chapter 4** [*Energy intensity and greenhouse gas emission of a purchase in the retail park service sector: An integrative approach*] presents the energetic metabolism of a particular urban subsystem: a retail park. This chapter is useful, on the one hand, to define environmental indicators for the retail sector (energy intensity and greenhouse gas emissions), and on the other, to highlight the role of urban form in energy consumption (the role of transportation compared to the stationary energy demand of buildings).

Part IV. Water flows and indicators in urban areas. A focus on rainwater harvesting

Part IV focuses on the flows of water in urban systems and in particular on rainwater flows. It is composed of three chapters. **Chapter 5** [*Indicators for sustainable water management in urban systems: case studies of retail parks in Spain and Brazil*] presents the water metabolism of the same previous retail park, and it compares it to another retail park located in a different context in terms of climate and economic development. This chapter is useful to define an indicator of water intensity, and to provide an indicator of potential water self-sufficiency by means of rainwater harvesting. The definition of this indicator raises several questions regarding the effects of roof selection on rainwater harvesting, as well as the financial implications of the necessary infrastructures, which will be the focus of the following chapters.

Chapter 6 [*Roof selection for rainwater harvesting: quantity and quality assessment in Spain*] deals with the estimation of the runoff coefficient of four different roofs, which is a parameter included in the calculation of the potential water self-sufficiency indicator. In addition, it presents the roof runoff quality results of an experimental campaign on the set of roofs.

Chapter 7 [*Cost-efficiency of rainwater harvesting in the (re)design of Mediterranean neighbourhoods*] presents the economic assessment of four different strategies of implementing rainwater harvesting in dense Mediterranean neighbourhoods.

Part V. Transfer of knowledge

Part V is composed of one chapter. **Chapter 8** [*Towards a transition*] reflects on the results of chapters 3 to 7, and shows how they result in a set of key methodological ideas to be incorporated in the process of urban ecodesign with sustainability in mind. This chapter presents how these ideas have been applied in several ecoinnovation projects developed by the author in parallel to the dissertation.

Part VI. General conclusions and future actions

Part VI concludes the dissertation. It consists of two chapters. **Chapter 9** provides the general conclusions from the research presented thus far. In **Chapter 10** some ideas for further work are outlined.

[*Note:* Each chapter from 3 to 7 presents an article –either published or in review-. For this reason, an abstract and a list of keywords are presented at the beginning of the chapter, followed by the body of the article].

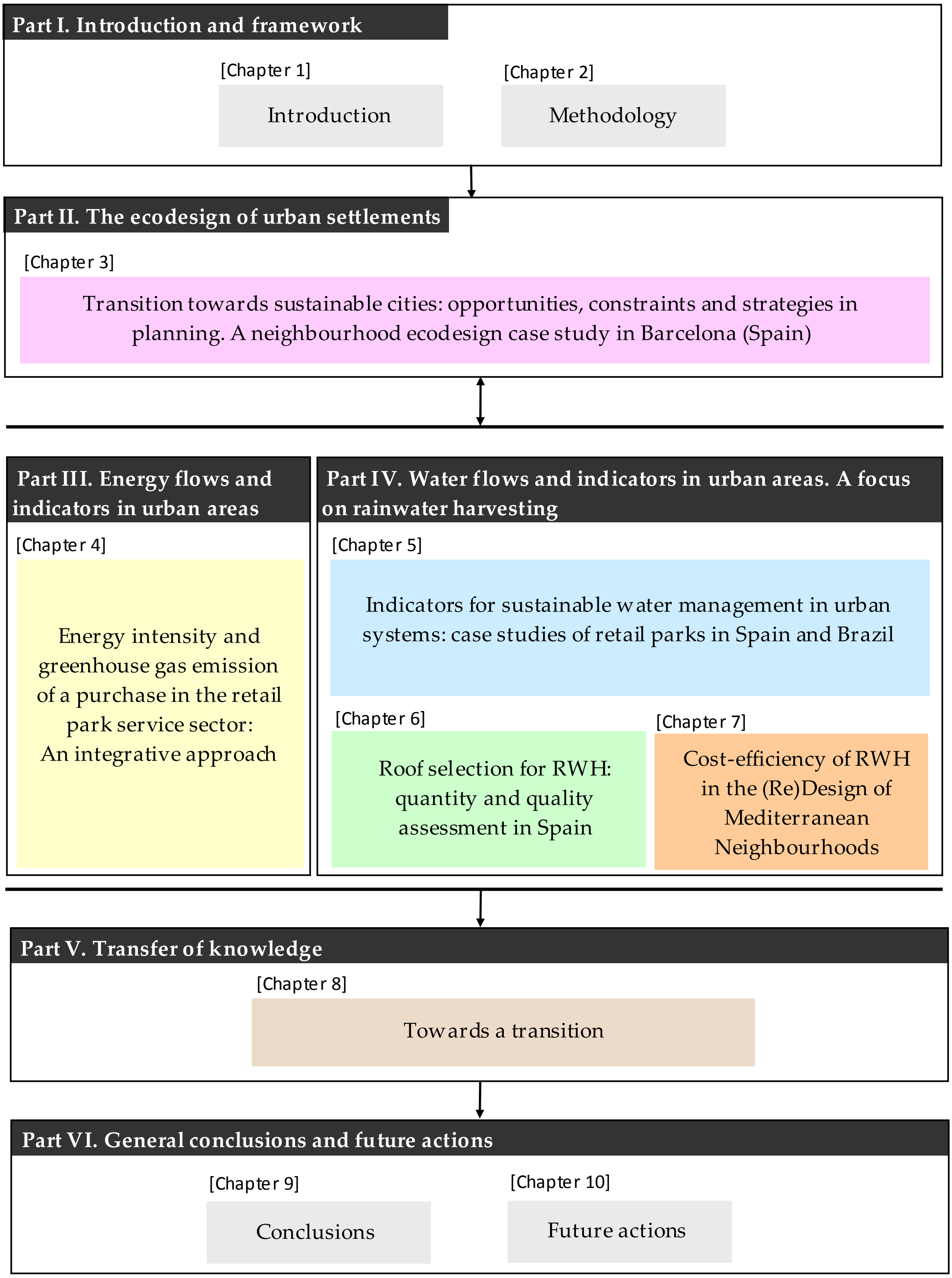


Figure A. Flow chart showing the dissertation map (structure of the dissertation). Abbreviations: RWH = Rainwater harvesting

PART I

Introduction and framework

Chapter 1.

INTRODUCTION

Chapter 1 presents an overview of the concept of sustainable development. Furthermore, it presents the role of urban settlements as a cornerstone for sustainability and highlights the approach of urban metabolism, in particular, regarding energy and water flows. Then, it presents the framework of industrial ecology, which is the base of some of the tools used in this dissertation. Finally, it presents the motivation of the dissertation and enumerates its objectives.

This chapter is structured as follows:

- Urban settlements as a cornerstone for sustainability
- Energy and water flows in urban areas
- Overview of the industrial ecology framework
- Motivation of the dissertation
- Objectives of the dissertation

1.1. Urban settlements as a cornerstone for sustainability

1.1.1. The sustainability concept

The global sustainability movement was initially launched by two documents: the Club of Rome's Limits to Growth [1] and the Brundtland Commission's Our Common Future [2]. It was this latter institution, the World Commission on Environment and Development, that coined what has become the most frequently quoted definition of sustainable development as:

> '*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*'.

After these documents, the popularisation of the sustainability agenda and debate was achieved with the first global gathering related to sustainable development, the 1992 United Nations (UN) Conference on Environment and Development, also named the Rio Earth Summit [3].

At its core, the concept of sustainable development is about reconciling "development" and "environment." Development, i.e., the meeting of people's needs, requires the use of resources and involves the generation of wastes. The environment has finite limits of many resources and of the capacity of ecosystems to absorb or break down wastes or render them harmless at local, regional, and global scales [4].

The field of sustainable development can be conceptually broken down into three constituent parts (Figure 1.1): environmental sustainability, economic sustainability and social sustainability [5]:

- *Economic*: An economically sustainable system must be able to produce goods and services on a continuous basis, to avoid extreme sectorial imbalances which damage agricultural or industrial production and to ensure a fair distribution and efficient allocation of our resources.
- *Environmental*: An environmentally sustainable system must maintain a stable resource base, avoiding over-exploitation of renewable resource systems or environmental sink functions, and depleting non-renewable resources only to the extent that investment is made in adequate substitutes. This includes the maintenance of biodiversity, atmospheric stability, and other ecosystem functions not ordinarily classed as economic resources.
- *Social*: A socially sustainable system must achieve fairness in distribution and opportunity, adequate provision of social services including health and education, gender equality, and political accountability and participation.

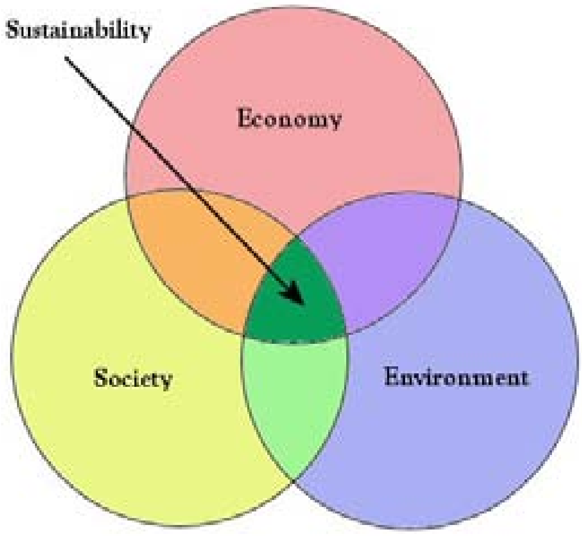


Figure 1.1. The three spheres of sustainable development. Only when all of them are fulfilled can we discuss sustainability.

Although the basic idea behind the concept is quite clear, many authors believe that the term ‘sustainable development’ is value-loaded and thus multi-interpretable. Campbell [6] argues that the concept can have no teeth: it is so malleable as to mean many things to many people without requiring commitment to any specific policies. The more practical question is whether sustainability is a useful concept for planners. The goal of sustainability may be too far away and holistic to be operational: that is, it may not be easily broken down into specific, short-term steps [6]. In any case, it seems that sustainability needs to be reinvented continuously and should be treated as an opportunity rather than a constraint [7].

It is probably true to say that the major environmental battles of the past were fought outside cities, but the awareness of the need to include cities in the global sustainability agenda is now universally recognised by environmentalists, governments and industry [8]. As early as in 1992, Yanarella and Levine [9] suggested that, from a global perspective, we will never begin to implement the sustainability process unless we can relate it to cities. They argued that sustainable development strategies need sustainable cities as nodal points and models of coherent and integrated sustainable development. In this same vein, Harper and Graedel [10] stated that it is in cities where the concept of sustainability must in the long term succeed or fail.

After this, the recognition of the role of cities and sustainable development has been expanding, to the extent that members of the Intergovernmental Panel on Climate Change have identified urban development as a priority for environmental sustainability during an era of unprecedented anthropogenic climate change [11].

Concerns about urban sustainability

The recognition of the importance of the urban environment by all related actors has led to a series of global summits and urban sustainable development initiatives over the course of the last years [12]. In 1976, the UN held its first global conference on human settlements: Habitat I in Vancouver, Canada. At that time, there was still hope that rapid urban growth could be mitigated or even diffused and the conference drew international attention to problems in all kinds of settlements, both rural and urban [13]. In 1992 the Rio Earth Summit resulted in Agenda 21, that outlined guiding principles on urban sustainability; this included strategies for sustainable energy and transport, shelter for all, conservation of historical and cultural heritage, combating poverty, community empowerment, promoting local labour and responsible fiscal policies [3]. However, the first time that the issues related to cities' living environment were clearly brought to the core of the global environmental agenda was in 1996, at the UN Habitat II summit that took place in Istanbul [12]. Habitat II focused on the urbanisation process itself, as cities and towns already accommodated the majority of the world's population [13]. Moreover, this was the first UN conference where city representatives, and not solely heads of states, were invited to deal with the problems of an urbanising world. The outcome was the Habitat Agenda, a programme similar to Agenda 21, calling for adequate shelter and sustainable human settlements for all, aimed at nation states, but with a designated role for cities and local authorities [3].

Six years later, in the Johannesburg World Summit on Sustainable Development, there was a special focus on local and urban environments in addressing global sustainability, as an aftermath of Habitat II. The two previous documents on local scale were brought to the fore and the formulation of a local development agenda, the Local Agenda 21, was initiated. Furthermore, a new action agenda was created; WEHAB, which stands for water, energy, health, agriculture and biodiversity [3].

Another relevant initiative is the World Urban Forum (WUF), a biannual global forum on cities, that started in 2002 in Nairobi, Kenya (its last session took place in 2010 in Rio de Janeiro, Brazil). The WUF was established by the UN to examine rapid urbanisation and its impact on communities, cities, economies and policies, through the promotion of open dialogue between a wide range of partners [3].

Other numerous projects and initiatives related to sustainability on the local or regional level have appeared since. For example, the World Bank recently launched the Eco^{2}Cities Program [14] and the World Bank's urban and local government strategy [15].

At the European level, the European Sustainable Cities and Towns Campaign was launched at the end of the First European Conference on Sustainable Cities and Towns which took place in Aalborg, Denmark in 1994. The Conference adopted the Aalborg Charter [16] which provides a framework for the delivery of local sustainable development and calls on local authorities to engage in Local Agenda 21 processes. Nearly 2000 local authorities in Europe participate in the Campaign. The Sustainable Cities and Town Campaign seeks to help local governments across Europe to make mainstream sustainability best practice and to bring about change through the implementation of the Aalborg Charter and Aalborg Commitment.

The European Commission also launched the Green Paper on the Urban Environment [17], and the European Thematic Strategy on the Urban Environment [18] which aimed 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.

In 2008, the European Commission launched the Climate and Energy Package. Afterwards, the Covenant of Mayors was first signed in 2009 as a commitment by signatory towns and cities to go beyond the objectives of the European Union (EU) energy policy in terms of reduction in carbon dioxide (CO_2) emissions through enhanced energy efficiency and cleaner energy production and use. The covenant cities committed to reducing their CO_2 emissions by 20% by 2020, as a result of a 20% increase in energy efficiency and a 20% share of renewable energy sources in the energy mix [19].

Other examples of international strategies for the urban environment are the 'International Council for Local Environmental Initiatives (ICLEI)', founded in 1990 and renamed as 'ICLEI - Local Governments for Sustainability'. It is an international association of local governments as well as national and regional local government organisations which are committed to sustainable development. ICLEI provides technical consulting, training, and information services to build capacity, share knowledge, and support local government in the implementation of sustainable development at the local level. Their basic premise is that locally designed initiatives can provide an effective and cost-efficient way to achieve local, national, and global sustainability objectives [20]. Actually, it is widely argued that local governments in most countries are the most appropriate focal point for coordinating and implementing environmental policies [21]. As a result, national-level policies are increasingly being supplemented with city-scale actions to mitigate climate change [22].

1.1.2. Cities and the environment

The history of cities is the starting point for an understanding of the relationships between cities and the environment. It began in the fourth millennium BC as the first civilizations started to emerge in the fertile plains and valleys of the Nile, the Indus, and the Tigris and Euphrates. The conventional view on the formation of cities links this to technological conditions; namely, the beginning of food cultivation and agricultural production that resulted in the concentration of people in the most fertile lands [23]. The development of agriculture eventually produced a surplus and made it possible to sustain a higher population density while also freeing up some members of the community for craftsmanship and the production of nonessential goods and services. Their economic base in agriculture (supplemented by trade) and their political-religious institutions gave cities an unprecedented degree of occupational specialisation and social stratification. The 'city' increasingly became the dominant social form, spreading its influence into the surrounding countryside [24].

Warka (also named Uruk), lying in the potentially rich farmland of the lower Tigris and Euphrates, was probably the first such city. Like all the cities that were to follow, Warka was to grow, develop, and then decline [24]. This evolution can be explained by the fact that these cities literally 'ate' their hinterland, ultimately bringing about their own demise [13]. After Warka, other cities such as Athens and Rome emerged and dominated their contemporary age [24]. Rome was Europe's greatest Ancient city, accommodating a million people by AD100.

The relationships between cities and their outer environment may be exemplified by the following quotation from Girardet [25], who examined the demands which cities place upon soil fertility and other natural resources and their environmental outputs in the form of solid wastes and air pollutants:

> *'Ancient Rome, at the height of its power, obtained much of the grain needed to feed its citizens from North Africa. Its freight ships crisscrossed the Mediterranean laden with the produce of its colonies. As its own land grew tired, and ever more farmers were turned into soldiers, the insatiable appetite of the metropolis could be met only with foodstuffs grown, or robbed, further and further afield'.*

This quotation is a good example of the pressure that cities, from their origins, exert on the outer areas, due to the concentration of the demand of resources (food, timber, water, fuels, minerals…) together with a limited supply within their territory. The Romans neglected their own local agriculture and the city was forced to import food from across its empire [13]. The impact of the first cities was largely confined to forests (extraction of timber and firewood), soil (removal of nutrients, erosions, and salination) and water (long range aqueducts, sewage disposal). However, contemporary cities have a much more complex metabolism than their ancient predecessors like Babylon, Carthage, Athens or, indeed, Rome.

After the fall of Rome and its centralised empire a new decentralised Europe emerged. Its mainly rural towns grew out of the fertility of local forests and farmland, which their inhabitants strove to keep productive. Like Chinese cities, Europe's medieval towns were rather sustainable urban systems. Many were 'free cities' under the control of the citizens rather than of the feudal overlords. Thousands of towns and cities built in the Middle Ages still exist today. Medieval towns were, above all, market towns, with traders and producers selling their wares. Long-distance trade also played a major role in many medieval cities, which led to the growth of several supreme trading cities such as Constantinople or Venice [13].

The subsequent age of the Renaissance put the aristocracy back in charge. It also reinstated ancient ideas of urban grandeur. In the early modern age, Europe's larger capitals benefitted from the growth of commerce following the emergence of Atlantic trade [13].

Since the 18th century Europe and North America have experienced an urban boom as a result of the Industrial Revolution and global trade. With the development of steam engines, Britain had a technological lead that contributed to its economic and urban growth. By the late 18th century, London had become the largest city in the world with a population of over one million. The growth of modern industry led to massive urbanisation and the rise of new great cities, first in Europe and then in other regions, as new opportunities brought huge numbers of migrants from rural communities into urban areas [13]. Many industrial cities grew and became dense urban settlements characterised by their unhealthy and polluted environment.

Ever since then, efforts have been made to counter unplanned and disorderly urban sprawl with coherent planning concepts, to turn settlements into 'orderly' places. But all over the world cities have tended to defy rational planners, sometimes spreading uncontrollably, driven by the engine of industrial growth.

Today, megacities are feeding off a global hinterland. Urban growth, a trend that started in Europe and America, is now gripping the world and it is centred on developing countries. This phenomenal urban growth symbolises the aspirations for financial and economic power of their elites and the determination of their populations, against all the odds, to develop 'urban' living standards [13].

An urban world

Cities have become the primary human habitat. Urban settlements represent only 2.7% of the world's land area [26]. However, the world's cities use over 75% of the world's resources [27], they 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 greenhouse gas (GHG) emissions [28] (Figure 1.2).

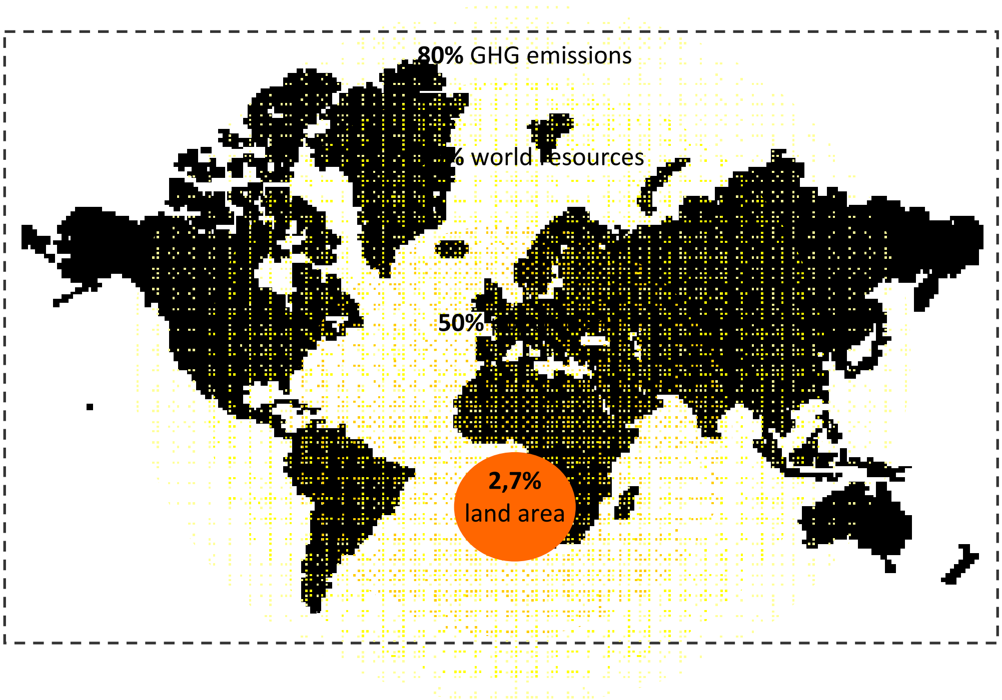


Figure 1.2. Representation of the role of cities in terms of land occupation, population concentration, consumption of resources and GHG emissions.

In addition, cities consume large amounts of water. In Europe, the total water use for urban purposes amounts for 18 % of total abstraction and 44 % of its consumptive uses (total abstraction excluding water use for energy production) [29]. The percentage of water abstracted for urban purposes at worldwide level is smaller, and could be estimated at approximately 10% [30]. Despite representing a reduced percentage of total water abstractions, water inputs to urban areas are expected to present high quality standards (i.e. drinking water guidelines) in contrast with water used for other purposes such as agriculture. Thus, they may require intensive treatment and infrastructures to achieve such quality standards.

This is the result of a rapid process of urban growth, the magnitude and speed of which are an unprecedented phenomenon in the history of the world [31]. Frenetic urbanisation is taking place globally - not only in the form of urban sprawl, as in North America and Europe -, but also through the construction of new cities, with China as a striking example [12].

The ecological consequences of urbanisation extend far beyond city boundaries, as urban residents rely on the extraction, transfer, and delivery of food, water, and energy from large source areas [32]. This trend toward urbanisation will lead to important but as of yet poorly understood impacts on the global environment [33], for which there is a necessity for a sustainability transition [34].

The metabolism of cities: understanding the pressure of urban settlements on the environment

Urban systems are open and interactive, constantly exchanging energy and materials with the natural environment (Figure 1.3). As such, they are not only connected to systems in the immediate hinterland, but have connections, in an ecological sense, with regions at national and global levels [12]. The urban environment is an open, dependent system, which necessarily interacts with the environments and economies of the city's hinterland, a hinterland which has become increasingly global rather than regional [21].

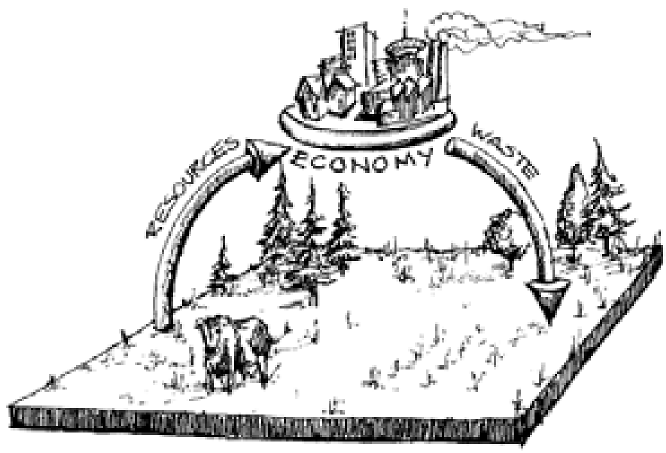


Figure 1.3. The metabolism of a city can be compared to a large animal grazing in its pasture. Just like the beast, the city consumes resources, and all this energy and matter eventually passes through to the environment again. ***Source:*** **[32].**

Urban centres are characterised by their routine use of energy as a driving force for power production, transportation of goods, construction of buildings and infrastructure, as well as for domestic comfort. Urban areas also import large volumes of clean water to cater for the water needs of their increasing populations; and produce large volumes of wastewater and stormwater that, together, are quickly evacuated, decontaminated and disposed of, usually away from the cities [35]. Their vast energy and material demands do not allow cities to be self-regulating without maintaining stable links with the hinterland from which they draw energy, food and materials and into which they release their wastes [12].

The impact of cities –and urban design- on the global climate is becoming increasingly important [36]. The footprint of a city can extend worldwide in terms of both the resources and other elements that flow into the city and of what the city transmits to the outside –people, products, waste, materials, pollution, heat loss, etc. [31]. Environmental problems arising from urban activities are not only associated with urban production and consumption patterns, but with a city's infrastructure, planning, buildings and transport systems [37]. The consequences of these environmental problems are not limited to having an impact on a city's immediate and surrounding environment, but they also have regional and global effects [12].

Forty-five years ago, in the wake of rapid urban expansion, Wolman published a pioneering article on the metabolism of cities [38] applied to a hypothetical American city of one million people. Since Wolman's work, a handful of urban metabolism studies have been conducted in urban regions around the globe [39]. One of the earliest and most comprehensive studies was that of Brussels, Belgium, by the ecologists Duvigneaud and Denaeyer-De Smet [40]. Figure 1.4 shows a diagram of the input and output flows of the city of Brussels. Without being necessary to look at the figure in detail, the interrelated flows into and out of the city are useful for exemplifying the concept of urban metabolism and its complexity.

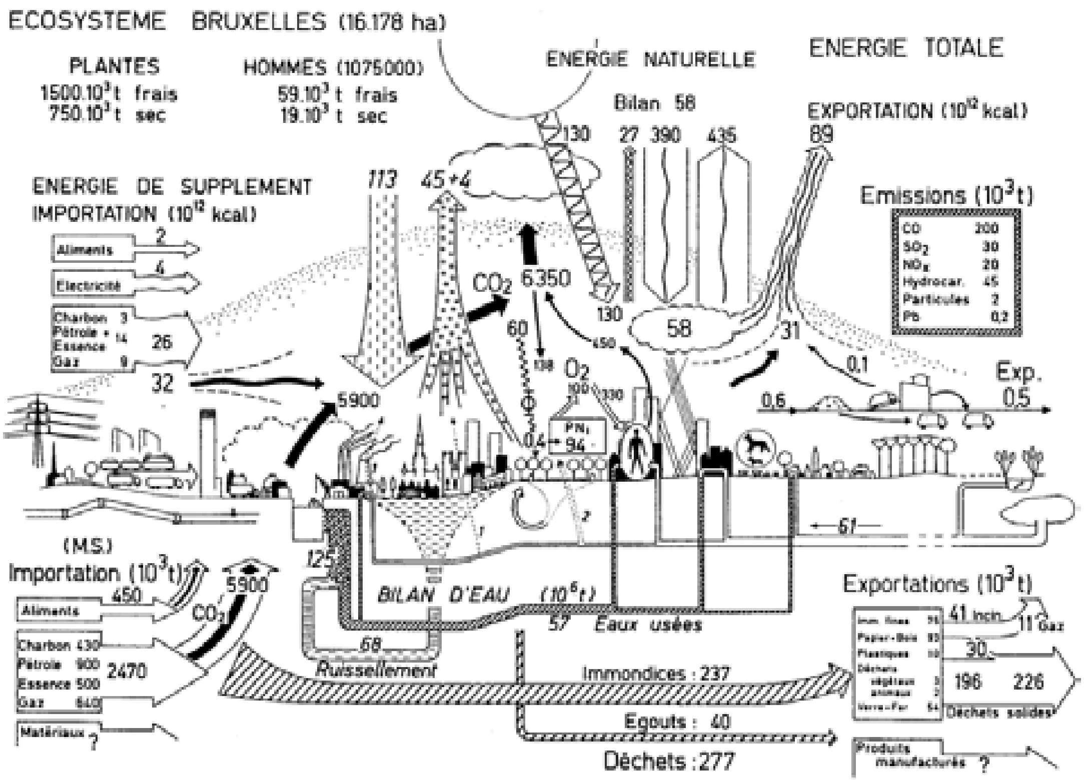


Figure 1.4. The urban metabolism of Brussels, Belgium in the early 1970s. ***Source*****: [40].**

The metabolic requirements of a city can be defined as all the materials and commodities needed to sustain the city's inhabitants at home, at work and at play [38]. The analysis of the metabolism provides suitable numbers to begin assessing strategies and technologies for reducing inputs and closing metabolic loops. Thus, urban metabolism has been established as an appropriate approach for assessing the sustainability of cities [41].

A conclusion from these studies is that the metabolism of cities has increased dramatically in recent decades [39]. Besides, it is broadly accepted that the linear processes by which cities transform environmental resources into waste products disrupt the planet's life support systems [25]. For this reason, a priority of urban sustainability should be "*…re-designing urban metabolism by `closing the circle' to make it truly compatible with the process of the living world…*" [25]. If cities are to become sustainable, they must reduce their use of all resources and decrease their waste outputs, by changing to a circular metabolism (Figure 1.5).

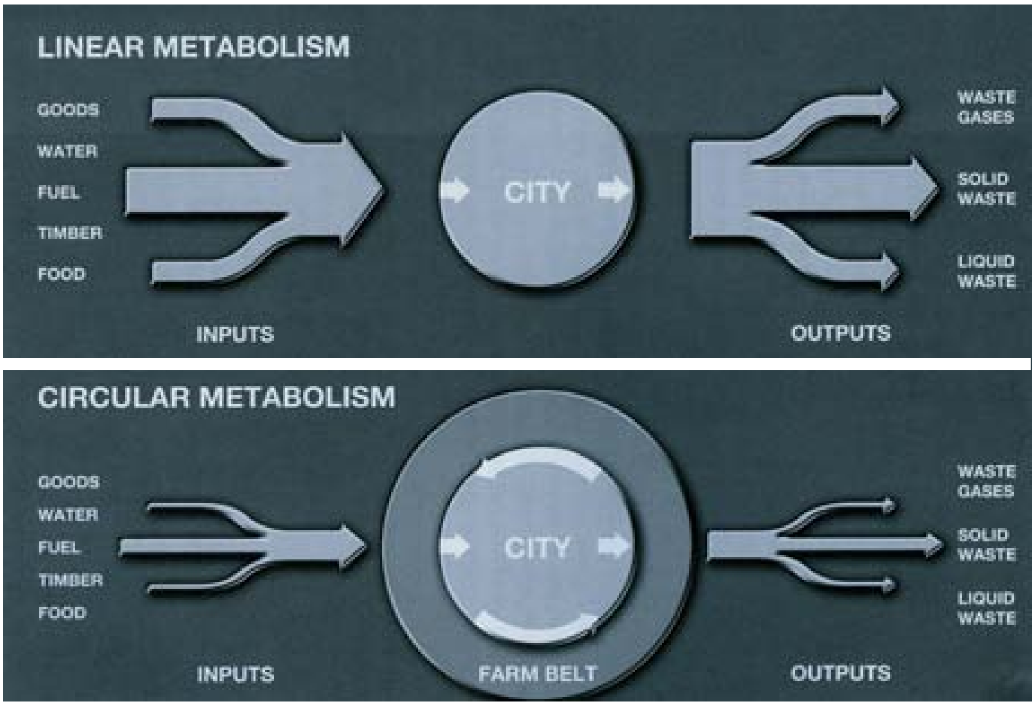


Figure 1.5. Linear vs circular. Modern cities in many rich countries have a linear metabolism –taking resources and discarding wastes without much concern about environmental impacts. Sustainable cities, by contrast, need to mimic the circular metabolism of natural systems. ***Source*****: [42].**

1.1.3. The sustainable city: concept and strategies

Although the term 'sustainable city' is value-loaded and thus multi-interpretable, it could be characterised as a more balanced development of the social-cultural, economic and environmental domains of a city and its surrounding area [43]. A sustainable city means an urban region for which the inflows of materials and energy and the disposal of wastes do not exceed the capacity of its hinterlands [39]. Thus, it means a reduction of the city's use of natural resources and production of wastes while simultaneously improving its livability, so it can better fit within the capacities of the local, regional and global ecosystems [8] in a framework of social equity and welfare [44].

The realisation of a sustainable and liveable city requires both an integrated planning and decision-making framework and a fundamental shift in traditional values and perspectives [27]. Furthermore, sustainable design principles have to trickle down to local planning and development regulations, which has not happened yet [45].

A focus on urban design and neighbourhoods

Despite much research being focused on the need for more sustainable design on the city scale, Engel-Yan et al. [46] suggest that the focus should be on the design of sustainable neighbourhoods. They argue that many of the problems encountered at the macro-city scale are in fact cumulative consequences of poor planning at the micro-neighbourhood level. For this reason, they point out that neighbourhood-scale analysis is necessary to evaluate and develop more efficient and sustainable local urban infrastructure, including buildings, transportation, urban vegetation, and water supply, wastewater, and stormwater systems.

Environmental concerns need to be more effectively addressed in the design process to reduce the environmental impacts associated with a product during its life cycle [47]. This is important since most impacts of a product (in this case, the neighbourhood) are determined in the early stages of design. In this regard, better urban design represents an important yet undervalued opportunity, which fortunately falls well within the reach of local governments and leaders [36].

On the other hand, it is relevant that a significant proportion of all new projects considered in developed countries consist of neighbourhood-scale developments (i.e. see [45]). Therefore, it seems appropriate to consider neighbourhoods as a basic unit of analysis and design of urban settlements.

1.2. Energy and water flows in urban areas

Three consumables –water, food, and fuel- are perhaps the most important materials imported into urban systems [48]. Of these, this dissertation will focus on energy and water due to the following:

- **Energy is a scarce resource.** Modern industrial societies are completely dependent on fossil fuel energy resources, which are limited and rapidly depleting [49].
- **Water is a scarce resource**. Water is an essential resource for life and good health. Globally, the problem of water scarcity is worsening as cities and populations grow, and the need for water increases in agriculture, industry and households. Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and can potentially be strongly affected by climate change, with wide-ranging consequences for human societies and ecosystems. In particular, it seems that current water management practices may not be robust enough to cope with the impacts of climate change on water supply reliability and flood risk, among others [50].
- Furthermore, **the flows of energy and water** in urban areas **are strongly influenced by certain urban characteristics** (i.e. urban density, compactness or imperviousness) that may be established during the (re)design of urban settlements (Figure 1.6).

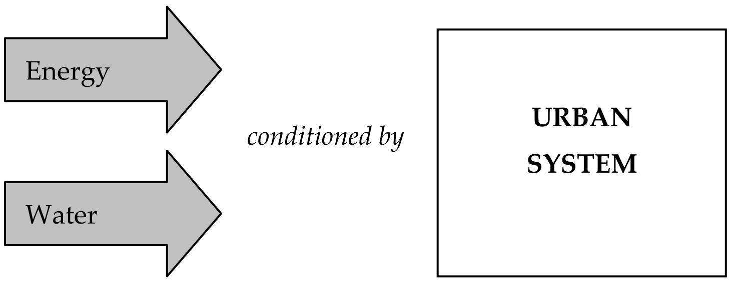


Figure 1.6. Energy and water flows within the city are conditioned by the characteristics of the urban system.

1.2.1. Energy and urban settlements

The role of energy and energy scarcity

In order to provide urban populations with the myriad of services demanded, cities need large amounts of energy. Clearly, over the past century or so we have created a way of life based on mining and consuming fossil energy resources in vast and increasing quantities. Our food and transportation systems have become utterly dependent on growing supplies of oil, natural gas, and coal [49].

The importance of energy can be expressed by means of the following quotation, from the economist Schumacher in 1973 [51]:

> *'There is no substitute for energy. The whole edifice of modern society is built upon it… It is not 'just another commodity' but the precondition of all commodities, a basic factor equal with air, water, and earth'.*

Industrial civilisation is based on the consumption of energy resources that are inherently limited in quantity [49]. Energy supply can be considered one of the main challenges facing modern societies, since most of the environmental problems confronting mankind today are linked to energy use in one way or another [52]. Evidence suggests that oil will become increasingly scarce and expensive, and no replacement can be supplied at a level that will meet the projected future demand [53]. For this reason, it is urgent to look for strategies that reduce the energy consumption of current urban patterns and layouts.

Energy flows in cities

Energy flows are an essential aspect of the sustainability of urban systems. In general, as cities grow, the flow of energy and material through them increases. This occurs through human socioeconomic activities of transforming and transferring food, goods, energy, and services [48].

The consumption of energy in buildings and in transport systems is directly affected by urban planning [54] (Figure 1.7), which is able to configure a certain urban form. In this context, urban form may be defined as the spatial configuration of fixed elements within a metropolitan region. This includes the spatial pattern of land uses and their densities as well as the spatial design of transport and communication infrastructure [55]. The spatial organisation of a city and its infrastructure affect the resources needed to support the city's human activities and thus the city's level of environmental pressure on the regional and global environment [56].

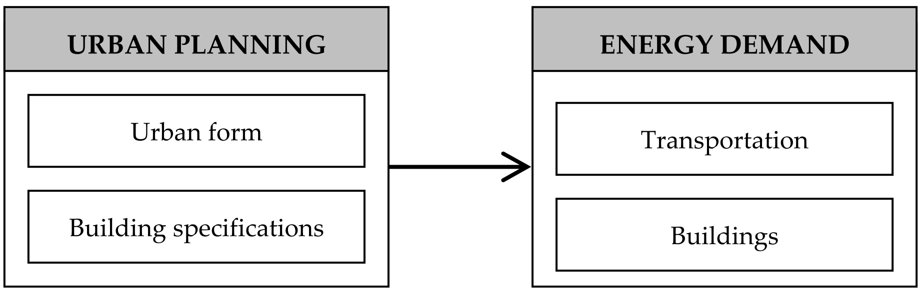


Figure 1.7. Urban planning directly affects the energy demand of urban systems.

Previous research has shown that transportation energy use is inversely correlated with urban population density [57, 58]. Figure 1.8 shows the relationship between urban density and energy used in transport. Travelling behaviour is affected by land use factors such as density, mix of uses, connectivity, parking availability, transit quality and accessibility [59]. In denser urban areas, trip origins and destinations are closer; driving disincentives are greater; and alternative modes of travel are more common [36].

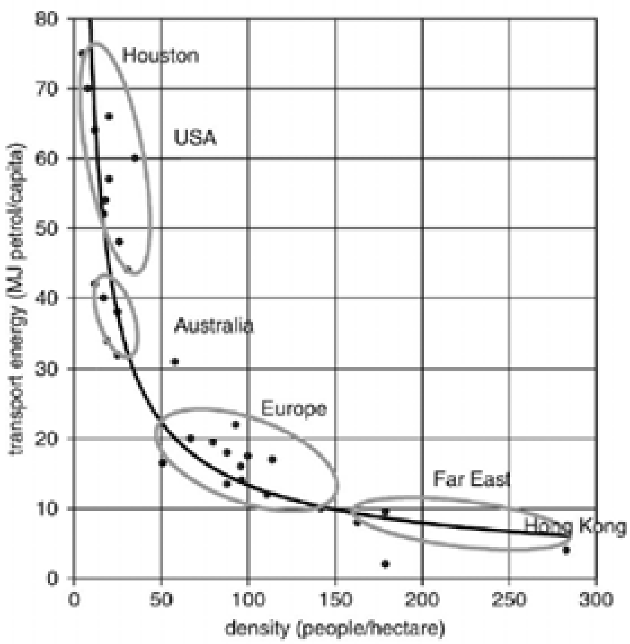


Figure 1.8. Transport energy vs. urban density for a selection of major cities. ***Source*****: [54].**

Improving city layouts and transportation networks could reduce carbon emissions. However, the role of urban form is often neglected in the debate of how to reduce GHG emissions. Urban form can also influence non-transportation CO_2 emissions, for example, via district-scale building thermal management; availability of local food and products, and CO_2 contained in roads, buildings, and other infrastructure [36].

On the other hand, urban planning sets out certain specifications for the construction of buildings, which may condition their energy demand. For example, building forms may be planned in such a way as to enable natural ventilation and daylight penetration as a means of reducing energy demands. Furthermore, their solar potential is largely affected by the presence/absence of obstructions and also because of planning constraints on orientation [54].

Therefore, urban planning and urban form can have a significant impact on energy use, particularly the housing and transportation sectors [60], although it does not determine the flows of energy completely [55].

1.2.2. Water and urban settlements

Water is an indispensable resource for life and for the development of humankind. The history of human civilization is entangled with the history of the ways in which humans have learned to manipulate and use fresh water [61].

The role of water and water scarcity

Different recent international forums have clearly noted that water will be one of the central issues of the 21st century in the globe, and thus the life of billions of people will depend on its wise management. Water is an essential and basic human need for urban, industrial and agricultural use and has to be considered as a limited resource [62].

A quote from Mikhail Gorbachev elucidates the important role of water [63]:

> *'Water, not unlike religion and ideology, has the power to move millions of people. Since the very birth of human civilization, people have moved to settle close to water. People move when there is too little of it; people move when there is too much of it. People move on it. People write and sing and dance and dream about it. People fight over it. And everybody, everywhere and every day, needs it. We need water for drinking, for cooking, for washing, for food, for industry, for energy, for transport, for rituals, for fun, for life. And it is not only we humans who need it; the whole life is dependent upon water for its very survival'.*

It is therefore clear that water is a very valuable good: water as a resource is nowadays comparable to oil; it is essential for all daily human activities.

The urban water demand is escalating as the world population is increasing and more and more urbanisation is taking place worldwide [64]. Population growth, industrialisation, urbanisation, agricultural intensification, and water-intensive lifestyles are placing great stress on freshwater systems, with both water use and pollution driving the scarcity of useable water. As a consequence, many cities now draw on freshwater resources from distant ecosystems, as their demand for freshwater has long exceeded and often destroyed local capacities by overexploiting groundwater and polluting surface water [65].

Water flows in urban areas

Water remains intrinsically bound up with human development and has been essential to urban growth processes throughout history [66]. As cities and towns have emerged, the inherent characteristics of the original land and the surrounding areas have been altered [67]. This transition in land use has caused a number of changes directly to the local environment and has had significant consequences on the local ecosystems [67].

Urban infrastructure has a profound effect on the water cycle [48]. Urban development increases the imperviousness of an area in the form of roadways, parking lots, and rooftops. While forested and grass areas allow 70 to 90% of the rainfall to infiltrate, roofs of houses and other buildings do not allow infiltration. This is also the case with pathways, driveways, and roads, which allow only a small amount of infiltration through cracks and small openings [67]. Thus, imperviousness has been identified as the greatest single attribute of the built environment affecting stormwater runoff quantity and quality [68]. The fraction of precipitation that runs off is a composite of all of the different types of land surface. As a result, developed areas produce more direct runoff from a site at the expense of infiltration (Figure 1.9) [67].

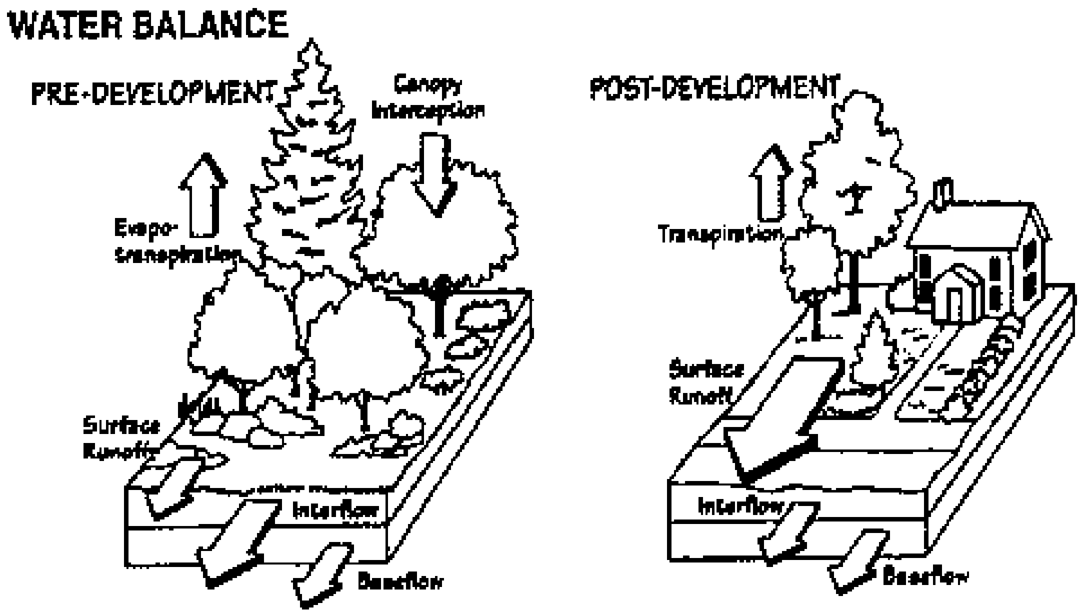


Figure 1.9. Change in water balance from land development. ***Source:*** **[67].**

Urban water cycle: water infrastructures in urban areas

An important component of any urban area is the water system, providing water supply, sanitation, and drainage services to its inhabitants. However, in many cases, the conventional approach to the provision of these services does not comply with the more recent aspirations of ecologically sustainable development [69].

Because of the lack of understanding of the consequences of development, most of the traditional stormwater control methods have been inadequate for mitigating the effects of sprawl development. Most stormwater control systems have been designed to remove and convey runoff from the site as quickly as possible, notably with curbs, gutters, and storm drains [67]. However, stormwater runoff has not been generally seen as a potential resource, since in most developed cities with centralised water supplies, urban rainwater is conceived as a nuisance, and rainwater is shunted through drain systems out of the city [70].

In a typical neighbourhood from most developed societies, water flows through the neighbourhood system following a relatively short, linear path (Figure 1.10). Water enters the neighbourhood system through a centralised piped water supply and from precipitation. Drinking water is used both indoor (domestic supply, industries and services) and outdoor (irrigation, street cleaning, etc.). The indoor water supply is converted to blackwater or greywater, which both leave the neighbourhood through the sanitary sewer system for centralised wastewater treatment. Water from precipitation and pipe water supply used in outdoor areas leave the neighbourhood by means of three main ways: (evapo)transpiration, storage in the sub-soil (it can eventually evapotranspire or reach the stream flow) or stormwater runoff. This stormwater runoff may leave the system by means of two ways: a separate stormwater sewer system (as shown in Figure 1.10) or a combined sewer system, in which foul water and rainwater are transported together (as occurs in many areas). In this latter case, a great deal of rainwater from roofs and paved surfaces is added to the sewage via the stormwater drains. At a broader level, sewage water from the entire city is discharged into the wastewater treatment plant, where the effluent is emptied into the stream flows.

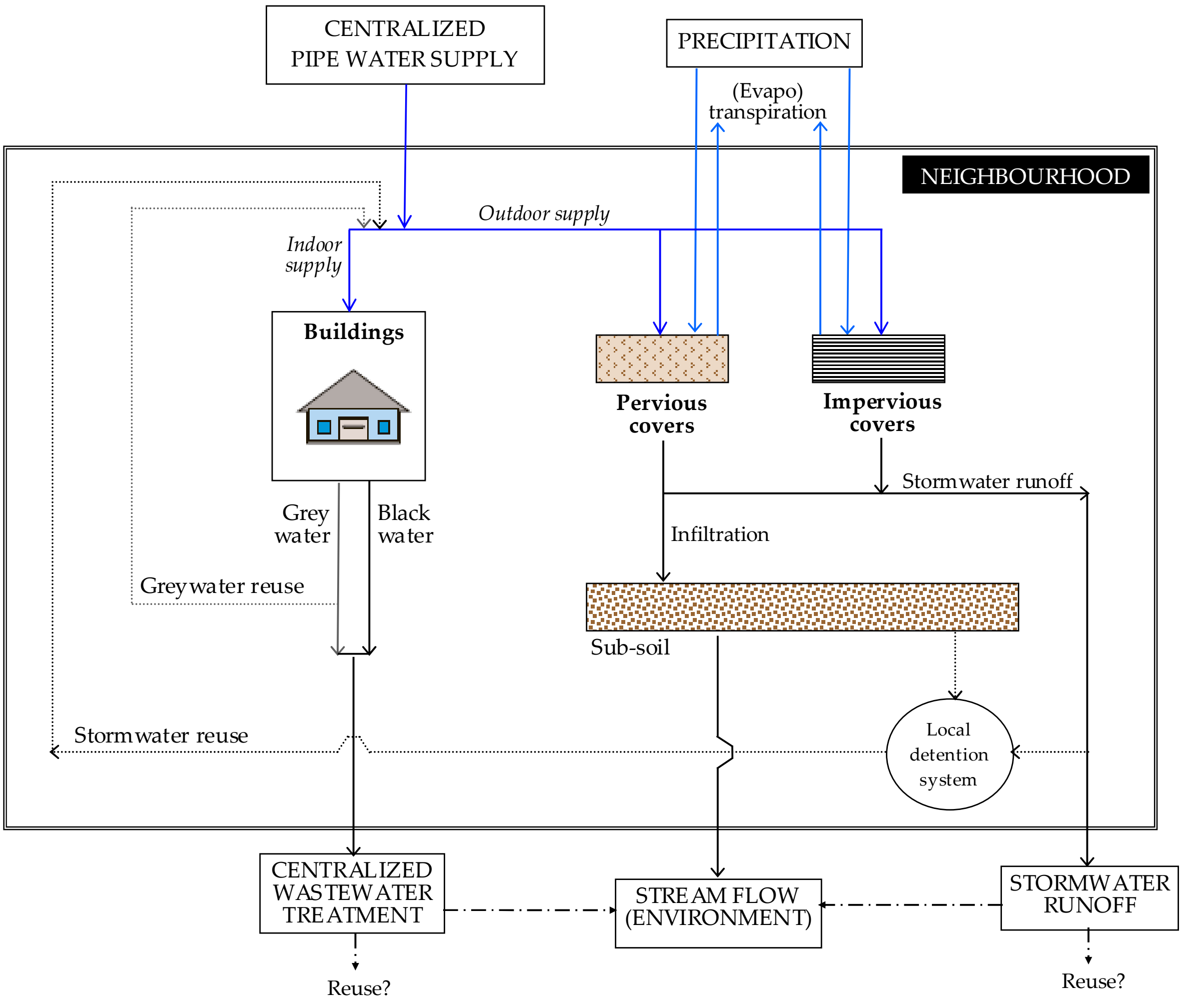


Figure 1.10. Water flows in a typical neighbourhood. ***Source*****: Adapted from [46].**

However, water entering and leaving the neighbourhood does not have to follow such a linear path. As shown in Figure 1.10, there are opportunities for stormwater and greywater to be reused, after appropriate infrastructures are installed, to reduce non-potable water demand (i.e. irrigation, toilet flushing, laundry). In addition, stormwater runoff rates can be reduced through local stormwater detention systems [46] or through other strategies that reduce the average runoff coefficient[1] (RC) of urban areas.

A particular situation that is worth mentioning occurs in the case of combined sewer systems. In the case of heavy rainfall, the situation occurs that the sewers are unable to handle the stormwater runoff flow. In this case, sewage-water flows via the overflows and ends up in the stream flow where the consequences are eutrophication and algal growth (this is what is known as a combined sewer overflow). Besides, when the supply of rainwater is large, the wastewater treatment plant functions less efficiently, so that the quality of the effluent worsens.

In view of this problem, a progressive although slow awareness of the need to plan urban sewage systems has emerged, with the aim of properly satisfying its three essential functions (flood prevention, environmental protection of the receiving waters and sanitary protection of citizens), both in dry weather and in rainy periods. Furthermore, the potential water savings by means of rainwater harvesting (RWH) are increasingly recognised. This must be clear in the first stages of territorial planning, since urbanism will be conditioned by the kind of water management [71].

Integrated Urban Water Management and Rainwater Harvesting

The emerging paradigm of integrated urban water management (IUWM) encourages water supply, stormwater, and wastewater to be considered concurrently as components of the total urban water cycle [72]. IUWM takes a comprehensive approach to urban water services, viewing water supply, drainage and sanitation as components of an integrated physical system, and recognising that the physical system is part of an organisational framework and a broader natural landscape [69]. The broad range of tools that are employed within IUWM include (but are not limited to) water conservation and efficiency, sustainable urban drainage systems (SUDS), utilisation of nonconventional water sources, stormwater and wastewater source control and pollution prevention, and non-structural tools such as education and regulations [69].

[1] The RC is the ratio of the volume of water that runs off a surface to the volume of water that falls on the surface.

SUDS -also known as water sensitive urban design in Australia or low impact development in the United States- is a philosophical approach to urban planning and design that aims to minimise the hydrological impacts of urban development on the surrounding environment. Stormwater management is a subset of SUDS aimed at providing flood control, flow management, water quality improvements and opportunities to harvest stormwater to supplement mains water for non-potable uses.

The increase in pressure on water resources in urban areas, with growing demand and limited water sources [73], combined with an increased awareness of environmental issues [74], results in an increased interest in the use of water resources generated within the urban boundary for potable supply substitution, as a means of augmenting current supply capacity [75] and reducing peak flows, annual runoff volume, and the frequency of runoff. Based on these grounds, the options of RWH should be further explored in our local context.

1.2.3. Interrelations between water and energy

Water and energy are the two most fundamental ingredients of modern civilization [76]. Because of the interconnection between water and energy, it is vital to manage them together, rather than in isolation [77]. Energy savings from water conservation and water savings from energy efficiency are inextricably linked, and these linkages should be considered when determining the best course of action from an economic, social or environmental perspective [77].

Woefully underappreciated, however, is the reality that each of these precious commodities might soon cripple our use of the other. We consume massive quantities of water to generate energy, and we consume massive quantities of energy to deliver clean water [76]. A nation's water and energy resources are inextricably entwined. Energy is needed to pump, treat, transport, heat, cool, and recycle water. On the flip side, the force of falling water turns the turbines that generate hydroelectric electricity, and most thermal power plants are dependent on water for cooling. The systems of manmade storage, treatment and conveyance structures require large amounts of energy to deliver quality water [77].

Many people are concerned about the perils of peak oil –running out of cheap oil. A few are voicing concerns about peak water. But almost no one is addressing the tension between the two: water restrictions are hampering solutions for generating more energy, and energy problems, particularly rising prices, are curtailing efforts to supply more clean water [76].

1.3. Overview of the industrial ecology framework

Modern society has largely used materials in a linear way: dig them up, process them, use them, and discard them [10]. However, conceptual thinking changed in 1989 when Frosch and Gallopoulos [78], wrote an article for *Scientific American* entitled 'Strategies for Manufacturing'. This article essentially constituted the birth of the field of Industrial Ecology (IE) by comparing the industrial approach to the use of materials and energy to that of nature [10].

Definition of Industrial Ecology

IE can be defined as [79, 80]:

> '*a systematic and integrated way by which an industrial system is viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to waste product, and to ultimate disposal'.*

IE is a systemic, comprehensive, integrated view of all the components of the industrial economy and their relations with the biosphere [81]. In its very essence, in its broader definition, IE aims to study the 'flow' of all resources (material, energy, forest, human resources, or any other) through an entire identified socioeconomic system (a town, region, state) with a view to strategically optimising their use [81, 82].

Objectives of Industrial Ecology

The principal objective of IE is to understand how the industrial society works (including all aspects of human activity) and what its interrelations with the biosphere are, with the aim of reorganising the industrial system so that it evolves towards a mode of operation that is compatible with the biosphere and is sustainable over the long-term [83]. In this context, the IE approach can be seen as a practical approach to sustainability [81].

Analogy between traditional ecology and industrial systems: the metabolism approach

The analogy between traditional biological ecology and industrial systems was first discussed by Frosch and Gallopoulos [84]:

> *'In a biological ecosystem, some of the organisms use sunlight, water, and minerals to grow, while others consume the first, alive or dead, along with minerals and gases, and produce wastes of their own. These wastes are in turn food for other organisms, some of which may convert the wastes into the minerals used by the primary producers, and some of which consume each other in a complex network of processes in which everything produced is used by some organism for its own metabolism. Similarly, in the industrial ecosystem, each process and network of processes must be viewed as a dependent and interrelated part of a larger whole. The analogy between the industrial ecosystem concept and*

the biological ecosystem is not perfect, but much could be gained if the industrial system were to mimic the best features of the biological analogue'.

Like traditional biological ecology, IE uses the concept of metabolism to describe the flows of energy and materials through the socio-economical system. In biology, metabolism describes the internal process by which an organism ingests energy-rich materials (food) to sustain its own maintenance and functions, as well as a surplus to permit growth and/or reproduction. The process also necessarily involves the excretion or exhalation of waste outputs, consisting of degraded materials.

Based on the definition of metabolism, industrial metabolism is defined as *"the whole integrated collection of physical processes that convert raw materials and energy, plus labour, into finished products and wastes in a (more or less) steady-state condition"* [85]. The concept of industrial metabolism serves as a framework to study the flows of materials and energy in industrial processes and systems. It also means the existence of limits in the use of natural resources, either imposed by nature, society or the functioning of the planet [60]. Besides, the ecosystem analogy draws attention to the differences between urban and wild ecosystems and provides a framework for addressing urban change [48].

Thus, a central concept to IE is the evolution of the industrial system from a linear system, where resources are consumed and damaging wastes are dissipated into the environment, to a more closed system, like that of ecological systems [47]. This outlines a useful concept for approaching sustainable planning, introduced by van Leeuwen [86]. Figure 1.11 (left) shows the individual planning unit or system (i.e. a city, neighbourhood/district or building) as a box with inward and outward flows which consist of materials, energy and water for example. The different planning levels can be represented by one box sitting inside the next bigger one like a Russian doll. So far, this is in accordance with the traditional planning approach. However, to achieve sustainability, it is important to go further and to also take responsibility for the processes happening inside each box. The aim must be to achieve some 'resistance' to incoming flows as well as 'retention' of outgoing movements. The guiding principle is to keep things out and to keep things in rather than to flush them through [86]. Although it will never be possible to keep materials, water or energy cycles always and completely within one spatial unit, this approach shows what sustainable planning as a process should work towards.

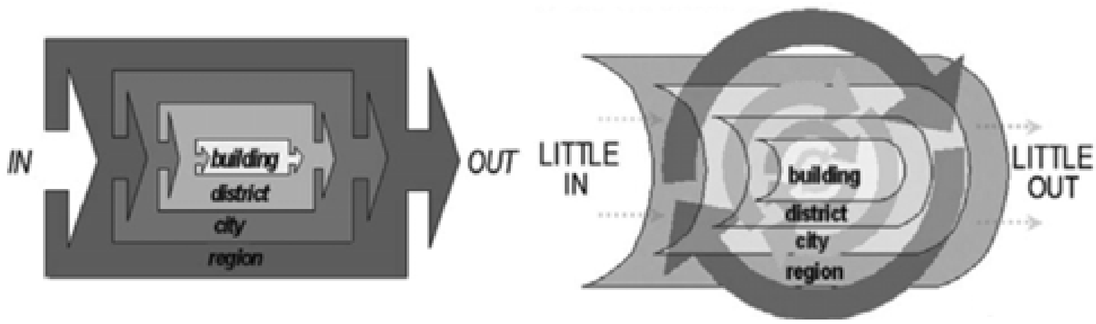


Figure 1.11. Flows in traditional planning (left side) and in closed-loops planning (right side). ***Source*****: [86].**

1.4. Motivation of the dissertation

The development of strategies and tools for a transition towards urban sustainability is imperative in the current context of environmental degradation and economic crisis. Only the understanding of the process of urban ecodesign, together with the definition of strategies and criteria for the sustainable city can result in practical and applicable prospects in the short and the long run. Thus, a new way to approach urban systems is urgent.

This dissertation is motivated by the following realities:

- The study of **urban systems requires a new perspective**, more **holistic in scope**, which incorporates the IE approach and relates the flows of materials and energy through the system to **the function** it provides, taking into account a **life cycle thinking** perspective.
- It is necessary to explore **the neighbourhood scale as the most appropriate scale of analysis of urban systems**. A **neighbourhood** can be defined as a district or community within a city, representing its basic unit. Thus, the aggregation of several neighbourhoods shapes the city and the whole urban environment. There are many **different types of neighbourhoods** (residential neighbourhood, service park, industrial estate, mixed neighbourhoods, etc.), which may be characterised by very **heterogeneous metabolism patterns**. However, given a city or an urban system, the metabolism within each type of neighbourhood is expected to vary within a narrower range, differences being attributable mostly to the era of construction, proximity to the city centre, and other factors. The fact that most cities are in a continuous state of construction but neighbourhoods may not be, also points at **the neighbourhood scale as the most adequate for the analysis and implementation of sustainability strategies**. However, studies including the IE approach at the neighbourhood scale are seemingly absent. Therefore, in the context of **a transition towards urban sustainability**, there is a need to **develop research at this intermediate scale.**
- **Current rapid urban growth** presents an opportunity to design and plan neighbourhoods, and urban settlements in general, with sustainability criteria in mind. The complexity of designing sustainable neighbourhoods and the singularity of each process and project highlight the **need to develop new methods and approaches to aid in the process of sustainable neighbourhood design**. In particular, the ecodesign methodology, initially conceived for the design of goods and products, needs to be adapted to the design of neighbourhoods.

- It is necessary to introduce **environmental prevention** strategies **both in new urban developments,** mostly taking place in regions undergoing rapid urbanisation processes (i.e. East Asia), **and in existing urban settlements** (as is common in Europe, due to stagnation in population growth and the ageing process of cities). Thus, urban sustainability concepts need to be incorporated in all kinds of urban settlements (new and existing ones).
- The **study of service neighbourhoods** is relevant since their metabolism is largely unknown and has been traditionally overlooked, and also because the **service sector contributes more than 70% to the Gross Domestic Product** in western economies. In particular, the case of retail parks (RP) requires attention because of their rapid expansion. Furthermore, RP present a good opportunity to study how their characteristics (location on the outskirts of urban areas, having high impervious fractions, etc.) affect **energy and water flows** in urban systems. On the one hand, their location entails potentially high energy demands related to transportation. Thus, two major components affecting urban energy demand (**buildings and transportation systems**) need to be studied. On the other hand, RP involve **soil sealing** of the territory, which strongly affects the urban water cycle, increasing peak flows during and after rainfall events. For these reasons, the assessment of RP can be useful for the purposes of this dissertation.
- There is a need for new **environmental indicators related to energy and water in urban areas** (i.e. intensity of resource consumption, self-sufficiency of resources, environmental impacts) as they can allow us to better organise, synthesise and use information and to provide performance measurement, reporting and communication to stakeholders in order to move towards sustainability.
- It is imperative **to carry out research into the potential of local endogenous renewable resources** (energy, water) in urban areas, especially given the resource scarcity that current societies are approaching. In order to do this, it is necessary to understand the energy and water **metabolism of urban systems.** Furthermore, there is a need to develop strategies aimed at **local self-sufficiency of resources** in order to reduce external dependence and prevent resource scarcity. With this aim, indicators can be useful to detect the potential of local resources in urban systems.

- There is a need to promote non-conventional water sources, particularly in the current context of **water scarcity**. Among these sources, little attention has been given to **RWH** in Spain, although it presents many **benefits** and it is considered an ancient technique that was present in the region in the past. Besides, **inappropriate stormwater runoff management** leads to many **problems in urban areas**, such as flooding and stream degradation (mostly due to combined sewer overflows), particularly in regions with heavy rainfalls concentrated in a short period of time, such as in Mediterranean-climate regions.
- The **assessment** of the quantitative **RWH potential** and the quality of stormwater runoff from several types of roofs is essential in order to set up criteria for the (re)design of urban systems from the perspective of sustainable rainwater management. On the one hand, there is a lack of specific **RC** for different roof types under diverse environmental climatic conditions. On the other hand, there is scarce data about **roof runoff quality** from Southern Europe, in particular from Spain.
- There is a **need to assess the cost-effectiveness** of the proposed **strategies** towards urban sustainability. In this context, it is necessary to provide economic criteria for the spreading of RWH systems in order to establish the most adequate scale for them (either at the building level or at the neighbourhood one) and to compare the financial implications of the implementation of RWH systems in new neighbourhoods compared to retrofit actions within existing urban developments, particularly in densely populated areas.

1.5. Objectives of the dissertation

The main objective of this dissertation is **to develop strategies and tools that could aid in the transition towards urban sustainable neighbourhoods**, paying particular attention to energy and water. These strategies are thought to be applicable for urban planning purposes.

In order to achieve this main aim, several goals are outlined:

1. To describe the **energetic metabolism of a service neighbourhood** (RP); to analyse the intensity of GHG emission deriving from its energy consumption; to define an indicator of energy intensity as a means of monitoring its environmental performance; and to assess the energy and environmental performance of several alternative strategies.
2. To describe the **water metabolism of a service neighbourhood** (RP); to quantify an indicator of water intensity as a means of monitoring its environmental performance; and to define an indicator of Potential Water Self-Sufficiency (PWSS) by means of RWH applicable at several scales in urban areas.
3. To determine the **RC** of several common roof types and to determine the **stormwater runoff quality** for each roof type in Eastern Spain, in order to provide **criteria for the roof selection** in the **(re)design of neighbourhoods** and cities in Mediterranean-weather environments.
4. To evaluate the **cost-efficiency** of several strategies for **urban RWH** in Mediterranean weather conditions, comparing different spatial scales (**building and neighbourhood level**) and two implementation times (new construction areas and existing urban developments).
5. To apply the methodology of **ecodesign** to a **new residential neighbourhood** and to highlight the most relevant **practical opportunities and constraints** found in the process of urban ecodesign, based on a real case study from the city of Barcelona.

Figure 1.12 shows the focus (energy, water or global) and approach of each goal.

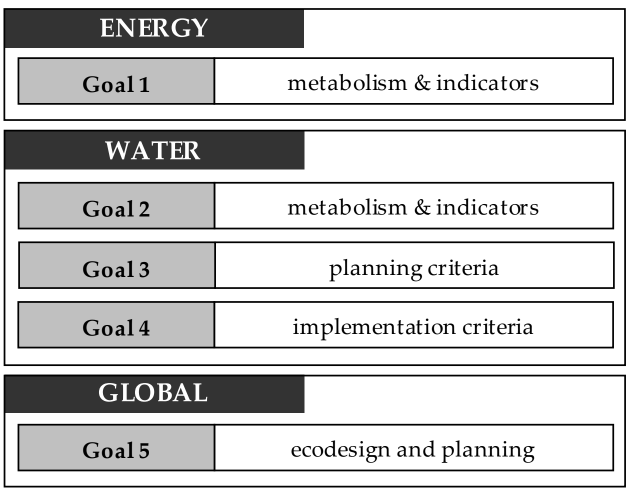
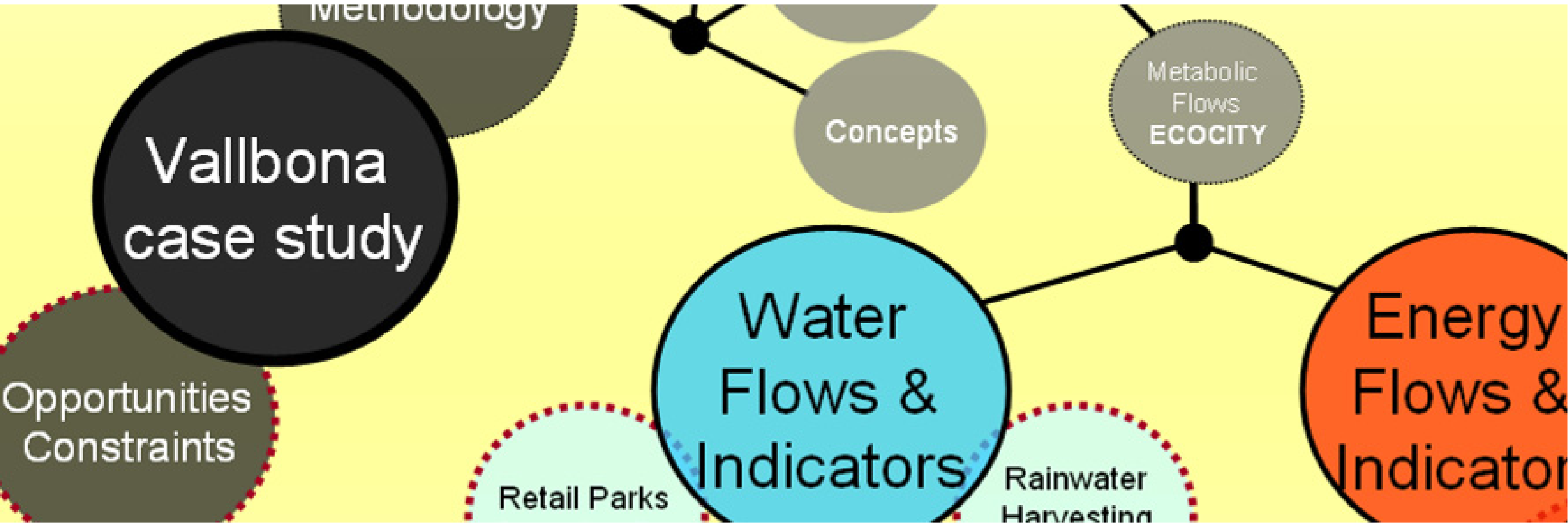


Figure 1.12. Focus and approach of each goal of the dissertation.

Chapter 2.

METHODOLOGY



Chapter 2 presents the main methodological aspects that have been involved in the development of the dissertation, divided into sustainability assessment tools and field and laboratory works. In addition, it briefly presents the several case study systems. Further details will be given in following chapters.

This chapter is structured as follows:

- Systems of study
- Methodological aspects
- Sustainability assessment tools
- Field and laboratory works

2.1. Systems of study

The research presented in parts II, III and IV is based on a total of 5 neighbourhoods of study: Vallbona, Sant Boi, São Carlos, Universitat Autònoma de Barcelona (UAB) Campus and Primer de Maig. Table 2.1 enumerates the systems of study and indicates the type of neighbourhood (either residential or services) and the current stage of the neighbourhood, that is to say, if it consists of the planning of a new neighbourhood or the assessment/study of a neighbourhood in operation (existing neighbourhood).

Table 2.1. Systems of study in the dissertation.

#	Name	Type of neighbourhood	Neighbourhood stage
1	**Vallbona neighbourhood**	Residential	Planning
2	**Sant Boi retail park**	Services (commercial)	Operation
3	**São Carlos retail park**	Services (commercial)	Operation
4	**Set of roofs in UAB campus**	Services (educational)	Operation
5	**Primer de Maig neighbourhood**	Residential	Operation

The main characteristics of these case study areas are summarised next, by means of a series of schemata (Figures 2.1 to 2.5). Later, in each chapter, more details about each case study will be provided. Each schema consists of the following parts:

- **Description** (brief presentation of the project).
- **Aims** (brief description of the aims of the project).
- **Urban subsystem** (description of the type of neighbourhood).
- **Duration** of the project (in months).
- **Location and area** of the case study system.
- **Image** (aerial view of the neighbourhood).
- **Main tools** used during the project (in accordance with the tools presented in this chapter, sections 2.3 and 2.4).
- **Role of the author** of the dissertation in the project.
- **Motivation** of the project (i.e. commissioned by a client, academic purposes, etc.).
- **Participating entities** directly involved in the realisation of the project.
- **Chapter** in which the case study is involved.

1 Vallbona Neighbourhood

Description
Vallbona is the last piece of territory in Barcelona to be urbanized. The town council plans to set up a sustainable neighbourhood that will host 2120 dwellings in this area, which is currently devoted to infrastructures, agricultural land and degraded/neglected areas.

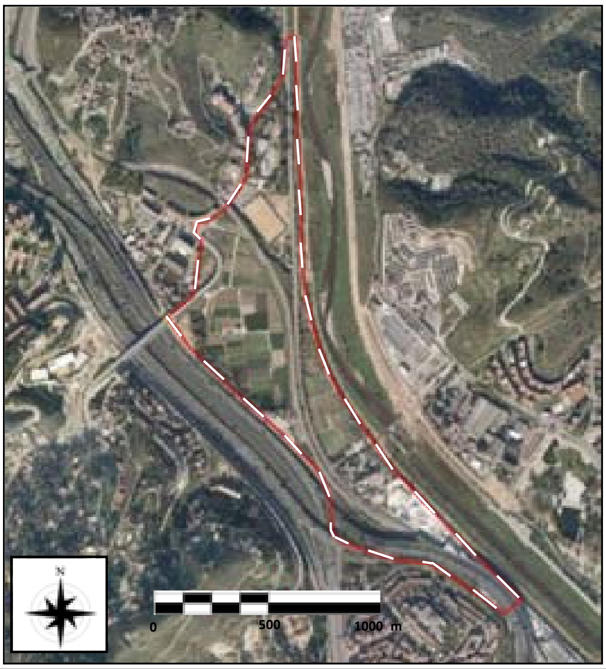
Aims
To ecodesign and plan a sustainable neighbourhood in this greenfield area.

Subsystem: Residential Neighbourhood

Duration (months): 15

Location and Area
Barcelona [Spain]
32.6 Ha

Image



Main tools*

ED	MEFA	LCA	Ind	EA	FLW
☒	☐	☐	☐	☐	☐

Role of the author
Participation in team meetings and discussions, edition of sustainability report

Motivation
Commissioned by Barcelona City Council

Participating entities
Barcelona Regional, SosteniPrA

Chapter
3

ED:** *Ecodesign;* ***MEFA*: Material and Energy Flow Accounting,* ***LCA****: Life Cycle Assessment;* ***Ind:*** *Indicators;* ***EA****: Economic Assessment;* ***FLW:*** *Field and Laboratory Works*

Figure 2.1. Main characteristics of the Vallbona neighbourhood case study.

2 Sant Boi Retail Park

Description
A RP is a group of many single storey retail units typically host to a range of chain stores, with abundant parking and within the proximity of major roads. Sant Boi RP is located in the dense metropolitan area of Barcelona and receives about 4.5 million customers/year.

Aims
To describe the energy and water metabolism and to define a set of environmental performance indicators.

Subsystem: Commercial Neighbourhood

Duration (months): 12

Location and Area

Sant Boi [Spain]

30 Ha

Image

Main tools*

ED	MEFA	LCA	Ind	EA	FLW
	X	X	X		

Role of the author

All tasks within the project

Motivation

PhD thesis

Participating entities

Sant Boi RP, SosteniPrA

Chapter

4 & 5

ED:** *Ecodesign;* ***MEFA*: Material and Energy Flow Accounting,* ***LCA****: Life Cycle Assessment;* ***Ind:*** *Indicators;* ***EA****: Economic Assessment;* ***FLW:*** *Field and Laboratory Works*

Figure 2.2. Main characteristics of the Sant Boi retail park case study.

3 São Carlos Retail Park

Description
Sao Carlos RP is located in the city of São Carlos (São Paulo state) and it has a subtropical humid weather. This RP receives about 2.3 million customers/year.

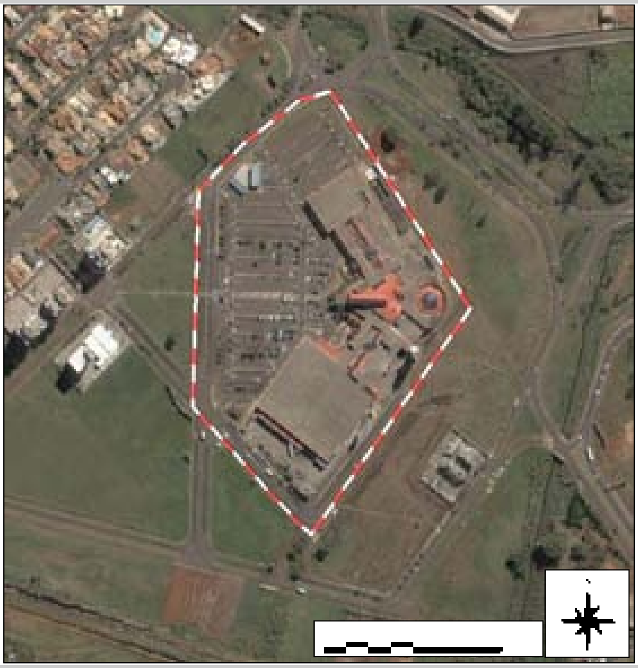
Aims
To describe the water metabolism and to define a set of environmental performance indicators.

Subsystem: Commercial neighbourhood

Duration (months): 6

Location and Area
São Carlos [Brazil]
7 Ha

Image



Main tools*

ED	MEFA	LCA	Ind	EA	FLW
☐	☒	☐	☒	☐	☐

Role of the author
All tasks within the project (except for data gathering)

Motivation
PhD thesis

Participating entities
Sao Carlos RP, Universidade Federal Sao Carlos (UFSCar), SosteniPrA

Chapter
5

ED:* *Ecodesign;* ***MEFA**: Material and Energy Flow Accounting,* ***LCA****: Life Cycle Assessment;* ***Ind:*** *Indicators;* ***EA****: Economic Assessment;* ***FLW:*** *Field and Laboratory Works*

Figure 2.3. Main characteristics of the São Carlos retail park case study.

4 Set of roofs in UAB campus

Description
The set of roofs is composed by: clay tiles (CT), pitched metal (M), pitched plastic (P) and flat gravel (FG) roofs. Thus, the roofs present differences in slope and roughness. In each roof an experimental design has been installed.

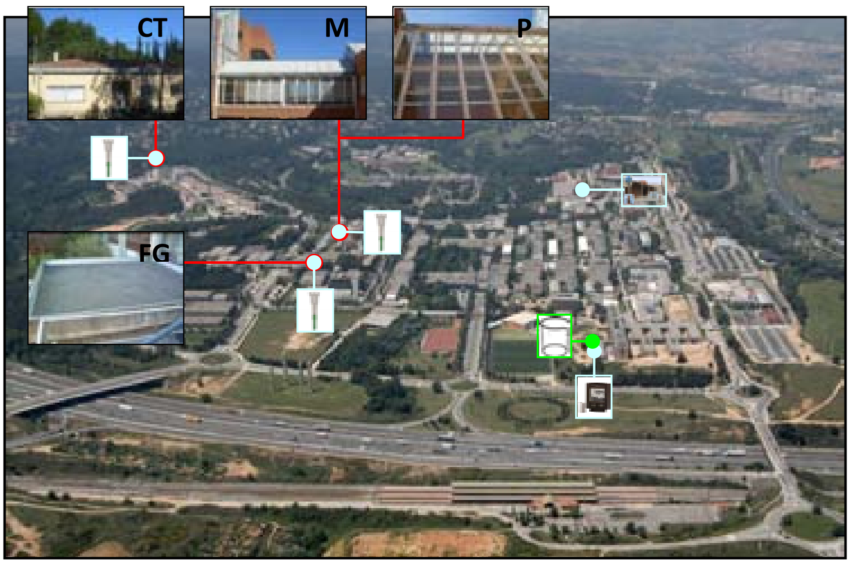
Aims
To assess the RWH potential from different roofs, in quantitative and qualitative terms.

Subsystem: Educational Neighbourhood

Duration (months): 27

Location and Area
Cerdanyola [Spain]
40.6-120 m²/roof

Image



Main tools*

ED	MEFA	LCA	Ind	EA	FLW
☐	☐	☐	☐	☐	☒

Role of the author
All tasks within the project

Motivation
PhD thesis

Participating entities
UAB, SosteniPrA

Chapter
6

ED: Ecodesign; **MEFA: Material and Energy Flow Accounting, **LCA**: Life Cycle Assessment; **Ind:** Indicators; **EA**: Economic Assessment; **FLW:** Field and Laboratory Works*

Figure 2.4. Main characteristics of the set of roofs in UAB campus case study.

5 Primer de Maig Neighbourhood

Description
The case study area is a social housing neighbourhood built in the sixties. It comprises 43 buildings with 558 households. Currently, 44.5% of the neighbourhood is covered by pedestrian areas, 29.0% buildings, 14.7% green areas and 11.8% trafficked streets.

Aims
To design the infrastructures for RWH and assess their economic performance.

Subsystem: Residential Neighbourhood

Duration (months): 27

Location and Area
Granollers [Spain]
2.6 Ha

Image

Main tools*

ED	MEFA	LCA	Ind	EA	FLW
☐	☐	☐	☐	☒	☐

Role of the author
Active participation in the whole project

Motivation
Commissioned by Adigsa

Participating entities
Adigsa, SosteniPrA

Chapter
7

ED:** *Ecodesign;* ***MEFA*: Material and Energy Flow Accounting,* ***LCA****: Life Cycle Assessment;* ***Ind:*** *Indicators;* ***EA****: Economic Assessment;* ***FLW:*** *Field and Laboratory Works*

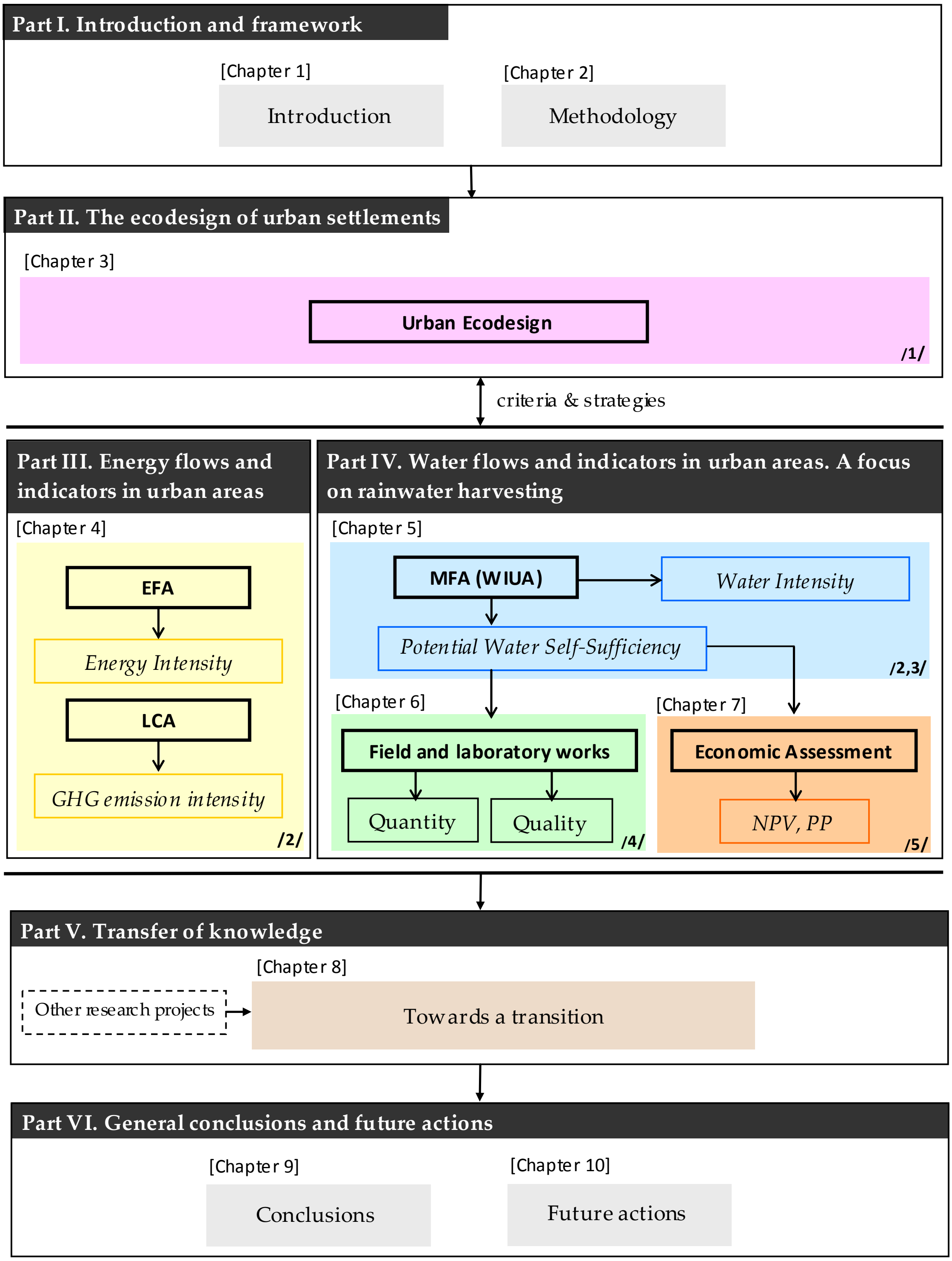
Figure 2.5. Main characteristics of the Primer de Maig neighbourhood case study.

2.2. Methodological aspects

The methods and tools applied throughout the dissertation can be grouped into two groups:

- **Sustainability tools**
    - Material and Energy Flow Accounting and Analysis (MEFA)
    - Life Cycle Assessment (LCA)
    - Economic Assessment
    - Indicators of sustainability
    - Ecodesign
- **Field and laboratory works**
    - Quantity assessment
    - Quality Assessment

Figure 2.6 presents a diagram showing the methods and tools that are applied in each chapter. After this, each tool is presented (further details are provided in each chapter).



***Acronyms** (in alphabetical order)*: **EFA**: Energy Flow Accounting; **GHG**: Greenhouse Gas; **LCA**: Life Cycle Assessment; **MFA**: Material Flow Accounting; **NPV:** Net Present Value; **PP**: Payback period; **RC**: Runoff Coefficient; **WIUA**: Water Input and Use Accounting.

Case studies (number between slashes): 1-Vallbona, 2-Sant Boi, 3-Sao Carlos, 4-UAB campus, 5-Primer de Maig

Figure 2.6. Overview of the methods used in Parts II, III and IV of the dissertation.

2.3. Sustainability assessment tools

2.3.1. Material and Energy Flow Accounting and Analysis

The MEFA framework is a tool based on the notion of socio-economic metabolism. It is used to empirically analyse important aspects of the interaction process between nature and culture in a way that can link socioeconomic dynamics (i.e. monetary flows, lifestyles or time allocation) to biophysical socioeconomic stocks and flows and these, in turn, to ecosystem processes [87].

This framework is the primary tool used to understand the metabolic processes of the anthroposphere, in an attempt to characterise human activity [10]. Within the system borderline, raw materials (material and energy) will be transformed into products or groups of products and environmental burdens, i.e. air emissions, waste and wastewater. Depending on the system borderlines, economic activities can be interpreted as a technical network aimed at producing goods and services.

Material and energy flow accounts and balances show the amounts of physical/energetic inputs into a system, material accumulation in the system and outputs to other systems or back to nature as illustrated by Figure 2.7.

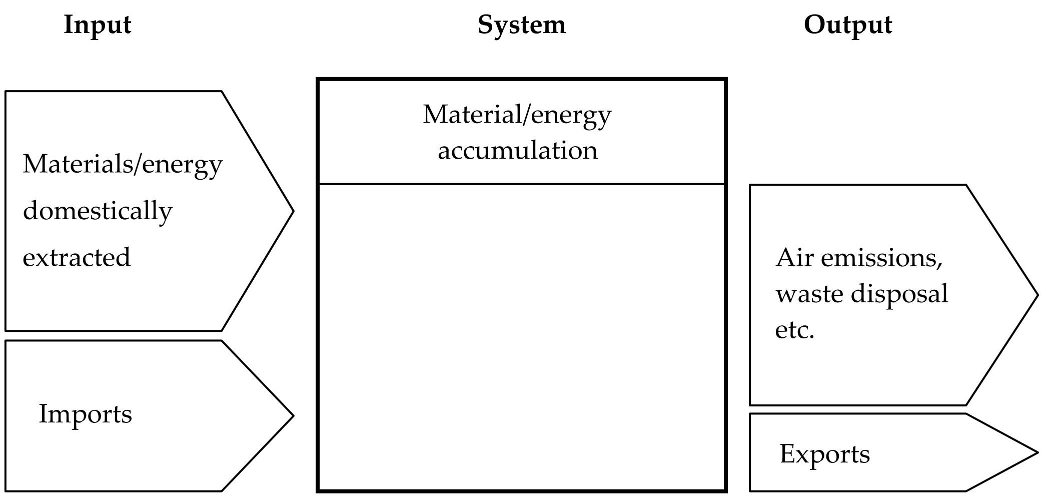


Figure 2.7. Scope of MEFA framework. ***Source*****: Adapted from [88].**

This methodology is well established at the macroscale level (i.e. economies, countries) but it requires further development and application at the microscale (i.e. neighbourhood) level.

Material Flow Accounting and Analysis

Material Flow Accounting and analysis (MFA) is the part of the MEFA framework that has received most attention [88]. MFA is one of the central sets of tools and methodologies that IE developed and has been using, along with LCA, all deriving from metabolic aspects of the analogy to natural systems [89].

MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time [90], applicable on a variety of spatial scales [87]. Thus, it focuses on tracking and quantifying a substance or substance group as it moves through a system.

MFA can be used as a tool to monitor environmental pressures, contribute to the integrated environmental and economic accounting, and plan and evaluate policies for sustainability [12]. A major field of MFA consists of the analysis of the metabolism of cities, regions, and national or supranational economies, connecting sources, pathways and intermediate and final sinks of the total material flows within the system [91].

Water flows represent enormous mass flows in any socioeconomic system with one order of magnitude more than all other materials. For this reason, these are not accounted for in national MFA studies [88]; Eurostat's recommendation is the drawing up and separate presentation of water flow accounts.

- In chapter 5, the MFA framework is adapted in order to account for the inputs of water into two case studies at the microscale level (Sant Boi and São Carlos RPs) and also to account for the uses of water.

Energy Flow Accounting and Analysis

Energy flow accounting and analysis (EFA) is part of the MEFA framework, together with MFA. The basic idea of EFA is to establish an account of socioeconomic energy flows that uses the same basic concepts and system boundaries as MFA, with energy instead of matter as the unit of analysis [92].

EFA aims to establish a complete balance of energy inputs, internal transformations, and energy outputs of a society, or of a defined socio-economic component. Its target is to assess in energy units (for example, tons of oil equivalent (TOE)) all inputs and outputs of a socio-economic system. EFA employs, as far as possible, existing notions and methods of conventional energy balances in order to trace energy flows through an economy and obtain indicators for the amount of energy a society is able to harness for its purposes [92]. EFA can also be applied to supra-national entities, subnational entities such as economic sectors or cities and regions [87]. EFA provides an important database for the derivation of a number of energy indicators (intensity of energy use, energy consumption patterns or energy use of regions) [92-94].

- In chapter 4, the EFA framework is applied to a case study at the microscale level (Sant Boi RP). In particular, it is used in order to account for:
  - *direct* energy use in the operation of a RP
  - *indirect* energy use, which refers to the energy used in the transportation of customers and employees to/from the RP. Here, we use the term 'indirect' because it is not within the physical boundaries of the RP. However, strictly speaking, the EFA framework considers that the term 'indirect' flows refers to up-stream resource requirements; in contrast to direct flows, which refer to the actual weight/energy content of the products and thus do not take into account the life-cycle dimension of production chains [91].

2.3.2. Life Cycle Assessment

The Society for Environmental Toxicology and Chemistry (SETAC) defined LCA as [95]:

> '*an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying energy and materials used and wastes released to the environment, and to evaluate and implement 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*'.

For such evaluation, it is necessary to compile an inventory of 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 [82]. Then, it is necessary to evaluate the potential environmental impacts associated with those inputs and outputs and interpret the results of the inventory and impact phases regarding the initial objective.

This is a methodology that has been well developed at the product and process scale, but fewer applications have occurred at the micro and macroscales (i.e. the neighbourhood level).

The LCA community has worked closely with the International Organization for Standardization (ISO) to produce standards for the LCA framework [96-100]. The current standard practice of LCA includes four steps [96, 101] (Figure 2.8):

- **Definition of the goal and scope of a project**. In this step, the goal of the assessment is stated, which includes the intended application, the reasons for carrying out the study, the intended audience and whether the results are aimed to be used in comparative assertions with the intention of being disclosed to the public. Furthermore, the scope is also stated, which includes the following items: the product system to be studied; the functions of the product system or, in the case of comparative studies, the systems; the functional unit; the system boundary; allocation procedures;

impact categories selected and methodology of impact assessment, and subsequent interpretation to be used; data requirements; assumptions; limitations; initial data quality requirements; type of critical review, if any; type and format of the report required for the study. The functional unit is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related. This enables the comparison of two essential different systems.

- **Inventory analysis**, also known as life cycle inventory, involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system (energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a system). This stage includes the allocation of flows and releases, since industrial processes normally yield multiple products that can be recycled or discarded as raw materials. Such inventory serves as the basis to evaluate the potential human health and global environmental impacts of the environmental resources and releases identified during the life cycle of the system.
- **Impact assessment.** The life cycle impact assessment is aimed at evaluating the significance of potential environmental impacts using the life cycle inventory results. In general, this process involves associating inventory data with specific environmental impact categories (such as climate change, ozone depletion, human toxicity, ecosystem toxicity, and biotic resource depletion) and category indicators, thereby attempting to understand these impacts. 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 [102]. Between the available normalised impact methodologies, the most used are CML 2 baseline 2000 [103]. There are several software packages for LCA practitioners. In this dissertation, the software Simapro 7.1 is used [104].
- **Interpretation of the significance of impacts.** Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together. The interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations to decision-makers.

These steps 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 [83].

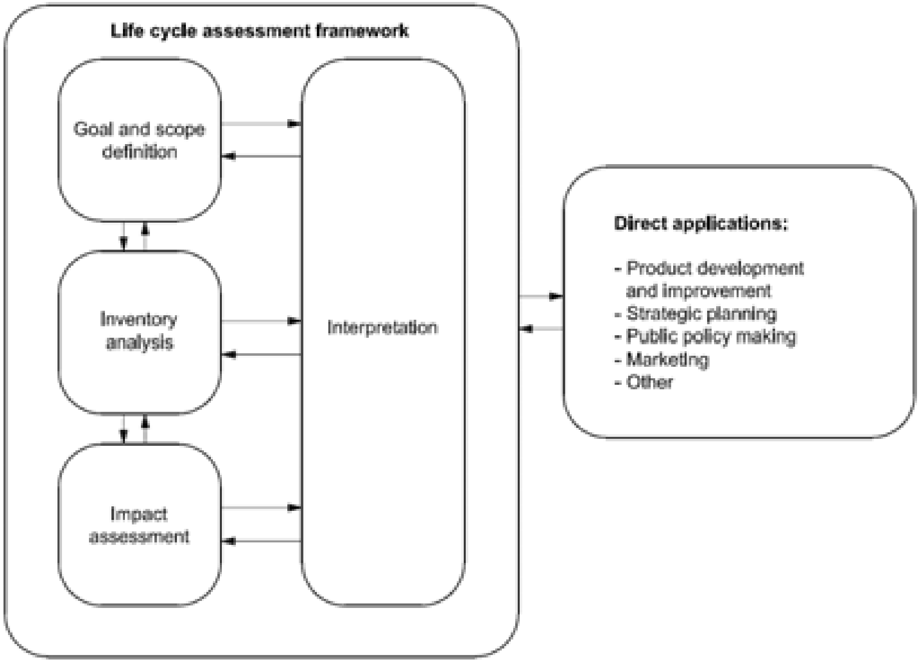


Figure 2.8. LCA framework. ***Source*****: [96].**

- In chapter 4, the LCA tool has been applied in order to estimate the global warming potential (GWP) of the energy consumption in a commercial neighbourhood case study (Sant Boi RP).

2.3.3. Economic asessment

There are many options available to perform an economic assessment. To us, the preferable option would be to perform a Life Cycle Costing Analysis (LCCA), due to its holistic approach. LCCA is an economic analysis technique to estimate the total cost of a system over its life span. Thus, it is a systematic approach that includes all the costs of the infrastructure facilities incurred over the analysis period [105, 106]. Costs considered include the financial cost of owning, operating, maintaining, and eventually disposing of the projected infrastructure, which is relatively simple to calculate, and also the environmental and social costs which are more difficult to quantify and assign numerical values. Biophysical and social aspects demand the definition of units of measurement, but there are a series of externalities for which no explicit market exists [107].

LCCA provides a significantly better assessment of the long-term cost effectiveness of a project than alternative economic methods that focus only on first costs or on operating-related costs in the short run [108]. However, considering the fact that LCCA methodologies are still incipient and given the constraints in the obtaining of economic data regarding social and environmental costs, we carried out a more traditional economic assessment by means of two major investment indicators, Net Present Value (NPV) and Payback Period (PP).

Net Present Value

The NPV is defined as the difference between the present value of a stream of benefits and that of a stream of costs. To achieve this, the discount rate is used (all costs are adjusted to reflect the time-value of money). The discount rate is the interest rate used in economic science to find the present value of future costs and benefits. By means of a properly chosen discount rate, the investor becomes indifferent regarding cash amounts received at different points of time.

The NPV of an investment is calculated as a function of the net cash flow (difference between benefits and cost) and the discount rate, as shown in equation 1:

$$\text{NPV} = \sum_{t=0}^{T} \frac{F_t}{(1+r)^t} \qquad \text{[Eq. 1]}$$

Where:

F represents the net cash flow (inflows minus outflows), at time t

r is the discount rate, expressed in real terms, net of any changes in the price level (inflation),

t is the time horizon of the project.

NPV results will determine the project's feasibility. A positive NPV occurs when the sum of the discounted benefits exceeds the sum of the discounted costs. Therefore, the decision rule is to select the option that offers to maximise the NPV. Hence, if NPV > 0, investment will be profitable and the project can be accepted. If NPV<0, the investment will lose money.

Payback Period

In contrast to a NPV analysis, which provides the overall value of a project, the PP gives the number of years it takes to break even from undertaking the initial expenditure. Thus, the payback method focuses on how quickly the initial investment can be recovered, and as such it is not a measure of long-term economic performance or profitability.

The PP can be defined as the time that a project is expected to take in order to earn net revenue equal to the capital cost of the project. If the time value of money is not considered, we are talking about the Simple PP. Otherwise, the discounted PP takes into account a discount rate in order to consider the time-value of money when comparing the future stream of savings against the initial investment cost.

The PP can be calculated by means of equation 2:

$$PP = \frac{\text{Capital costs}}{\frac{(B_t - C_t)}{(1+r)^t}} \quad \text{[Eq. 2]}$$

Where:

B represents the annual financial benefits or revenues,

C represents the annual costs or expenditures,

r is the discount rate, expressed in real terms, net of any changes in the price level (inflation),

t is the time horizon of the project.

(the consideration of a discount rate of 0% entails that the simple PP is obtained, otherwise it is the discounted PP the one that is calculated).

- In chapter 7, the NPV and PP indicators are used to carry out a cost assessment of several strategies for RWH at different scales and under different conditions.

2.3.4. Sustainability indicators

An indicator is a numerical value that helps provide insight into the state of what we are measuring. It quantifies and simplifies phenomena and helps us to understand complex realities. Indicators are developed based on quantitative measurements or statistics that are tracked over time. By simplifying a vast amount of information into a simple form, they make it much easier to read and understand.

Indicators are useful to show where we are, which way we are going and how far we are from where we want to be. So far, indicators have been used as performance indices to be compared with yardsticks in order to indicate potential for improvements and progress over time [109] and to inform policy decisions [12, 110] as feedback mechanisms for decision making.

The need for indicators of sustainability has been widely recognised and various efforts have been invested into constructing such indicators [111]. For this reason, the development of 'indicators of sustainability' is perceived as a first step towards the operationalisation of the sustainability concept [111], in order to assess sustainable development and monitor the progress towards sustainability. In this context, urban indicators are crucial to help local and national policymakers improve their action towards sustainability [56].

However, there is no agreement on what the best sustainability indicator should or can be, partly because there are no fixed or exact definitions of the concept [111]. Thus, the selection of adequate, relevant and robust indicators is quite challenging [12].

Sustainability indicators may be classified into environmental, economic and social indicators. This dissertation develops several environmental indicators, which are aimed to be used at a wide variety of geographic scales, from the building level to the regional one.

- In chapters 4 and 5, several indicators are defined based on the environmental assessments carried out. These indicators of energy and water intensity of RP are of interest in the environmental arena. However, they should be complemented with social and economic aspects to reflect the links between the various dimensions of sustainability.

2.3.5. Ecodesign

Ecodesign presents itself as one of the key tools in the move towards a more sustainable city [83] and it has become one of the central elements of IE [102]. Ecodesign (also known as design for the environment) is an approach that considers the environmental implications of each stage in a product's life cycle during the design process [10]. Thus, it consists of considering environmental criteria in the development of a product, without obviating other key aspects of design (costs, functionality, aesthetics, etc.); with the aim of using the minimum amount of resources and generating the minimum emissions throughout the life cycle of the product.

The benefits of ecodesign are many: reducing environmental impact, reducing costs, innovating, satisfying legal environmental requirements, increasing the quality of the product and improving the image of the neighbourhood and the whole municipality [112].

The ultimate goal of ecodesign, applied at the neighbourhood level, is to reduce the environmental impact of the neighbourhood throughout its whole life cycle. The life cycle is understood as all the stages through which it evolves, which may include (a) the planning stage, (b) the architectural design and construction stage, (c) the neighbourhood management stage and eventually (d) urban transformation (rebuilding the neighbourhood/city) and revision of planning schemes (Figure 2.9). However, at the planning stage the only possibility to condition the following stages is to set a basis for the professionals who are going to carry out the architectural design and construction (stage b) and also the people responsible for the management of the neighbourhood (stage c). Hence, stages (b) and (c) should be circumscribed to the orientations and requirements stated earlier in the planning (a).

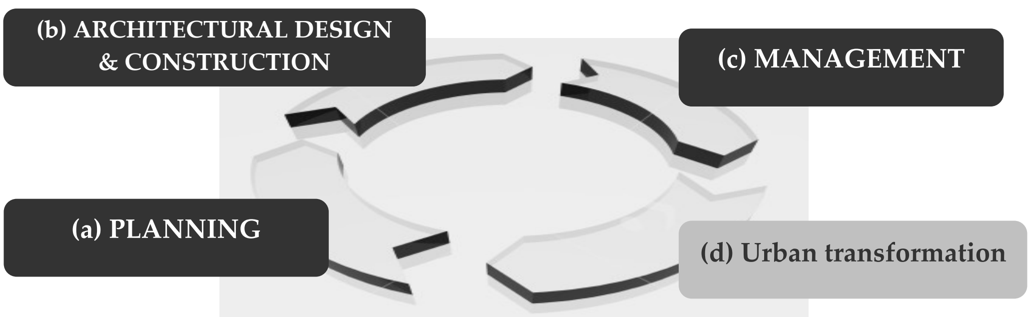


Figure 2.9. Stages of the life cycle of an urban settlement.

The incorporation of the life cycle approach at the design and planning stages implies the recognition that each decision made in the early stages of planning has consequences (social, economic and environmental) on the following urban stages. Often these are not obvious or immediate and they are only observed when examining the complete life cycle of the neighbourhood.

In addition, it is well-known that including sustainability criteria at an early stage of the design/planning process is the best strategy for environmental prevention, since most environmental impacts are conditioned from the design of the product [113]. Through a life cycle approach, decisions can be made in a more deliberate and systematic way. Furthermore, it can lead to a decrease in financial spending in the mid-term and, at the same time, less environmental pressure in terms of reduced depletion of resources.

Figure 2.10 shows a diagram of the methodology followed throughout the design and planning process of the case study neighbourhood (Vallbona). The different steps are described next.

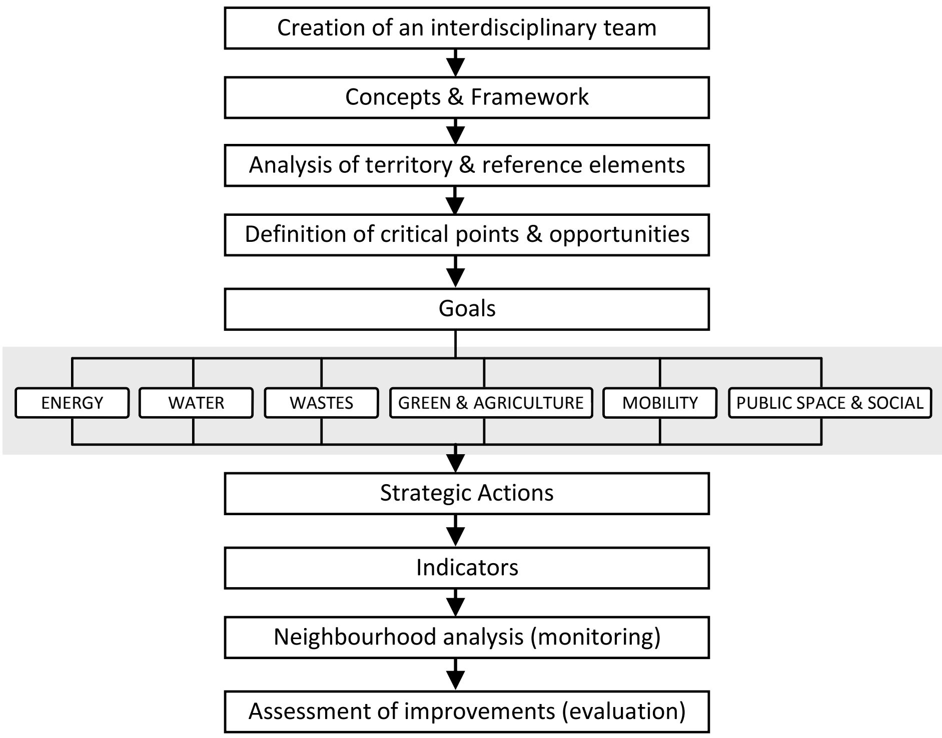


Figure 2.10. Diagram of ecodesign methodology applied on urban systems.

Creation of an interdisciplinary team

The first step is to create an interdisciplinary design team, which is of great value [46] and it is essential in urban planning [114]. The design team should have sufficient understanding of sustainable design practices, constraints, existing conditions and specifications [46]. Practical experiences, together with the rapid evolution of the sustainability science, provide planners with a body of knowledge at their disposal. From these experiences, data and criteria may be obtained for the design of future neighbourhoods. The close collaboration between scholars and practitioners coproduces the necessary knowledge to harness science and technology for sustainability [34].

Concepts and framework

Once the interdisciplinary working team is formed, several sessions are planned to debate and decide how the neighbourhood should be and what are the best strategies to achieve it. A session is dedicated to general concepts about urban sustainability and sustainable neighbourhoods in order to set a framework for debate and decision-making. Here, the definition of 'sustainable neighbourhood' may be defined and agreed upon within the working team, in order to move from a political aspiration to a specific result. Together with the definition, the team debates and agrees upon several key concepts, the fulfilment of which should be necessary for the achievement of a sustainable neighbourhood.

Analysis of the territory and of reference elements. Definition of critical points and opportunities

This step consists of carrying out an environmental, social and financial analysis and diagnosis of the territory where the neighbourhood is going to be located and also an analysis of some reference elements (other neighbourhoods in the metropolitan area and in other regions) in order to detect their critical points but also their strengths and opportunities.

Goals

Next, several thematic sessions are carried out in order to set goals for each topic of interest (i.e. energy, water, wastes, green and agricultural areas, mobility and transportation, public space and social environment). For each one, the set of goals is proposed having as an indication the analysis and diagnosis for the reference elements.

Strategic actions

Then, the strategic actions aimed at the achievement of the goals are defined for each topic, for which several different options in terms of the overall package are considered. Strategic actions can arise from the experiences of the working team and from the analysis of reference elements and territory. These actions are debated within the working team and with the policy-makers, and are tested for economic viability in terms of cost-benefit analyses. The actions take into account the different stages that shape the neighbourhood through its life cycle. It is recommended to focus most attention on certain specific actions which could have the highest positive impact on the neighbourhood.

Indicators

Several indicators are defined throughout the design process, in line with the definition of goals and strategic actions. A set of environmental indicators is necessary to visualise the path of the neighbourhood in order to determine its position compared to the strategy formulated and thereby enabling the diagnosis of the current status, but also the prognosis of the future situation [43]. The final selection of indicators endeavours to meet the following criteria: quantifiability, representativeness, low cost, homogeneous measure over time and clarity in the interpretation. Each indicator is described considering its definition, how its variables are defined, which is the desirable trend, calculation equation, data source and other complementary comments. The indicators are defined for the management stage, since most environmental and financial costs are related to the operation of the neighbourhood.

Neighbourhood analysis and assessment of improvements

The next step of the ecodesign methodology consists of an analysis of the final product, that is to say, the neighbourhood. The aim of this procedure is to obtain an environmental diagnosis of the neighbourhood. There are several methodologies and tools in order to achieve this, one of them being the monitoring and control of the set of indicators. The systematic collection and analysis of information along the use stage of the neighbourhood (monitoring) can let decision-makers know when things are going wrong. If done properly, it is an invaluable tool for good management, and it provides a useful base for comparison of actual project performance against the agreed goals (assessment of improvements or evaluation). Monitoring and evaluation are both tools which help to know when something is not working, and when circumstances have changed. Thus, they are useful for decision making.

From the whole ecodesign process, a sustainable neighbourhood planning proposal is defined.

- In chapter 3, the ecodesign methodology is applied to the Vallbona case study, in order to design and plan a sustainable neighbourhood.

2.4. Field and laboratory works

The following section describes the experimental methodology used in Chapter 6 for the quantity and quality assessment of the potential of RWH in different catchment areas.

2.4.1. Experimental setup

A rainwater conveyance and storage system was installed on each roof from the set of roofs in the UAB campus (Figure 2.11), consisting of:

- Clay tiles (CT) hip sloping roof
- Metal (M) sheet single pitch sloping roof
- Polycarbonate plastic (P) single pitch sloping roof
- Flat gravel (FG) roof

Figure 2.11. Set of roofs in the UAB campus where the experimental design was installed.

The criteria for roof selection were:

- Reduced dimensions (≤120m^2) in order to simplify the complexity of the harvesting and storage infrastructures (mainly the size of rainwater tanks).
- Diversity in the roof type in terms of materials and slope.
- Representativeness of the type of roof in the Mediterranean region.
- Accessibility for the installation and monitoring of the experimental design.

The experimental design consisted of connecting the building's gutters and downpipes to one or more polyethylene rainwater tanks, without first flush diversion system (Figure 2.12). This experimental setup was installed from June 2008 to October 2010.

Figure 2.12. Rainwater tanks installed in the set of roofs in UAB campus (from left to right: rainwater tanks in CT, M, P and FG roofs).

2.4.2. Quantity assessment

The quantity assessment consists of the calculation of the runoff-rainfall regression models, the estimation of the global RC and of the initial abstraction (methodology further explained in chapter 6).

For these calculations, it is necessary to compile rainfall data for the case study area. A manual and/or automatic rainfall gauge was installed above or next to each roof.

Besides this, the rainfall height obtained after each rain event was systematically compared to data from nearby weather stations (Figure 2.13), namely:

- **Station 1.** UAB weather station, located in the Faculty of Education (Experimental Sciences Laboratory),
- **Station 2.** *Servei Meteorològic de Catalunya* (SMC) weather station in Cerdanyola del Vallès, located 2000m outside the UAB campus (available at http://www.meteo.cat).
- **Stations 3 and 4.** MeteoCerdanyola weather stations (Serraparera -3- and Centre -4- stations), located in Cerdanyola del Vallès (available at http://www.meteocerdanyola.com).

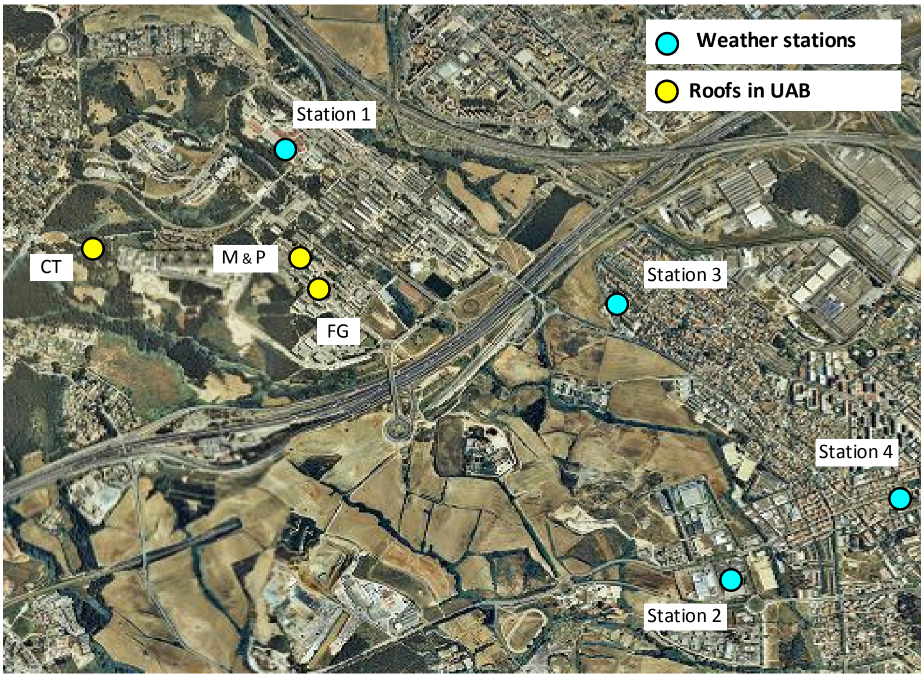


Figure 2.13. Location of the roofs and the weather stations around the UAB campus Abbreviations: CT: clay tiles roof, M: metal roof; P: plastic roof; FG: flat gravel roof.

Furthermore, it was necessary to compile data on the amount of water harvested in each tank after each rain event. The tanks had a nominal storage capacity of 1000L and had a measure (a ruler) in order to show the amount of water contained. However, in order to have more precise readings of the volume of water, the tanks were calibrated with the aid of a measured water bucket and a tape measure. With this calibration, the volume of water for each cm of column of water was obtained (differentiating three parts in the tank: the bottom, the middle and the top). This calibration enabled the runoff volumes to be estimated with the aid of a tape measure as well as the volume of water/cm of water column.

The data on rainfall height and runoff volume were used for the quantity assessment. Then, each tank was emptied, and prepared for the next rain event.

2.4.3. Quality assessment. Analytical techniques

A composite sample (V=0.6L) of the rooftop runoff content was taken after several rainfall events. Samples were kept in the fridge until laboratory analyses took place. The physical-chemical analyses, which were carried out by technical staff from the Department of Chemical Engineering at UAB, included the parameters shown in Table 2.2.

Table 2.2. Physical-chemical parameters that have been analysed in the samples of stormwater rooftop runoff.

Parameter	Detection limit	Units
Physical-chemical parameters		
Conductivity (EC)	0.5	µS/cm
pH	-	upH
Sum parameters		
Total Suspended Solids (TSS)	0.1	mg/L
Total Organic Carbon (TOC)	2.5	mg/L
Total Inorganic Carbon (TIC)	2.5	mg/L
Nutrients		
Phosphates (PO_4^{3-})	1	mg/L
Total Ammonium nitrogen (TAN)	0.015	mg/L
Nitrates (NO_3^-)	1	mg/L
Nitrites (NO_2^-)	1	mg/L
Main ions		
Sulphates (SO_4^{2-})	1	mg/L
Chlorides (Cl^-)	1	mg/L
Total Carbonates (CO_3^{2-} + HCO_3^- + H_2CO_3)	0.04	mmol/L
Carbonates (CO_3^{2-})	2.5	mg/L
Bicarbonates (HCO_3^-)	2.5	mg/L
Carbon acid (H_2CO_3)	2.5	mg/L

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PART II

The ecodesign of urban settlements

Chapter 3.

TRANSITION TOWARDS SUSTAINABLE CITIES: OPPORTUNITIES, CONSTRAINTS AND STRATEGIES IN PLANNING. A NEIGHBOURHOOD ECODESIGN CASE STUDY IN BARCELONA (SPAIN)

This chapter is based on the following paper:

Farreny R, Oliver-Solà J, Montllleó M, Escribà E, Gabarrell X, Rieradevall J. Transition Towards Sustainable Cities: Opportunities, Constraints and Strategies in Planning. A Neighbourhood Ecodesign Case Study in Barcelona (Spain). Accepted with revisions in *Environment and Planning A*.

Abstract

Despite representing only 2.7% of the world's total surface area, the world's cities are responsible for 75% of the world's energy consumption and 80% of GHG emissions. For this reason, the redesign of cities is essential in the transition towards sustainability. However, planning and designing sustainable neighbourhoods is not a simple task given that there is no agreement on what the sustainable settlement should be and which path should be used to achieve it. Furthermore, planners have to strive to achieve a balance between financial, environmental and social goals and must tackle with multiple actors and stakeholders and with site-specific characteristics. The aim of this work is to describe the key determining factors –both opportunities and constraints- found in the process of designing and planning a neighbourhood, based on a case study in the city of Barcelona. This practical experiment, led by the authors, follows the ecodesign methodology applied on an urban scale in the neighbourhood of Vallbona (Barcelona), which occupies an area of 32.6 Ha and will host 2120 dwellings. From this neighbourhood ecodesign process, it is found that territorial (urban form, urban fabrics and density; availability of local resources), financial, legal (regulatory determinants) and political (local government’s wish and leadership) determinants are the most important ones. It has been concluded that there is no one unique path to achieve urban sustainability since the design of neighbourhoods in different locations will lead to different results.

Keywords: Industrial ecology, life-cycle approach, interdisciplinary team, self-sufficiency, urban planning

3.1. Introduction

Urban areas and environments are expanding worldwide as statistics for urban population share reach figures of 70% in Europe, America and Oceania and even 50% on a global level [1]. This ever-increasing urban population is likely to become even larger still [2]. Old cities are being restored and new ones are emerging worldwide. With this unprecedented growth in urbanisation, which will lead to important but as of yet poorly understood impacts on the Earth's environment [3], global sustainability is increasingly an issue of urban sustainability –considering the impact that people living in cities have on the rest of the globe and the sustainability of life in the cities themselves [4]. Despite representing only 2.7% of the world's surface area [5], the world's cities are responsible for 75% of the world's energy consumption and 80% of greenhouse gas emissions [6]. Therefore, managing urbanisation is one of the most urgent practical challenges of sustainability; it is essential to encourage more benign trajectories of urbanisation [7].

Many efforts of urban design and planning have focused on the need for more sustainable design on the city scale, but as Engel-Yan et al. [8] suggest, some of this focus has recently shifted towards the design of neighbourhoods, which eventually are the backbones of cities. The incorporation of sustainability principles into neighbourhood design is important because many of the problems encountered at the macro-city scale are in fact cumulative consequences of poor planning at the micro-neighbourhood level [8]. However, the design of sustainable neighbourhoods and cities is not a simple task since there is no agreement on what a sustainable settlement should be [9] and which is the path for achieving it [10]. The model for sustainable planning places the concern for environmental issues on an equal footing with its traditional economic and social objectives [11]. According to this, we define a sustainable neighbourhood as an urban settlement that is adapted to the local environmental characteristics and makes an efficient use of resources (foremost local or, in its defect, regional), minimises its emissions, and shows an increase in quality of life (including aspects of health, education and welfare) without compromising the carrying capacity of the natural environment, so it can better fit within the capacities of the local, regional and global ecosystems. Thus, sustainable neighbourhoods encourage environmentally friendly planning, architecture, and construction; cooperation and innovation; new technologies and knowledge sharing among people.

All in all, it is clear that to understand cities, we have to analyse their metabolism, a concept which was first proposed by Wolman [12] and that has been widely supported and extended [13]. The incorporation of this approach to the planning process may help to move away from the essentially linear nature of the metabolism of modern cities [2], characterized by consumption of resources and dissipation of wastes to the environment without offering any resistance to the flow of resources through them. Furthermore, the planning process generally takes place in a complex institutional frame with a large number of public and private actors (technicians, politicians, builders, real estate agents, citizens, property owners, NGOs), each of them with their own interests and responsibilities [14] that should be aligned and re-assigned, respectively. According to Campbell [11], the reality of practice restricts planners to serving the narrower interests of their clients, that is, authorities, bureaucracies and financial budgets, despite efforts to work outside those limitations and achieve a balance between the financial, environmental and social goals. At the same time, the local context -that is to say, site-specific characteristics (territory, financial context, technological aspects, society, policy and legal framework) and given conditions (such as existing buildings, infrastructure, vegetation and landscape [8])-, may provide both opportunities and constraints for planning. Therefore, the complexity of designing sustainable neighbourhoods becomes evident, as well as the singularity of each process and project. For this reason, there is a need to develop methods and approaches to aid in the process of sustainable neighbourhood’s design.

In this paper, we adapt and apply the methodology of product ecodesign at the neighbourhood scale in a real case study. As a result, a planning proposal is defined, which is largely conditioned by the local context and, therefore, can not be generalised. Besides this, a collateral outcome of the process is the obtaining of a set of determining factors that need to be taken into account in the design of any neighbourhood.

The aim of this paper is twofold: first, to apply the methodology of ecodesign to a future neighbourhood; and second, to detect and highlight the most relevant practical opportunities and constraints found in this process based on a real case study from the city of Barcelona.

3.2. Case study area: the neighbourhood of Vallbona (Barcelona, Spain)[1]

Barcelona, the capital city of Catalonia, is located on the north-eastern coast of Spain with a population of approximately 1.6 million inhabitants, and an area of 100 km^2. It is the capital city of the dense Metropolitan Area of Barcelona (5000 inhabitants per km^2). It has a Mediterranean climate with average rainfall of 600 mm and an average annual temperature of 15.5ºC.

The city has rapidly evolved over the past decades during which it has gained worldwide recognition. It is currently as keen as ever to lead and to inspire, with ambitions towards global horizons [15]. The city council of Barcelona unanimously approved, in October 2008, to establish sustainability as the driving force for the planning of the last section of its territory to be urbanised. Currently, environmental criteria are becoming more and more important in the planning process of the city, including issues of water consumption, waste, GHG emissions, and efficient use of energy [16].

[1] Case study previously introduced in section 2.1 (Figure 2.1)

This new neighbourhood will be situated in an area called Vallbona located in the northern part of the city (Figure 3.1). It occupies an area of 32.6 Ha and is currently mainly devoted to degraded or neglected areas, infrastructures and agricultural land. It is within the proximity of residential areas at risk of social exclusion. This neighbourhood will host 2120 dwellings and will have a floor area ratio of approximately 0.7. The area lacks urban continuity and presents many structural deficiencies as well as isolation from the rest of the city. Currently it is almost completely surrounded by natural and artificial barriers: the Besós River and several roads, highways (with an average intensity of more than 315 000 vehicles/day) and several railways, which delimit the neighbourhood in all directions and of which just one stops in the surroundings of the neighbourhood.

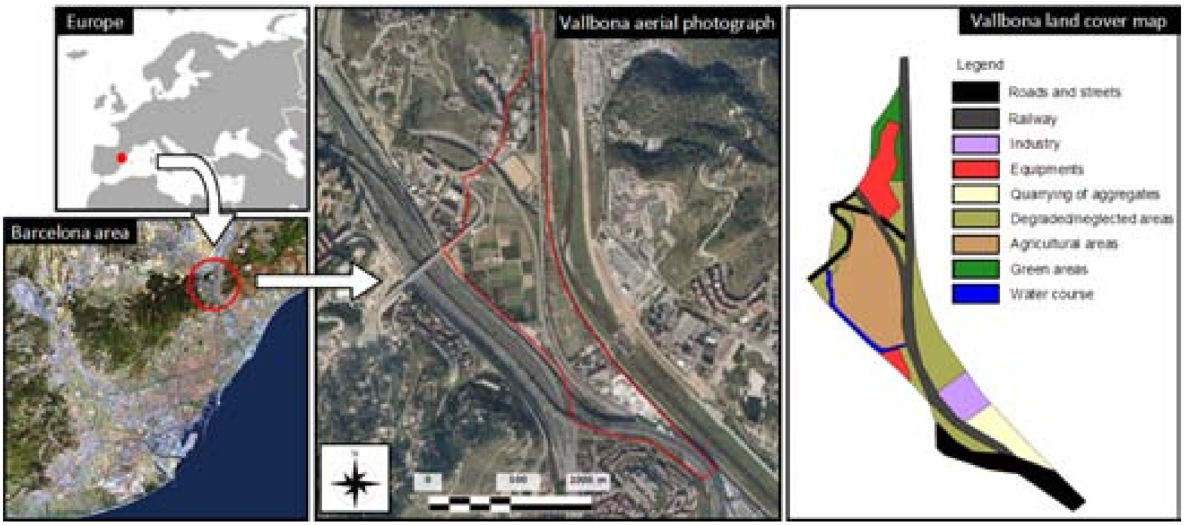

Figure 3.1. Location of Vallbona. The aerial photograph shows the limits of the future neighborhood. ***Source*****: Own elaboration based on most recent aerial photographs [17].**

It is important to highlight that the development of this neighbourhood as a sustainable neighbourhood is conditioned by its previous classification as a Strategic Residential Area (SRA) under the auspices of the Catalan government in order to solve regional housing shortages [18]. This constitutes an important determining factor since it makes certain compulsory specifications, such as the extent to which land use is mixed, heavily influenced by the need to provide housing (90% of the ceiling will be residential).

3.3. Methodology. Ecodesign and planning process.

The methodology of ecodesign was followed throughout the design and planning process of Vallbona (see section 2.3.5 for more details). Vallbona was originally designed as a conventional neighbourhood in early 2008. This was the case until a specific political request came from the town council to build a sustainable neighbourhood in October 2008. From that moment, the ecodesign methodology was applied at the neighbourhood scale.

Figure 3.2 shows the ecodesign methodology in the framework of the planning process. After the political request, the interdisciplinary team was reformulated, led by Barcelona Regional (the agency for the development of urbanism and infrastructures in the Metropolitan Area of Barcelona), which is an entity with wide experience and proud of having a highly interdisciplinary team. Furthermore, a team of researchers from ICTA was integrated within the working group. Their main goal was to reinforce the environmental approach of the planning and design, both in terms of methodology and concepts. All in all, a total of 23 professionals were directly involved in the definition, discussion and redaction of the proposal; and many other professionals were consulted and/or interviewed.

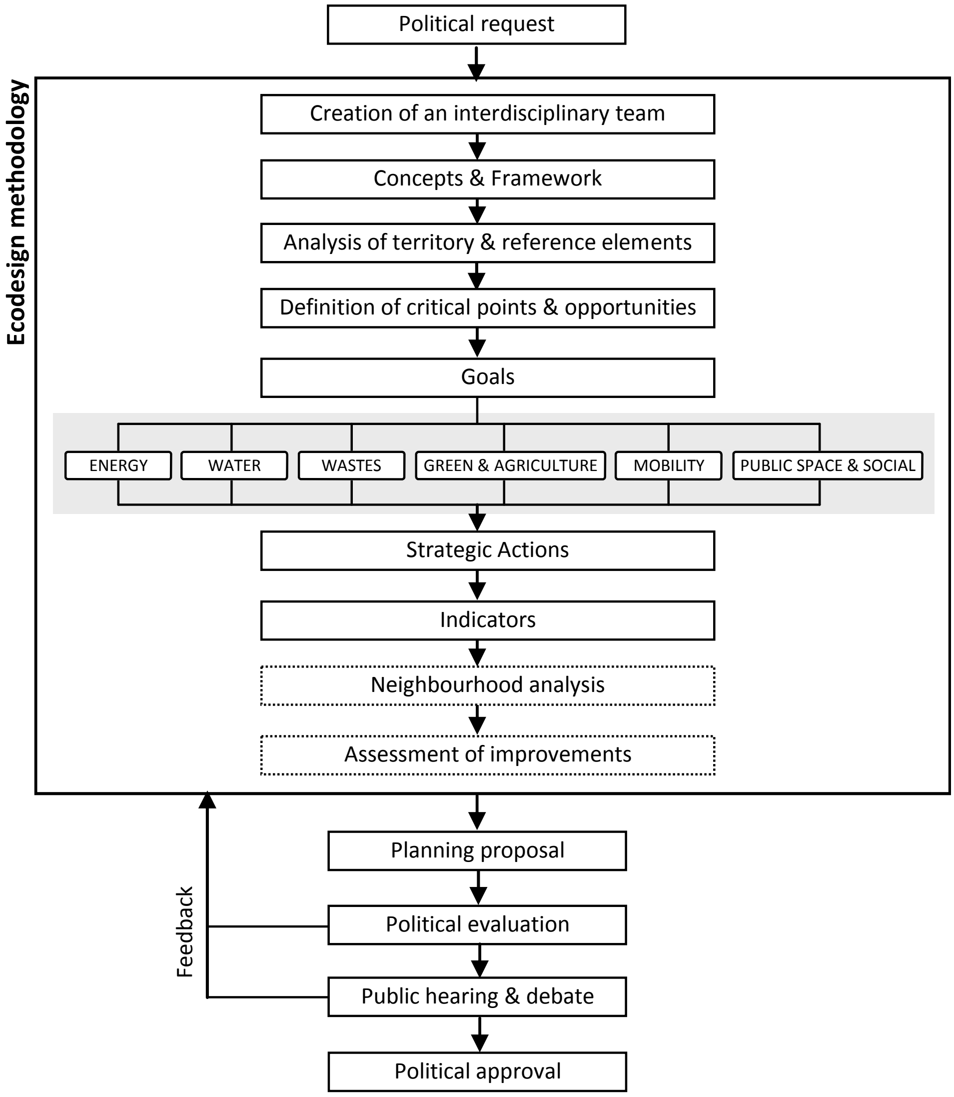

Figure 3.2. Diagram of the ecodesign and planning methodology applied at the neighbourhood scale in Vallbona case study (Barcelona, Spain).

From the whole ecodesign process, which had to be done within a short period of time due to time limits determined by the SRA policies, a neighbourhood planning proposal was defined. Then, it was evaluated by the responsible local government (i.e. city council). This procedure resulted in feedback and, where necessary, the proposal had to be adapted. Eventually, the city council passed an initial approval of the planning proposal in March 2009 (section 3.6 contains some details of the planning proposal). After this, a public hearing and debate process took place. After this initial approval, and once the indications from the public agents, objections and preceptive reports are considered, the definitive approval will take place (supposedly, at earliest, in early 2011).

It must be kept in mind that the planning of a sustainable neighbourhood does not necessarily mean that the eventual neighbourhood will actually be sustainable. However, a good planning proposal is the basis for the achievement of the sustainability goals and, consequently, the environmental performance of the neighbourhood is expected to achieve high standards.

As an outcome of this whole design and planning process, several opportunities and barriers were detected in Vallbona. From them, a list of determining factors to be considered in the design and planning of sustainable neighbourhoods was obtained.

3.4. Results and discussion

This section describes the key determining factors that arose from the Vallbona process, categorised into 6 groups: territorial, financial, technical/methodological, political, legal and social-cultural (Table 3.1). The items of local character that are not of general interest have been excluded from this paper. Each factor is described in the following sections and, when appropriate, recommendations in order to overcome possible constraints are given. The process of designing and planning a neighbourhood is initiated in each location from a certain starting point (site specific characteristics and given conditions). Depending on this, each determining factor may be considered a constraint or an opportunity (or in between these two). It may be helpful to consider and/or assess them in order to help in the design and planning of sustainable settlements. Although a universal model for a sustainable city cannot be found, nor implemented [19], it may be useful to consider these aspects in the design of any neighbourhood. Table 3.1 shows the particular assessment for the Vallbona case study, evaluated qualitatively.

Table 3.1. Determining factors in the design and planning of sustainable neighbourhoods.

DETERMINING FACTORS		Vallbona Assessment[a]		
		-	-/+	+
Territorial	Urban form, urban fabrics and density			●
	Spatial scale of planning		●	
	Availability of local resources			●
	Social surrounding factors		●	
Financial	Hierarchy among the sustainability pillars	●		
	Environmental externalities	●		
	Temporal development		●	
Technical/ Methodological	Design team composition			●
	Availability of environmental data for decision-making			●
	Objectives setting		●	
	Time lag between planning and operation		●	
	Life cycle approach		●	
Political	Local government's wish and leadership			●
	Current trends in environmental policies			●
Legal	Regulatory determinants (zoning regulations and legal specifications)	●		
	Legal framework to support an integrated manager of the neighborhood's resources	●		
Social-cultural	Society's values and evolution		●	
	Community participation processes			●
	Social surrounding factors	●		

[a]The last columns correspond to the assessment of each factor in the Vallbona case study (either negative "-", neutral "-/+" or positive "+")

3.4.1. Territorial determining factors

Urban form, urban fabrics and density

Urban form is defined as the spatial configuration of fixed elements within a metropolitan region. This includes the spatial pattern of land uses and their densities as well as the spatial design of transport and communication infrastructure [20]. As such, urban form must be seen as a preeminent concern of planning [21]. Since neighbourhoods do not exist in isolation but have many interactions with the larger urban system and are open systems in constant interaction with other regions at national and global level [19], the urban form of the whole metropolitan area strongly affects the neighbourhood's capacity of being sustainable. Actually, changes in urban form have implications for the environmental sustainability, integration and cohesion, and longer term quality of life in and around cities [21].

Sustainability in its broadest sense is much more difficult to imagine in a dispersed settlement than in a compact city [9, 22, 23]. This is explained because urban population density and compactness present many advantages in terms of transportation [2, 24-26] and in terms of metabolic flows (they enable a high level of interactions, i.e. introduction of communal heat and power systems [16, 25]). The case study neighbourhood, Vallbona, is expected to have a density of 15 000 inhabitants/km^2; similar to the average density of the city of Barcelona. This is a much higher density than the average European city, much more than American ones and within the range of Asian cities [27]. This high density is not only beneficial due to the aforementioned aspects, but it also enables a city centre to develop within the neighbourhood, which can contribute to the creation of own dynamics and to a sense of community [28].

Significant to the 'compact city' discussion is that, not only the density of the built-up area but also the minimum size of the open space is important [29]. Thus, creating higher-density development will mean less land being devoted to sprawl and more land for open space, gardens, urban agriculture and forestry within the neighbourhood, preserving biodiversity and farmland on the urban rural fringe [30]. In this regard, the strategy of colonisation of the environment is relevant since it requires an analysis of the most adequate layout for the future elements of the neighbourhood (buildings, streets, open areas...) and also a decision on what needs to be preserved due to its natural or social value. In Vallbona, for example, it was a priority to maintain the traditional agricultural areas and the riparian forest, which forced the residential buildings to be of a certain height in order to occupy less ground space with people's dwellings. Greater emphasis on community spaces should also mean more opportunity for locally managed systems for waste, energy and water, while closing loops locally, and more interaction among citizens.

However, compact cities are not `win-win' on all dimensions of sustainability [31]. Thus, compactness presents some drawbacks. High urban densities have a negative effect on the potential resource self-sufficiency of a neighbourhood since the natural resources (sun, water, soil) from a certain area are shared by a greater amount of people. Another issue is the difficulty of further greening our cities and keeping them dense and compact simultaneously [25].

Spatial scale of planning

Urban plans are circumscribed by specific geographic boundaries and, consequently, are not able to directly interfere in areas outside the area under planning. In order to achieve sustainability it is necessary to develop adequate planning policies at the right scale; that is the socially, environmentally and financially appropriate one. Bio-regionalists advocate to have the spatial scale for planning reflect the scale of natural phenomena (i.e. the extent of a river basin, vegetation zones, or the dispersion range of metropolitan air pollution) while financial planners call for a spatial scale to match the social phenomena (i.e. highway networks, municipal boundaries, labour market areas, new industrial districts) [11]. For this reason, it may happen that some strategies at the neighbourhood level are not fruitful because of an inadequate planning scale in cases in which the area under planning is restricted to a spatial scale which does not coincide with natural systems and/or socio-economic structures. Thus, it would be necessary to integrate the financial, social and environmental scales of planning and overlay their geographies.

Availability of local resources

The availability of natural resources such as water, insolation, wind, forests or agricultural land is of interest in order to approach neighbourhood self-sufficiency, which has to be understood as the ability to (partially or completely) supply the neighbourhood with those local resources that have potential within the area and that could be efficiently managed, but not as an isolation per se of resource flows. The desire of resources self-sufficiency in urban areas should be a premise for any sustainable settlement, in order to reduce the ecological footprint on the outer territory. Planning schemes may require that these resources are adequately locally managed in order to satisfy as much as possible the demand for neighbourhood resources through RWH or solar collection, for instance. Sometimes, the use of some resources competes with others, for example forest and agriculture. Then, the priority depends on what is most scarce and most necessary in the area. This priority may change over time, for which the reversibility of urbanised areas is well appreciated.

Vallbona has a relatively high availability of water, insolation and agricultural areas. All these resources help greatly to reduce its external dependency. They are also considered as a basic distinctive element of the neighbourhood, for which they are planned to be proficiently locally managed. Sun availability will be used through passive as well as photovoltaic and thermal solar energy systems in order to reduce external energy demand. The protection of urban nature, which provides important social and psychological benefits to human societies [32], is also guaranteed along the river corridor. The protection of agricultural areas within the urban environment, which can provide food and, at the same time, can raise awareness of the inhabitants' links with nature, has emerged as a strategy to achieve urban sustainability [33]. By minimising the amount of resource consumption and maximising the use of local resources, the neighbourhood can significantly reduce the level of resources imported to the area [23] and increase its resilience (in Vallbona it is expected to locally produce more than 10% of its domestic demand for vegetables).

3.4.2. Financial determining factors

Hierarchy among the sustainability pillars

Economy is subsidiary from the biosphere [34]. However, the rationale of logic may operate inversely, as has been common since the industrial revolution, being environmental sustainability the one that tries to fit within financial sustainability. This may create a false hierarchy that prevails during the entire planning process. Currently, the financial criterion appears to be a limiting factor for innovative and more sustainable neighbourhood strategies [23, 35] since budgets are limited and generally dimensioned for business as usual planning strategies which give poor environmental results. This way of thinking was initially present in Vallbona when the conceptual definition of the sustainable neighbourhood was established. In particular, the definition included a passage which stated 'the development of the neighbourhood has to be circumscribed within a traditional cost-benefit balance', which does not incorporate 'environmental capital'. Therefore, it is recommended to develop planning schemes that integrate the environmental and social agenda into the financial structure.

Environmental externalities

Environmental externalities refer to the economic concept of uncompensated environmental effects of the neighbourhood design that affect consumer utility and enterprise cost outside the market mechanism [36]. Most sustainable strategies entail environmental and social benefits that are not incorporated into the market mechanism and, hence, they are not financially accounted for. Some examples are urban agriculture, RWH, pedestrian streets or a district heating system. If their benefits were considered as positive externalities, the real cost of the implementation of such strategies would be reduced and prices would reflect the full benefits of their establishment. However, this is still not a common approach. In Vallbona, for example, in the case of RWH only the installation costs of the rainwater recovery and reutilisation infrastructure were accounted for, but the multiple favourable benefits it has (flood prevention, resource use alleviation, reduction in water treatment…) were not. Hence, it is necessary to prompt the person(s) in charge of the neighbourhood accounts to internalise externalities in its plans and budgets.

Temporal development

The neighbourhood may not be built all at once but it may consist of a number of phases during which several building promotions are established. This may be a constraint if there is any infrastructure that is planned at the neighbourhood scale (i.e. in Vallbona it was expected that a district heating system or a common underground car park would be built). Furthermore, the success of many of these strategies requires economies of scale, which are only feasible when the neighbourhood is at full yield. Therefore, if it takes a long time to fully occupy the new urban development, some strategies may not be successful for practical reasons. Furthermore, this would provoke financial losses for the operator since the first developer has to initially afford these urbanisation costs (i.e. district heating net) for the entire neighbourhood. However, if the town council is involved in the urbanization process, as happens in Vallbona (where 40 % of the urban area is of municipal property), this constraint may be overcome as it can assure a rapid urbanization of the area.

Another obstacle is the delinking between those who make the initial investments to build up the neighbourhood (development companies) and those who obtain the benefits of living in such an efficient place (inhabitants). This aspect might discourage development companies to invest larger amounts of money for future savings that will not benefit them. If the land developer, promoter, managers and owners were the same, it would probably be easier to incorporate this approach.

3.4.3. Technical and methodological determining factors

Design team composition

An interdisciplinary design team is of great value [8] and it is essential in urban planning [37]. In Vallbona, the team exploited the synergies that were created among its members and their previous experiences in other town-planning projects [38-43] and in the field of environmental analysis [44-56]. However, in some specific occasions, the lack of some sort of active players in the discussion, i.e. certain city councillors and administrators, who where reluctant to accept some of the decisions proposed by the design team, jeopardized certain strategies (although finally they accepted them). However, not having them in the team enabled the group to think independently about new ideas and concepts. For this reason, it is important to establish a balance between working comfortably and working under the pressure of politicians.

Availability of environmental data for decision-making

Access to information is crucial to the decision-making process [53]. During the planning process of a neighbourhood many decisions need to be taken according to certain prevalent criteria. The immediacy of planning processes, which may take a short period of time –a few months-, means that there is frequently not enough time to obtain environmental data for decision-making; this may take months or even years. Thus, there is a decoupling between planning schedule and environmental data availability, which might be a limitation for rational environmental decision-making. In Vallbona, the inclusion of a local research group in the design team provided a source of high-quality previously collected environmental data which was useful for decision-making in the local context.

Objectives setting

Walsh et al [57] argue that urban sustainability becomes truly meaningful only after quantified sustainability requirements are proposed, both because quantification encourages discussion of the correctness of the quantification itself, and because a transition to sustainability cannot be designed and implemented until numerical goals are agreed upon and targets and timescales established. In this sense, a set of indicators measuring the neighbourhood's performance in relation to the goals provides a basis for planning and monitoring progress toward sustainable cities. In Vallbona, a set of indicators was defined (see section 3.6). However, numerical goals were not established for most of them, because of either lack of data regarding the reference elements (which impeded to set a goal), a lack of consensus or because planners were reluctant to set goals against which their work could be judged.

Time lag between planning and operation

The development of the neighbourhood may take many years to be completed, but the key elements of infrastructure must be laid down early in the strategic planning process to encourage a sustainable solution [58]. The planning of a neighbourhood in a certain moment will be translated into a real operational neighbourhood after some years have gone by –maybe five or more depending on various factors-. Then, current solutions stated in planning might not be innovative enough for the neighbourhood of the future, as the whole environment (economy, society and ecology) will change. For this reason, the neighbourhood should be adaptable to future conditions. Previous experiences show, for example, that in some cases the energy requirements of buildings stated in the initial planning have been out of step and behind current regulations at the moment of their construction some years later. In Vallbona there was a particular attempt to solve this challenge: the parking places will be built in a way which enables them to be converted into other uses (reversible parking places) since it is expected that future private vehicle use will decline, according to the Mobility Plan for Barcelona. Therefore, it is essential to plan with strategic and innovative ideas for future sustainable neighbourhoods, which will come into practice several years after the planning is approved, bearing in mind the mid-term evolution of cities.

Life cycle approach

The life cycle approach at the design and planning level implies the recognition that each decision made in the early stages of planning has consequences (social, economic and environmental) on the following urban stages. However, the whole life cycle is not generally considered in most planning proposals. Policies, plans, and projects tend to be assessed on their short term financial returns, or on an economic valuation based upon narrowly structured cost benefit analysis. Decisions are dominated by immediate capital cost, despite the fact that often over 90 % of life cycle costs for typical infrastructures are spent during operational maintenance and rehabilitation [59]. This lack of life cycle approach contrasts with current legal frameworks for other kinds of products (such as cars, electrical appliances or packaging systems), which do take into account their life cycle.

3.4.4. Political determining factors

Local government's wish and leadership

Most local governments aspire to be a reference on a specific area, and sustainability is an attractive one. Thus, there is a tendency for many local governments to promote sustainable neighbourhoods as a means of demonstrating support for sustainable development. This phenomenon has also been observed in the promotion of eco-industrial parks [58]. However, a lack of practical experiences related to innovative solutions scares planners and particularly politicians into taking on innovative "risky" strategies. Public discourse is often preoccupied with limited time horizons and narrow interest group perspectives where the aim is to gain adoption of a plan that most benefits a particular group [60]. Then, some strategies may cause controversy and inertia likely slows the diffusion of sustainable planning and design concepts in neighbourhood-scale projects [35]. Despite this, there are many examples of cities that have leaded the sustainability transition process with practical examples. The city of Barcelona has wide experience on implementing pioneering environmentally friendly strategies, such as district heating, SUDS, selective waste collection... although the town council has implemented most of them just on a small scale. However, the town council does not show enough interest yet in certain decentralised environmental technologies (i.e. local composting plants, rainwater and graywater reuse systems…) although these strategies would be desirable from the environmental point of view [61]. The effect of traditional practices, such as trying not to change that which does not cause problems to the community, has been to reduce and constrain opportunities headed towards innovative sustainable solutions. As stated by Rudlin and Falk [23], almost all the success stories about sustainable neighbourhood planning have involved someone taking risks, and going against the tide. Then, it would be necessary to cultivate political leadership, which is necessary for change and also to take risks and take on innovative solutions for the cities of the future.

Current trends in environmental policies

It is well known that trends in current policies at all levels (international, regional, local) are aimed at sustainable development. In particular, special attention is increasingly given to the urban environment. Some examples of this are the UN Habitat Program [62], The World Bank's strategy on urban environment [63], the Eco^{2}Cities Program [59], the European Thematic Strategy on the Urban Environment [64] and, more locally, the many country-based strategies which have already been implemented to promote urban sustainable development [65]. These policies can be helpful as a support for the neighbourhood sustainability goals.

3.4.5. Legal determining factors

Regulatory determinants (zoning regulations and legal specifications)

From general metropolitan planning to building codes and municipal by-laws, there are many specifications to accomplish in any urban development. Although it might seem that greenfield neighbourhood planning proposals are at the first stage of intervention in the territory, they are circumscribed to other regulation at higher levels (city, metropolitan area, regional, national, European decisions, international agreements…). These regulatory determinants may serve as a way of ensuring the implementation of strategies towards sustainability, such as water and energy municipal by-laws (i.e. ordinances on the incorporation of solar thermal energy collection in the buildings, i.e. Barcelona Solar Thermal Ordinance [66], or on efficient water use) or Building Codes (i.e. Spanish Technical Building Code [67]). However, regulatory determinants also may limit the range of innovation possibilities if the aims towards a sustainable neighbourhood go against certain legal provisions.

In this sense, urban sustainability is a concept from the last decade. Consequently, most current regulatory determinants are not planned with a focus on sustainability since urban regulatory determinants evolve and adapt at a slow pace, particularly when no clear references exist. Planning systems should be responsive to changes in society and technology and adaptable to the future context. A clear example of regulatory determinants is the SRA set of specifications which unavoidably conditions the characteristics of the future neighbourhood. Given that this neighbourhood was originally promoted to deal with the housing shortage, the most important one was to devote 90% of the ceiling to housing purposes. This makes it difficult to have a rich mix of uses and activities within the neighbourhood, increasing the need to commute and, according to Kenworthy [27], reducing the economic performance of the neighbourhood and the creation of employment. Planning policy should be moved away from segregated land uses and towards mixed neighbourhood areas in order to increase natural synergies. Furthermore, it was compulsory to allocate a minimum car parking availability (established at 1.5 parking spaces/dwelling) even though the proposed planning aimed to reduce the need for private car ownership. Other examples from Vallbona were the impossibility of building a composting plant for the neighbourhood, since the Waste Management authority does not support decentralised composting plants, which would enable cycles to be closed within the system. However, Vallbona presents an advantage which is that 60% of the dwellings are public housing, which enables planners to make some strategies compulsory, such as household greywater reuse.

Legal framework to support an integrated manager of the neighbourhood's resources

City management has become a complex undertaking because social-cultural, economic, environmental and institutional processes have become increasingly intertwined in cities [68]. Therefore, there is a need for a resources manager who could proficiently handle local resources and manage the neighbourhoods' environmental facilities. This need has already been detected in the industrial sector as a key concept for its sustainable development [58], but it is rarely observed in neighbourhoods or cities. The resources manager could deal with local resources such as solar energy installations, public vegetable gardens, own water distribution systems (greywater, stormwater runoff…), organic wastes… and could take care of environmental facilities such as common parking areas. This actor is essential for sustainable development since the holistic system approach to resource management is a must for the efficient use of resources.

3.4.6. Social-cultural determining factors

Society's values and evolution

The evolution of society towards more environmentally responsible attitudes might allow a decrease in the demand for cities' resources and, consequently, a reduction in wastes and emissions. Common spaces and areas such as laundries, basements, parking lots or living/dining rooms have many virtues on all levels of sustainability: financial, environmental and social. Firstly, they facilitate relationships among neighbours creating a sense of community membership, which is an important determinant of general quality of life among all social classes [69]. At the same time, common spaces optimise the use of resources, release space in dwellings and diminish the environmental impacts of the collectivity [70], not only because of sharing space but also because of having more efficient equipment in them. These environmental benefits are also translated into financial savings for the community. However, benefits of common spaces will only be realised if they are managed and maintained, which requires some ongoing public outlay and also community engagement.

Some cultures are better prepared than others to accept sharing common items such as spaces and areas, therefore these strategies may be differently welcomed by citizens according to their values regarding common areas. Mediterranean values on private property as opposed to common areas may challenge on this, as was discussed along the design of Vallbona.

Community participation processes

Community involvement is seen as vitally important to planning and the achievement of sustainable development [23]. With participation, residents are actively involved in the development process; there will be a better-maintained physical environment, greater public spirit, more user satisfaction, and significant financial and material savings [71]. Besides, it may be useful to engender in its residents a feeling that they belong to the area and a sense of responsibility for it [23]. However, in the case of greenfield urban developments, as in Vallbona, community participation processes have a secondary role in the neighbourhood design, since there is no community living there. In these cases, participation processes may only be conducted with neighbouring communities. Nevertheless, community participation processes are a determining factor in areas where there is a community already living there.

Surrounding social factors

Surrounding social factors condition the potential of a territory to give rise to a sustainable neighbourhood. The area of Vallbona is isolated from the rest of the city due to several physical barriers, and its neighbouring areas accumulate social degradation in terms of concentrating people with low income, high unemployment rates and criminality. For this reason, it is important to physically connect the neighbourhood with the rest of the city in order to avoid isolation, making the territory more permeable.

3.5. Conclusions

About the design and planning of sustainable neighbourhoods

Global sustainability is increasingly an issue of urban sustainability. In order to set in place a framework to contribute to the design of more sustainable urban settlements, the ecodesign methodology has been successfully applied to the design of a neighbourhood. The process of urban ecodesign differs from a conventional process of urban design due to the incorporation of environmental criteria along the whole life cycle of the neighbourhood, the highly interdisciplinary team, the initial analysis of reference elements and the integration of the metabolism approach. Among these aspects, the first one is of particular relevance since the incorporation of the life cycle approach in the early design of a neighbourhood encourages urban environmental prevention and guarantees the achievement of urban sustainability goals.

From the case study, a list of determining factors has been obtained, which have been grouped into six categories: territorial, financial, technical/methodological, political, legal and social-cultural.

The consideration and/or assessment of this set of factors may be helpful in order to promote the design and planning of sustainable settlements. It has been observed that these factors condition the possibilities of a certain territory to give rise to a sustainable neighbourhood. Therefore, the design of neighbourhoods in different locations will lead to different results, without the existence of a unique path to achieving urban sustainability or a uniform solution. The challenge that lies ahead is to take full advantage of the many opportunities and to turn constraints into opportunities.

About Vallbona

Vallbona is aimed to be sustainable neighbourhood. This is defined as an urban settlement that is adapted to the local environmental characteristics and makes an efficient use of resources (foremost local or, in its defect, regional), minimises its emissions, and shows an increase in quality of life (including aspects of health, education and welfare) without compromising the carrying capacity of the natural environment, so it can better fit within the capacities of the local, regional and global ecosystems.

However, there were several constraints in Vallbona which made it difficult to achieve a sustainable solution. One of these was the set of regulatory determinants, such as the SRA specifications, which limited the leeway of the planners. Another important constraint was within the economic arena, namely, the incorrect hierarchy among the sustainability pillars and the fact that positive environmental externalities were not taken into account.

Fortunately, there were many other determining factors which were decisive as they offered many opportunities for the plan to move towards a sustainable neighbourhood in the case study area. Among these, it is important to highlight the territorial factors, such as the availability of local resources and the urban form, urban fabrics and density of the region, and to a lesser extent, the political factors, with the government aspiring to give rise to an environmentally friendly neighbourhood.

In our point of view, the achieved design of the neighbourhood is satisfactory since the planning proposal incorporates many strategic actions that make possible to forecast a higher environmental performance than the reference neighbourhoods in the region.

3.6. Addendum to chapter 3. The proposal for Vallbona

This section briefly describes some basic aspects of the proposal for the Vallbona neighbourhood.

3.6.1. Concepts

The team debated and agreed upon several key concepts whose fulfilment was, in our opinion, necessary for the achievement of the sustainable neighbourhood. These aspects, which are at the basis of the conceptual proposal for Vallbona, are the following:

- Circular metabolic flows and trend towards self-sufficiency (trying to close the flows of materials, water, energy, food…, developing synergies within the neighbourhood and with the surrounding areas, environmental protection…).

- Neighbourhood for people (streets for pedestrians, healthy environment, environmental education, participative processes…).

- Mixticity of land uses (agriculture as an urban land use, vertical integration of land uses, multifunctionality of spaces…).

- Biodiversity (protection of characteristic local elements, creation of new biotopes related to water management and/or to buildings…).

3.6.2. Goals and strategic actions

Several goals and a total of 68 strategic actions were defined for each topic (energy, water, wastes, green and agriculture, mobility and public space and social arena) (Table 3.2). The strategic actions took into account the different stages that shape the neighbourhood through the life cycle of a city (planning, architectonical design and construction, and operation).

It was strongly believed that it was necessary to focus most of our attention on certain specific actions which could have the highest positive impact on the neighbourhood. Therefore, from the set of actions, all of them important, there were five which were highlighted as particularly important in order to assure the development of the neighbourhood. These actions were:

- **To minimize the energy demand of buildings**. There is large room for this at the planning level through the layout of buildings and blocks in order to take advantage of solar passive architecture and natural ventilation systems. It is also possible to set a minimum requirement for energy efficiency in buildings.

- **To use local renewable energy sources and a district heating network**. The intense solar radiation enables us to efficiently introduce thermal and photovoltaic solar systems. Furthermore, a district heating network may take advantage of thermal solar energy and cover most heating, ventilation and air conditioning needs.

- **To maintain as much as possible the agricultural mosaic of the area**. The area under planning hosts one of the last pieces of agricultural land in the city, which has a great landscape value and represents a distinctive element of Vallbona.

- **To diversify the water sources, adapting the quality of water to its uses.** There are several potential water sources in the area (rainwater, groundwater, surface water, pipe water, grey and black waters …) which have to be efficiently managed and assigned to the most adequate use.

- **Local resources manager.** This last action, which is thought to be put in practice along the management stage of the neighbourhood, is a relatively new concept. There is a need for a resources manager who could proficiently handle local resources and manage the neighbourhoods' environmental facilities. The resources manager could deal with local resources such as solar energy installations, public vegetable gardens, own water distribution systems (grey water, stormwater runoff…), organic wastes and composting… and could take care of environmental facilities such as common parking areas.

3.6.3. Indicators

A selection of 15 indicators was obtained. The indicators are defined for the management stage, since most environmental and financial costs are related to the operation of the neighbourhood (often over 90 % of life cycle costs for typical infrastructures in cities are spent during operational maintenance and rehabilitation [59]).

Table 3.2 summarizes the goals, strategic actions and indicators for the case study neighbourhood. The list of strategic actions has been simplified for reasons of space. After the table, two of the indicators will be briefly described as an example.

Table 3.2. Summary of goals, strategic actions and indicators for the Vallbona neighbourhood.

TOPIC	GOALS	STRATEGIC ACTIONS	INDICATORS
ENERGY	• To minimize energy demand per inhabitant in buildings • To use local renewable energies	• Passive saving measures: Orientation optimization (minimum 4 hours direct insolation/day in winter) • Natural ventilation • District heating • Efficient architecture	• Primary energy consumption • Renewables production • Equivalent CO_2 emissions
WATER	• To diversify water sources, adequate water quality to its uses and use local water sources • To reduce consumption	• Separative sewer • RWH from roofs and non-trafficked areas • Irrigation with local river sources • Groundwater use • Greywater reuse	• Total pipe water consumption/ inhabitant • Water self-sufficiency
WASTES	• To maximize selective waste collection • To cover the manure demand of agricultural areas with local compost	• To compost organic waste within the neighbourhood • Waste collection at street level (not pneumatic)	• Urban solid wastes production • Selective collection of wastes
GREEN & AGRICULTURAL SPACES	• To preserve and foster local biodiversity • To maintain the agricultural mosaic as a distinctive landscape element • To foster the local river as a structural element • To design new green areas with environmentally-friendly criteria • Participative management of non-professional vegetable gardens	• Preservation of an irrigated agricultural plot of 2,3 Ha • To make compatible professional agriculture and social vegetable gardens • Xerogardening • Promoting green areas with sustainable criteria and aimed at preserving local biodiversity within the urban fabric	• Local food production • Bird biodiversity in green areas
MOBILITY	• To improve the connectivity with the surrounding areas • To rationalize the mobility flows • To recover the public space for people • To reduce private mobility	• New connections with the surrounding areas • To keep 75% of the road network for pedestrians • To foster bicycle use • To minimize public space devoted to parking • Improvement of the bus network	• Transportation modal split • Car sharing clients • Average time for several trips
PUBLIC SPACE & SOCIAL ENVIRONMENT	• To minimize acoustic pollution • To assure the permeability of public spaces • To design public space in order to foster social relationships	• Installation of noise-reduction elements • To facilitate access to public transportation systems and to services through new accesses • New equipments so as to serve people's needs and to integrate the neighbourhood in the whole city	• Proximity to basic urban services • Ecodesigned urban furniture • Social participation

Indicator: Water self-sufficiency

It is desirable for any urban system not to depend too much on external water resources. This indicator measures the capacity of the neighbourhood to self-provide the water it demands. It is calculated as the ratio between the local endogenous water resources consumption (groundwater and rainwater) to the total water consumption (including pipe water). The desired trend is to move towards a value of one, which would mean not depending on reticulated mains water.

Indicator: Local food production

Urban agriculture is emerging as a strategy for urban sustainability [33] since it presents many benefits: it creates occupation, reduces transportation demands and costs, enhances the links of people with nature, improves the quality of urban environments... This indicator evaluates the local food production of the agricultural areas in the neighbourhood, expressed in tonnes/year. As sub-indicators, it is also expressed in production per unit of area of agricultural land and per inhabitant.

3.6.4. Layouts of the proposal

The following figures present an aerial view of the area (Figure 3.3), an extract from a news in the local newspaper (Figure 3.4) and the planning proposal (Figure 3.5).

The whole planning proposal can be downloaded from the Barcelona city council web page [72].

Figure 3.3. Aerial view of the neighbourhood location in Vallbona (Barcelona, Spain).

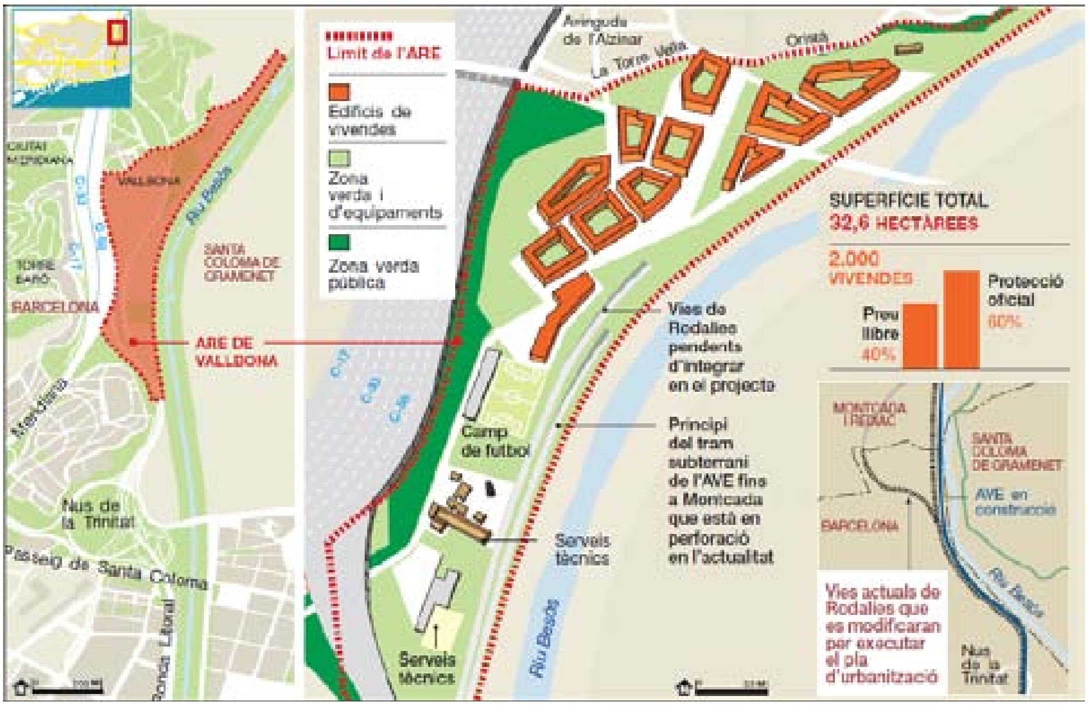

Figure 3.4. Sketch of the proposal for a sustainable neighbourhood in Vallbona (Barcelona). ***Source*****: [73].**

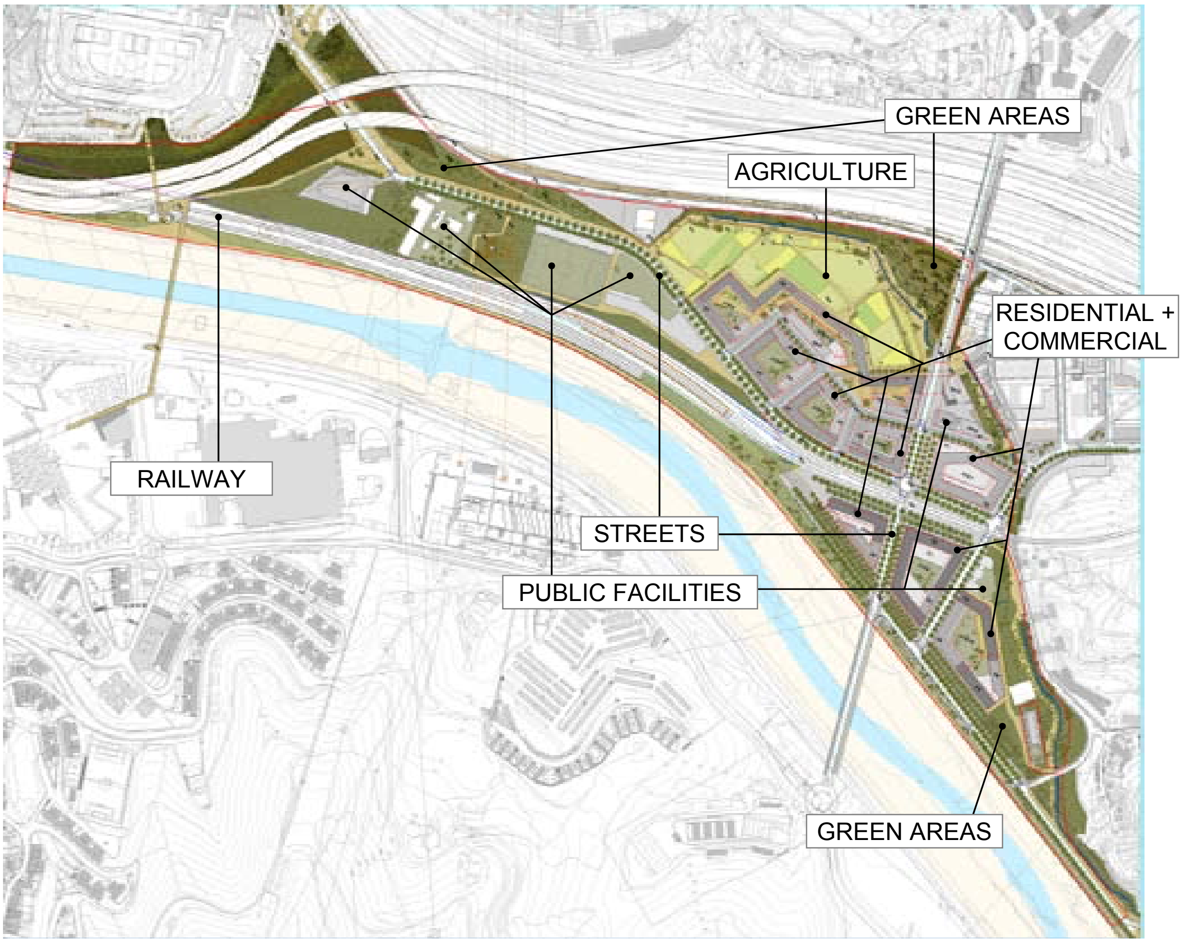

Figure 3.5. Vallbona (Barcelona, Spain) planning proposal. ***Source:*** **[72].**

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PART III

Energy Flows and Indicators in Urban Areas

Having examined some of the opportunities and barriers in the process of urban ecodesign, we have observed that understanding the metabolism of urban systems is essential. Besides, the role of urban form has appeared to be determining for urban sustainability.

Part III takes these ideas further by looking more particularly at the energy metabolism of a service neighbourhood, which brings into discussion several aspects, such as the effect of urban form on anthropogenic energy demand, and the need to use indicators of resources demand and environmental impact for monitoring and policy-making. The focus of this part goes in line with the findings from Codoban and Kennedy [1], who have analysed the metabolism of different neighbourhoods and show that reducing energy uses for buildings and transportation must be the first step towards sustainable neighbourhood design.

Chapter 4.

ENERGY INTENSITY AND GREENHOUSE GAS EMISSION OF A PURCHASE IN THE RETAIL PARK SERVICE SECTOR: AN INTEGRATIVE APPROACH

This chapter is based on the following paper:

Farreny R, Gabarrell X, Rieradevall J (2008) Energy intensity and greenhouse gas emission of a purchase in the retail park service sector: An integrative approach. *Energy Policy* 36(6):1957-1968.

Abstract

The aim of this chapter is to describe the energetic metabolism of a RP service system under an integrative approach. EFA was applied to a case study RP in Spain, representative of the sector across Europe, after redefining the functional unit to account for both direct energy use (buildings, gardens and outdoor lighting) and indirect energy use (employee and customer transportation). A LCA was then undertaken to determine energy GWP and some energy intensity and GHG emission indicators were defined and applied. The results emphasise the importance of service systems in global warming policies, as a potential equivalent emission of 9.26 kg CO_2/purchase was obtained for the case study, relating to a consumption of 1.64 KOE of energy, of which 21.9% was spent on buildings and 57.9% on customer transportation. Some strategies to reduce these emissions were considered: increased supply, energy efficiency, changes in distribution of modes of transport, changes in location and changes in the mix of land uses. A combination of all of these elements in a new RP could reduce GHG emissions by more than 50%, as it is planning strategies, which seem to be the most effective.

Keywords: Global warming potential; Life cycle assessment; Transportation energy

4.1. Introduction

Urban areas and environments are expanding worldwide as statistics for urban population share reach figures of 70% in Europe, America and Oceania and even 50% at a global level [2] and this ever-increasing urban population is likely to become yet larger still [3]. The goal of sustainability in these areas could be defined as a reduction in their use of natural resources and waste production, while simultaneously improving livability in order to better fit within the capacities of local, regional and global ecosystems [4] in a framework of social equity and welfare. The study of anthropogenic systems has been revisited many times as urban ecology and IE approaches have proved to be successful in conceptualizing the relationship between societies and their natural environment [5, 6]. In this respect, energy supply can be considered one of the main challenges facing modern societies, most of the environmental problems confronting mankind today being connected to energy use in one way or another. According to the literature review carried out by Zia and Devadas [7], some of the environmental impacts accompanying energy supply include, among others, soil, water and air pollution, ozone depletion, GHG effects and risks of nuclear energy use.

Nevertheless, this alarm concerning energy consumption and environmental impacts has traditionally centred only on economic sectors such as industry. There has been significant concern with regard to environmental impact in this sector and energy policies have focused on this, concentrating on emissions and on final disposition of wastes and not on resource flows [8]. As a result, over the past 30 years little attention has been paid to other sectors. A case in point would be the services sector, which policies have tended to overlook despite its contribution to the economy in western countries coming to represent more than 70% of gross domestic product [9]. This discourtesy is probably due in part to a lack of interest, as it is still the smallest energy consumer of the four main end-use sectors—residential, industrial, transport and services—representing 15% of EU-25 end-use energy consumption [10]. This would explain why the services sector has the least amount of energy end-use data available, a fact which poses significant challenges to companies within the sector attempting to benchmark their energy performance and inform energy management decisions [11]. Furthermore, analysis of the relative performance of services has also encountered various obstacles, such as the lack of a well-defined unit of production [12], the lack of approaches and suitable metrics for measuring the environmental responsibility of a service [8] and the fuzziness of system boundaries or the lack of clarity of functional units [13], making it difficult to assess their relative performance over time or between companies.

Several distinct trends have occurred in urban areas since the introduction of the private car: an outward expansion of the metropolitan boundary, a density decline in all forms of land use, a higher connectivity of transport networks and, mostly in peripheral suburbs, a segregation of residential from other land uses [14, 15]. These trends partly explain the expansion of service parks which accommodate many different service facilities, a phenomena of particular importance around cities in the United States and Europe, an imitation of the industrial estate phenomenon. This accelerated development of businesses located in the suburbs was initially experienced in the retail sector, but eventually extended to all economic sectors such as offices, factories and hotels, consistent with the underlying processes of urban sprawl [14, 16].

Energy analyses conducted in RP are of particular interest due to the potentially high energy demands resulting from their location: they require the transportation of large numbers of customers, who tend to use private automobiles. A RP is a group of many single-storey retail units, which typically host a range of chain stores, including supermarkets and clothes or footwear, electrical and 'Do It Yourself' superstores, with abundant free parking and proximity to major roads. Initially found on the fringes of most large towns and cities, RP are no longer an exclusive feature of major city suburbs, as sites are being sought around many secondary cities all over the world [17] due to the fact that they are becoming increasingly popular and their users are numbered in the millions. Recent estimates suggest that in western European countries there are almost 1400 large-format stores and several thousand non-food stores, many of which are clustered into over 700 RP [18]. The leading retail manufacturers, with mature markets in their original countries—largely the United States, France and the United Kingdom—are attempting to increase their market on their own continents and also in Asia and Central and South America. The resulting RP share similar characteristics everywhere as the leading companies reproduce replicas of the original successful formats. The retail warehousing sector is consequently undergoing strong expansion: in Europe alone more than 200 new RP are due to open by 2008, with the main development hotspot in the south, particularly Spain and France [19].

The metabolism approach, which involves conceptualizing a city or an industrial system as an organism and tracking resources that enter the system and products and wastes that leave it [3] is a concept that should be extended to the service sector, particularly to RP. To date, most energy assessments in the sector have only focused on some parts of the service system, misunderstanding its real metabolism. Many authors have studied the energy performance of the sector by focusing only on building energy consumption, that is to say, building infrastructure and technical equipment—for providing heat, lighting, mechanical work and data processing— (for examples, see [20-23]) and even also on street and garden energy consumption (see [24]). Some authors such as Junnila [25] and Modahl and Rooning [26] have also included employee transportation in their analysis of the environmental performance of service companies, arguing that staff commuting should be included due to its being closely related to the working processes of a service company. However, customer transportation has attracted little attention and has rarely been included in the analysis of services to date, only being considered when comparing e-commerce with conventional retail stores, for example, in the case of the book sector [27] or more recently in the qualitative analysis of the tourism sector [28]. Generally speaking, the consideration of customers in the analysis of service parks differentiates it from industrial park analyses, which only take employees into account, customers not being relevant. According to Graedel's services classification [8], RP can be considered a type of Alpha service—i.e. one provided in a fixed location, which the customer travels to—and this aspect must be taken into account as part of the service requirements. We propose the inclusion of both employee and customer transportation in accounting for energy consumption in RP service systems.

Energy-intensity indicators have been widely used to measure the energy consumed per unit of activity, as they are most closely related, but not equivalent, to the inverse of energy efficiencies (a measure of output per unit of energy consumed) due to the fact that an increase in energy efficiency helps reduce energy intensity [29-31]. Indicators have been used as performance indices to be compared with yardsticks in order to indicate potential for improvements and progress over time [20] and inform energy policy decisions [11]. One of the most common energy-intensity indicators for the retail sector is energy consumption per m^2 of commercial building [29], although this only considers building infrastructure and technical equipment. These kinds of indicators are therefore only partial, as part of the service system is omitted by their not taking into account employee and customer transportation needs. In this respect, energy-intensity indicators in the service sector require further development, implementation and precision.

The objectives of this research are fourfold:

- firstly, to describe the energetic metabolism of a standard RP service system considering not only the facilities but also the transportation of employees and customers;
- secondly, to analyse the intensity of GHG emission deriving from this energy consumption by calculating its GWP;
- thirdly, to define the energy intensity of a purchase as an indicator of the environmental performance of the sector to show progress over time and indicate the potential for improvements for RP managers and local authorities;
- fourthly, to assess the energy and environmental performance of several strategies, which take into account the implementation of diverse measures to be applied in two scenarios: an existing RP or a new one.

4.2. Case study area[1]

The selection of the case study area meets two determining criteria. Firstly, it is representative of this kind of service activity all over Europe and has similar structural characteristics and dimensions to many European RP, as has been observed in previous research projects [32]. Thus, other parks with similar characteristics can be found in many places, most of them located on the outskirts of cities in suburban areas [33, 34]. Secondly, the RP in question is located in Spain, a country which is facing a rapid increase in the number of RP—30 schemes are currently being developed and 20 more are awaiting permission but likely to obtain it, all of them scheduled to open between now and 2009 [17]. Moreover, Spain is highly energy dependent and faces a rate of external energy dependency of about 80% [35].

The RP case study is located in Sant Boi de Llobregat, less than 10km SW of Barcelona, in an area of 30 Ha in the Metropolitan Area of Barcelona. It is a dense urban area of some 5000 inhabitants per km^2 (Figure 4.1) with stress problems related to urban sprawl and unsustainable mobility [36]. From Figure 4.1 we can see that it is located outside compact urban areas close to major roads. It includes nine single-floored buildings, of which the largest and most representative includes the supermarket run by the leading company at the park and also a shopping gallery with approximately 60 stores and other establishments, mostly clothes shops. The other buildings include four retail warehouses (clothes, electrical, do it yourself and toy superstores), two fast-food restaurants, a garage and a petrol station. It is closely linked to a motorway and has 4000 free parking spaces, of which 75% are open-air. The climate in the study area can be characterized as semi-wet Mediterranean and the average annual temperature is 15.5 ºC. The average daily temperatures range from 8.9 ºC in winter to 23.6 ºC in summer. Buildings are in heating mode approximately 6 months of the year, from November to April with an average of 1286 degree days below 18 ºC.

[1] Case study previously introduced in section 2.1 (Figure 2.2)

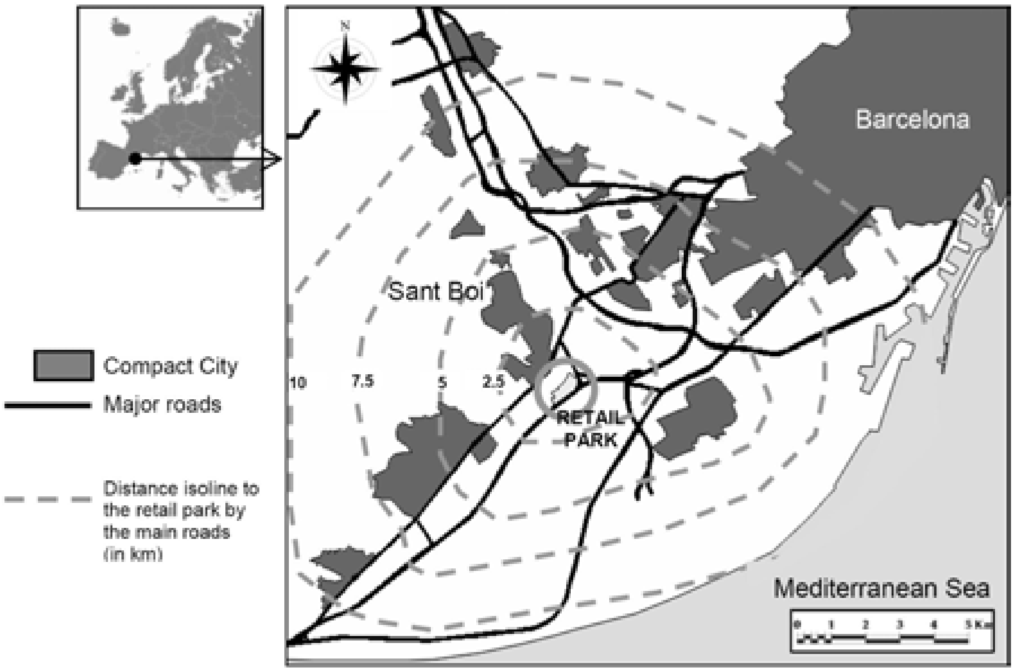

Figure 4.1. Location of the RP in the metropolitan area of Barcelona. Compact urban areas (mostly residential), major roads and distance isolines are shown.

4.3. Methods and approaches

This section is divided into two parts: firstly, the description and assessment of the energetic metabolism of the RP service system—which includes EFA, GWP assessment and the indicators— and, secondly, the assessment of several potential strategies in order to gauge their environmental performance.

The functional unit under study is the energy necessary to purchase a standard total-RP shopping basket, considering the energy used for normal operation of the RP and that used for customer and employee transportation within an urban area. Freight goods transportation is not included as we consider that this corresponds to another stage, the supply chain, although it is recognized that the environmental effects it has appear to be significant and merit further consideration [12].

4.3.1. Energetic metabolism description and assessment

EFA is conducted to track all technical energy flows and LCA methodology is applied to assess environmental impact related to energy consumption. Following this, some energy-intensity indicators are defined and applied to shape an environmental monitoring framework for the sector (Figure 4.2).

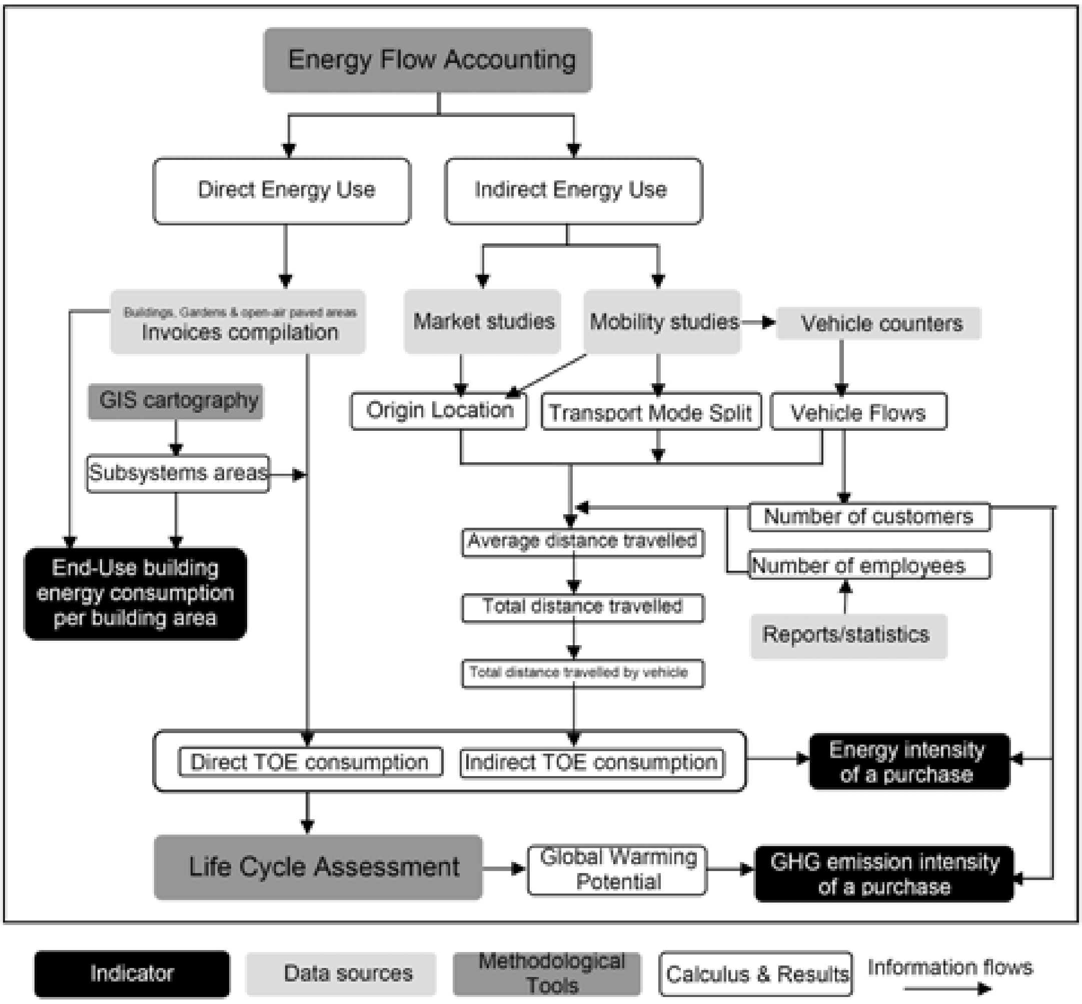

Figure 4.2. Energetic metabolism description and assessment methodology.

A land cover analysis of the RP is carried out using Geographical Information Systems (GIS) with TNTmips software (version 2005:71) in order to create maps based on the more recent aerial photographs available. In the event of a lack of maps from local or regional cartographic sources, aerial photographs from all over the world are available from the web [37]. If field work is possible, however, it is recommended that the generated maps be validated and updated.

A standard RP land cover is divided, according to previous research [32], into three main subsystems:

- buildings,
- vegetation subsystem—which may include gardens (trees, bushes and small grassed areas)
- neglected/degraded open-air areas, and open-air paved areas (RP roads, car and logistics parking and paved pedestrian areas).

The land cover analysis has been carried out in detail for the RP object of study based on the most recent aerial photographs provided by a local cartographic source [38] and validated and updated with field work in 2007 (Figure 4.3).

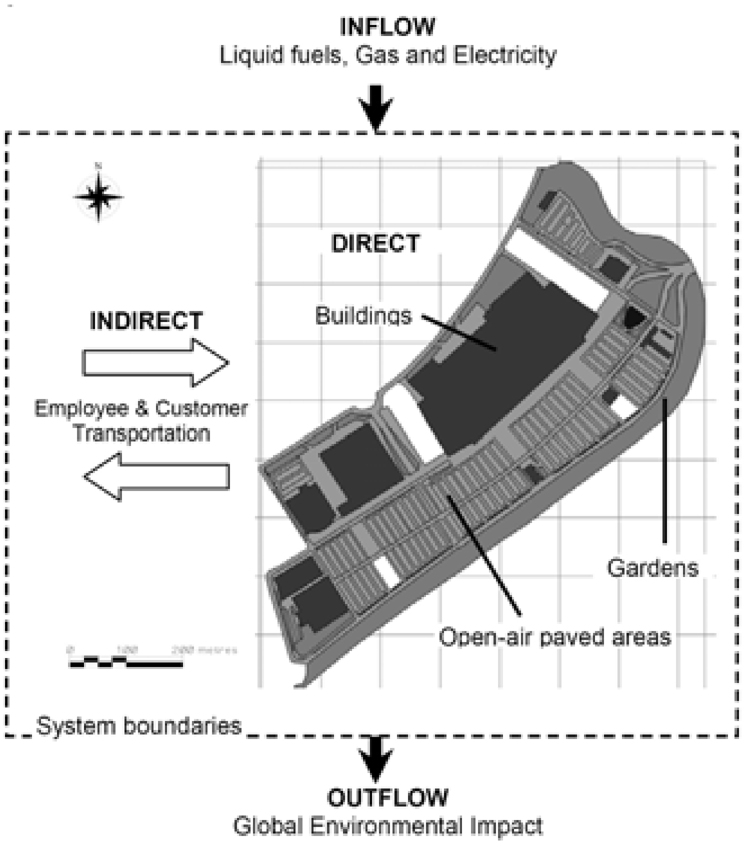

Figure 4.3. Representation of the energy consumption subsystems in the RP object of study (direct and indirect energy use). The sectors in white colour are in construction in year 2006.

Energy flow accounting

EFA method has been applied following the methodology proposed by Haberl [5, 6] and Krausmann and Haberl [39] (see section 2.3.1 for more details). The energy accounted for is that used for the normal operation of RP activities, which means that the energy consumed in the construction and deconstruction of the infrastructures related to the park is not considered.

The anthropogenic energy flow of the service system object of study has been divided into two subsystems (Figure 4.3):

- **Direct energy use**: total energy consumed in buildings (heating, ventilation and air-conditioning systems, lighting, cleaning, maintenance of equipment and infrastructures), gardens and open-air paved areas.
- **Indirect energy use:** total energy consumption for employee and customer transportation in urban areas.

Therefore, the total energy consumption (E) from the operation of a RP can be expressed as it follows (equation 3):

$$E_{SERVICE\ SYSTEM} = E_{DIRECT\ USE\ (RP)} + E_{INDIRECT\ USE\ (TRANSPORTATION)} =$$

$$[\ E_{BUILDINGS} + E_{OPEN\text{-}AIR\ PAVED\ AREAS} + E_{GARDENS}\ ] + [\ E_{CUSTOMER\ transp.} + E_{EMPLOYEE\ transp.}\ ]$$

[Eq.3]

Direct energy use

A compilation of invoices for fuel and related energy carriers for the park's service facilities is necessary to account for all the energy consumed inside the park. All energy must be expressed in tonnes of oil equivalent (TOE) in order to be able to compare the energy consumption of the different subsystems of the RP.

2006 was used as a reference year for the exhaustive compilation of invoices for fuels and related energy carriers—electricity, natural gas, gasoline and diesel—for the RP object of study. Since case study invoices do not include energy consumption in gardening practices (fuel consumption by vehicles and machinery), this data are estimated from previous studies in other service systems. We assume the consumption in the case study to be 0.014 KOE/year/m^2 of gardens, half the consumption accounted for by Oliver-Solà et al. [24] in an urban park in Barcelona, in accordance with the intensity of the gardening maintenance tasks and the climate in the RP object of study.

Indirect energy use

The analysis of energy use from transportation requires mobility studies in order to locate customers' and employees' journey starting points, to obtain the breakdown of different modes of transport used, and to quantify vehicle flows (this also available from vehicle counters). The two primary travel modes to be considered in RP transportation analysis are motorized and non-motorized. The former includes private car and public transit, which in turn generally includes bus, train and other urban collective means of transport.

Data regarding number of employees can be obtained directly from fieldwork by compiling reports and statistics provided by local agents—park managers and representatives from the various retail warehouses.

The number of RP customers can be obtained by making some general assumptions. A customer is defined as a person or a group that travel together to the RP to purchase a standard total-RP shopping basket (in one or more establishments); therefore, a customer can have one or more tickets related to him or her. The number of customers can be estimated according to the annual number of tickets issued or, preferably in order to avoid multiple accounting, the number of vehicles travelling to the park. Vehicle counters provide a record of the transportation activity entering and leaving the RP (including customers, employees and freight goods), in which vehicles are classified according to the number of axles. To discern the number of customer vehicles from these transport flows, some assumptions are made. Firstly, if necessary, a proportion of vehicles are disregarded as they are assumed to be travelling through the RP in order to get to other destinations but not the RP; secondly, only two-axle vehicles are taken into account, as these correspond with passenger vehicles; and lastly, employees' automobiles are subtracted considering a car occupancy local average. This final figure for private passenger vehicles corresponds to the number of customers that travel to the RP to satisfy their purchasing needs. The number of customers that get to the park by public transport can be obtained by considering the breakdown of different modes of transport used by customers compared with the figure for car travellers.

The average distance of travel between origin–destination pairs (from any municipality to the RP) is determined by weighting each distance pair by the number of people accounting for that trip, in accordance with mobility studies. It is assumed that the distances covered are the shortest between two points travelling by major roads (Figure 4.1.). Single-purpose trips to and from the RP are considered.

If the breakdown of different modes of transport used by customers includes walking, the average distance covered by 'walkers' consists of the distance from the closest city to the RP, as it is not realistic to consider longer distances on foot.

For the analysis of employee transportation, the total travelled distance is obtained by multiplying the average distance by the number of employees and by working days (224 days/year). In the case of customers, an estimate for the total travelled distance is obtained by multiplying the number of customers by the average distance travelled.

Total distance travelled estimates are converted to total distance travelled by vehicle by dividing it by the average occupancy of the vehicle. By using these factors, total distances travelled by vehicle are determined for both private car and public transit. The distances are then translated to fuel and TOE consumption by using conversion factors (Table 4.1).

Table 4.1. Summary of vehicle energy efficiencies and conversion factors for transportation operation. ***Source*****: [40].**

Vehicle	Efficiency (km/L)	Conversion to TOE (L/TOE)
Diesel auto	10.20	1150
Gasoline auto	9.34	1250
Diesel Bus	2.85	1150

Case study service system data: Data were obtained from the manager of the park, one of the world's leading retailers, by means of a survey and an interview, and also from the many retail warehouses and other establishments in the park via mail, fax and telephone calls. This information was provided in the form of unpublished market studies.

Data were also obtained from fieldwork (installation of a vehicle classifier and counter system, namely Metro-Counts 5600 series over 16 days in January–February 2007). In the RP object of study, public transit consists of trips made by bus, this being the only public transport available to reach the RP.

The number of employees was provided. Since there were no mobility studies referring exclusively to employees, an alternative source of data was necessary. Official local statistics relating to labour mobility [41, 42] provided a trip count to all origin–destination municipality combinations for the case study municipality (Sant Boi) with regard to trips from the place of residence to the work place, revealing the work travel patterns of local residents. This data were provided according to professional occupation (our focus was on the category 'employees in the service sector and retail salespeople') and to transport mode distribution. According to the mode share of these statistics, trips made by private car, by public transit and on foot represented an average distribution of 65%, 14% and 21%, respectively. A region-wide passenger car fleet breakdown by fuel type for the region (Catalonia) was considered of 37.9% diesel and 62.1% gasoline [43]. The average distance travelled, total distance travelled and total distance travelled by vehicle were calculated. Average automobile and bus transit occupancy for the region of Catalonia was 1.28 and 20 travellers per vehicle, respectively [44].

The park manager provided information based on market studies with regard to the customers' starting point and also their transport mode distribution, which has a distribution of 99% by car and 1% by public transport. A proportion of 10%—detected from fieldwork—of the remaining vehicles were disregarded as they were assumed to be travelling through the RP on their way to other destinations. Passenger vehicles (with 2 axles) were taken into consideration, representing 89.75% of the total vehicles. The number of customers that arrived at the park by public transport was obtained by considering that 1% of the customers travelled using this mode of transport.

Global warming potential assessment

This section provides an assessment of the environmental impact resulting from the previously conducted EFA. Life cycle carbon emissions from primary energy consumption were analysed to demonstrate the ultimate resource impact of energy demand for the service system with respect to CO_2, attributing the amount of CO_2 created from the generation of electricity and fuel availability to the activities undertaken.

An LCA is used as a tool to calculate the GWP of the RP service system in terms of GHG emissions. The LCA was first defined by the SETAC as a method to evaluate the environmental burdens associated with a product, a system or an activity [45] (see section 2.3.2 for further details). It has been recognized as a successful tool for identifying and then implementing strategies to reduce the environmental impacts of specific products, processes and to compare different options. In order to avoid subjectivity in the analysis we have only conducted the steps of classification and characterization. For each source of energy the processes of raw material extraction, production, stocking, transportation and consumption have been taken into account, calculated with the aid of the Ecoinvent database associated with SimaPro v.7.0. With regard to electricity, the Spanish electricity generation profile was applied (coal 37.0%, nuclear 30.5%, hydropower 16.0%, natural gas 7.5%, petrol 4.8%, wind 2.3% and other 1.9%). The contribution of a given source of energy to the GWP impact category is expressed in equivalent units of CO_2 (CO_2eq) which incorporates CO_2, methane, nitrous oxide and hydrofluorocarbons as GHG.

Energy intensity indicators

Three different indicators are proposed for the analysis of the RP service system. If the goal is to control energy expenditure (economic objective of the park companies), end-use energy consumption per area will be useful. This indicator has commonly been quantified by dividing the total end-use energy consumption of the entire building with the total surface area of the building (for examples, see [11, 20-22]).

However, according to our service system approach, we have further defined the energy intensity of a purchase in the RP service sector, calculated as direct and indirect end-use energy consumption per purchase by the average customer. This indicator is a closer approximation than those used previously of the actual energy consumption of a purchase in one or more stores in RP. It must be interpreted as a gauge of integrated energy performance, which is useful for park managers and local authorities in identifying potential improvements and informing energy policy decisions. It could also be established as an essential reference point for the subsequent evaluation of improvements in future energy consumption.

If the policy objective concerns the environment, the appropriate indicator must involve carbon emissions. The GHG emission intensity of a purchase in the RP service sector is therefore calculated by dividing total GHG emissions by number of customers.

4.3.2. Strategy proposal and sensibility analysis

Five strategies are proposed to test the (un)feasibility of reducing GHG emissions in the RP service system. These strategies are focused on buildings (increased supply and energy efficiency), transportation and planning (location and mix of land uses). A sensibility analysis is conducted by assessing the energy and environmental performance of each strategy. In order to determine the combined effect of the strategies, two scenarios are proposed. Scenario 1, which considers an existing RP, can be improved using strategies, which involve building and transportation measures, while scenario 2, which considers the creation of a new RP, can also consider the implementation of planning strategies.

Strategy 1. *Increased supply: widespread implementation of renewable energy technologies.* Electrical energy supply can be increased by taking advantage of local resources due to the fact that solar photovoltaic energy has high potential in the area. Moreover, the design of RP buildings is particularly adequate for this energy source as they tend to have relatively wide extensions of roofs free from solar radiation obstacles. The solar photovoltaic potential is estimated following the methodology described by the Spanish Energy Agency [46], using BP3165 solar panels [47] on the entire roof area (73 512m^2). It is considered that each unit of energy generated is equivalent to a unit of energy saved or conserved.

Strategy 2. *Energy conservation: introduction of energy efficient technologies in the RP buildings and streets.* This scenario offers companies a large scope for energy efficiency improvements involving refrigeration systems, illumination and heating, ventilation and air conditioning systems. The European Commission proposal for a Directive on the promotion of end-use efficiency and energy services [48] identifies the building sector in particular as an area where significant energy efficiency gains could be made at negative or zero cost.

Strategy 3. *Changes in personal behaviour related to transportation: transport mode distribution*. Differences in specific energy consumption per passenger-km for the different modes of travel (Table 4.1) clearly indicate the environmental preference for collective modes of transport. This scenario considers a shift of 50% of the employees and 20% of the customers that travel by car to bus mode. We assume that reducing the number of customers travelling by car is difficult due to the fact that buses are not adequate for carrying some types of purchase.

Strategy 4. *Changes in RP location: inside the city, in a compact urban area*. This would reduce the average distance travelled as we consider that the average distance for customers and employees to the RP municipality (Sant Boi) is reduced from 2.2 to 0.5 km. It is considered that the average distance from the other cities to the park remains unaltered as changes in distances between cities are, on the whole, compensated.

Strategy 5. *Changes in land mix uses: accounting for the multipurpose use of automobiles.* This methodological change significantly reduces the energy use allocated for travelling to the RP since the single-purpose journey overestimates the energy consumption used in transportation. This scenario considers only the distance covered to reach the park but not the return journey (reduction of 50% in distance covered), as it is assumed that the latter journey has another purpose and is therefore allocated to another process. This is possible if considering a mix of land uses integrated within the city as opposed to a mono-service system.

4.4. Results

4.4.1. Energetic metabolism of the service system object of study

This section provides the EFA, LCA and indicator results for the RP object of study. General data relating to the number of employees and customers (each of them equivalent to a purchase of a total-RP shopping basket), and to the average distance they travel is shown in Table 4.2. The average distance covered by customers is 46% greater than that covered by employees, considering this last group as a whole.

Table 4.2. General data about the retail park object of study. ***Source:*** **Produced using data from market studies and vehicle counters.**

Category	Aspect	Value	Units
Employees	Number of employees	1400	equivalent employees
	Average distance for walking employees	2.2	km/trip (one-way)
	Average distance for motorised employees	5.8	km/trip (one-way)
Customers	Number of customers (purchases)	4 498 037	customers/year
	General customer profile	2.2	Persons travelling to the park/customer
	Average distance for motorised customer	7.3	km/trip (one-way)

The overall EFA results and the contribution of each subsystem to the GWP are shown in Table 4.3. The results for the energy-intensity indicators are shown in Table 4.4.

Table 4.3. EFA and GWP in the RP object of study, including energy consumed as electricity and other fuels for the year 2006.

Type of energy use	Consumption Item	TEC[a] (TOE/yr)	Contribution to TEC (%)	GWP (kg CO_2 eq/year)	Contribution to GWP (%)
DIRECT	**Buildings**	**1611.2[b]**	**21.9**	**$1.66 \cdot 10^7$**	**39.9**
	Outdoor lighting	45.6	0.6	$5.03 \cdot 10^5$	1.2
	Gardening	0.7	0.0	$1.96 \cdot 10^3$	0.0
INDIRECT	Employees transportation	165.6	2.2	$4.49 \cdot 10^5$	1.1
	Customer transportation	**5550.7**	**75.3**	**$2.41 \cdot 10^7$**	**57.9**
	Total	**7373.8**	**100.0**	**$4.17 \cdot 10^7$**	**100.0**

[a] TEC = Total Energy Consumption

[b] 90% of the energy consumed in buildings corresponds to electricity and the remaining 10% to natural gas.

Table 4.4. Results for proposed energy and GHG emission intensity indicators applied to the RP service sector for the year 2006.

Energy Intensity Indicator	Result	Units	Goal
End-use building energy consumption per building area	21.92	KOE/m^2	Economic
Energy intensity of a purchase in the retail park sector	1.64	KOE/purchase	Economic
GHG emission intensity of a purchase in the retail park sector	9.26	Kg CO_2 eq /purchase	Environmental

4.4.2. Sensibility analysis

Table 4.5 shows energy consumption if the five strategies were to be implemented, with indications of the variation with respect to the case study. The first two strategies represent a reduction of 25% and 27.2% of direct energy use, respectively, while the remaining strategies show reductions in indirect energy consumption of between 9% and 50%.

Table 4.5. Sensibility analysis results. The strategies are compared with the reference service system object of study (the variation of energy consumption is displayed in brackets as a percentage). The scenario in which the strategies can be applied is shown.

Scenario 1	Scenario 2	Strategy		Energy Use (TOE) Direct	Indirect	Total
x	x	Buildings	1. Increased supply	1207.2 (-27.2 %)	5716.3	6923.4 (-6.1%)
x	x	Buildings	2. Energy efficiency[a]	1243.3 (-25.0%)	5716.3	6959.6 (-5.6%)
x	x	Transportation	3. Breakdown of different modes of transport	1657.5	4983.7 (-12.8%)	6641.2 (-9.9%)
	x	Planning	4. Retail park location	1657.5	5203.0 (-9.0%)	6860.5 (-7.0%)
	x	Planning	5. Mix of land uses	1657.5	2858.1 (-50.0%)	4515.6 (-38.8%)

[a]Scenario 2 considers an average efficiency improvement of 25% in buildings and open-air paved areas. Research has shown that more than 20% of energy consumption in buildings could be saved by 2010 by applying stricter standards to buildings undergoing refurbishment and new buildings [49]. More specifically, in the supermarket sector, Arias [50] has demonstrated the possibility of reducing energy consumption in different proportions (up to 60%), whereas other authors believe energy efficiency of the sector may be improved by 10-15% with little investment [51].

Figure 4.4 shows the GWP related to each of the scenarios. Under the different strategies, GHG emissions are reduced by between 5.0% and 29.3%, the mix of land uses being the one that shows the best performance. Scenario 1, which considers only the implementation of building and transportation strategies, shows a reduction of 27.0% in GHG emissions. Meanwhile, the joint effect of all strategies in scenario 2 (new RP) implies a reduction of 56.5% of the total GWP.

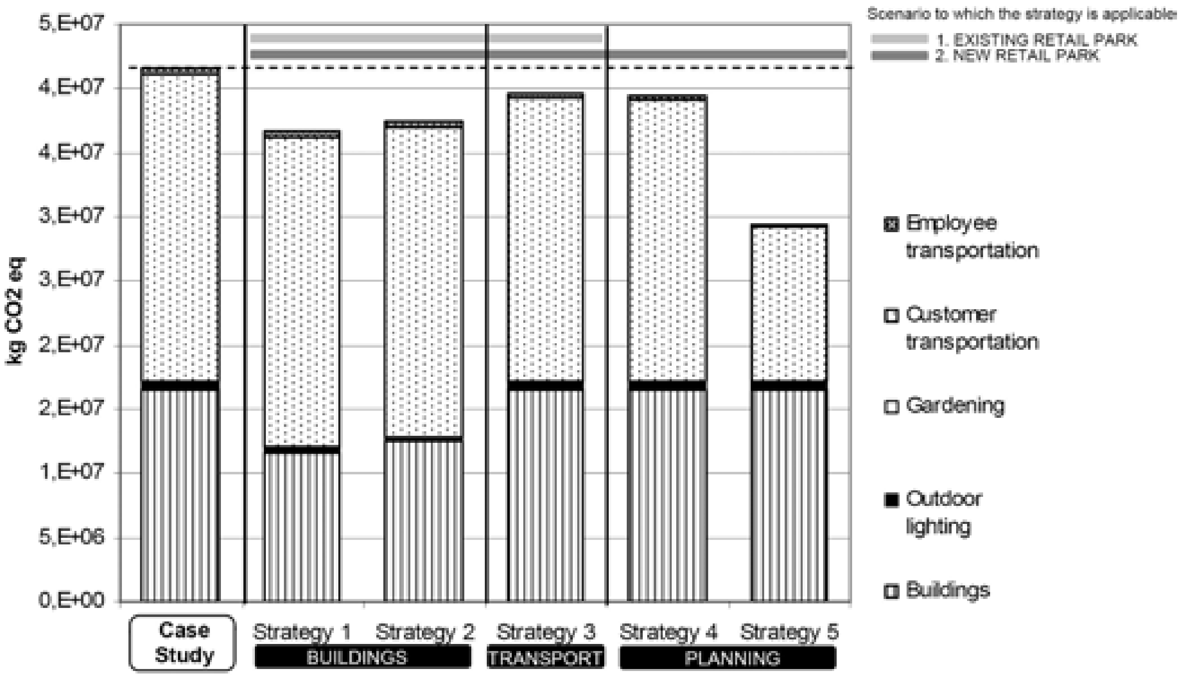

Figure 4.4. GWP profile under the strategies described. The broken line represents the benchmark greenhouse gas emission of the retail park object of study.

4.5. Discussion

Definition of the functional unit for the RP service sector is a determining factor for our study. Once we have included customer and employee transportation in our understanding of the service metabolism, the EFA results provide us with a new picture of actual energy consumption in RP services. The focus is on transportation energy demands, which exceed direct RP energy demand by more than three times (Table 4.3).

The total energy consumption of the service system is highly conditioned, although not completely determined, by urban form. Since the RP is located on the outskirts of cities close to major road infrastructures (Figure 4.1) in an area with no mixed-land uses where only service activities are offered, employees and customers are required to travel long distances with the sole purpose of reaching the park. Furthermore, activity at the RP is intense, attracting as it does large numbers of customers to a distant place, and vehicle energy intensities are high as cars are the predominant mode of transport. Despite all of this, transportation has not commonly been included in service systems analyses, although it is broadly accepted that it accounts for a significant proportion of urban anthropogenic energy [52], as shown by the EFA results.

By contrast, energy consumption in buildings—representing approximately only a fifth of total energy consumption (Table 4.3)—has been the main focus of research to date. In this case study, it has not been possible to determine which equipment consumed this energy due to a lack of measuring systems, which is one of the main drawbacks in services sector monitoring [11].

On the other hand, energy consumed in RP outdoor areas (lighting and gardening) appears to be negligible, representing less than 1% of the total energy consumption (Table 4.3). As a consequence, efforts should not be focused on these subsystems.

When we assess the GWP of service system energy consumption, direct energy use significantly increases its relative contribution to the whole calculation, ascribing to the buildings subsystem a share of almost 40% of the total CO_2eq (Table 4.3). This higher share is due to potential GHG emissions depending not only on the amount of energy consumed, reflected in the EFA, but also on the energy source consumed. As 90% of the energy consumed in buildings consists of electricity, the mixed production of electricity in Spain and electricity network losses have been considered, increasing their contribution to the GWP.

Indicators have been defined to monitor variations in energy consumption and GHG emissions, both being relevant in understanding changes to the system metabolism. End-use building energy consumption per building area has been calculated in order to benchmark the RP and permit comparisons, as this has been the common means of expressing energy intensity in the sector. Nevertheless, we would like to focus on the following two indicators, which include indirect energy use, to assess the real energy intensity of a purchase in a RP. The results reveal the substantial impact of service activities— each RP purchase has an equivalent emission of CO_2 of 9.26 kg, which is increasingly becoming a focus of attention across the research literature (for examples, see [12, 53, 54]). This result is comparable to the ones obtained by Oliver- Solà et al. [24] of 2 kg CO_2eq per user of an urban park without considering transportation. In a broader context, the average Spanish CO_2 emission is estimated to be 10.153 tonnes CO_2eq/year [55]. If we consider that each purchase made by a customer supplies the shopping needs of a household unit, which corresponds to 2.79 people for the area under study [56], each action of purchasing in a RP would contribute 0.03% to the total yearly emissions of the members of a household. Considering that this action occurs on a weekly basis, purchasing at a RP would contribute to more than 1.5% of the country's annual total emissions. Therefore, the role of services in GHG emissions management and their significant GWP is consequently enhanced.

The relative contribution of each subsystem to the GWP highlights the importance of both direct and indirect energy uses within service systems. An individual strategy, one which considers changes in land mix uses, turned out to have a major influence on the reduction of RP energy consumption and emissions (Table 4.5, Figure 4.4). These results can be interpreted as agreeing with the hierarchy of energy-related choices presented by Jaccard et al. [57], who placed urban land use and infrastructure at the highest level, as urban form affects the level of energy service requirements.

In terms of energy consumption, the transportation strategy provided the next best performance (Table 4.5), although this could have been improved still further had more ambitious initial assumptions been considered. However, the GWP assessment indicates higher relevance for direct energy use strategies as they imply a reduction in electricity consumption, an energy carrier with higher related GHG emissions. Consequently, the potential improvement with respect to the case study in terms of emissions is rather limited for strategies 3 and 4.

An existing RP (scenario 1) could reduce its emissions by focusing efforts on electricity supply and conservation measures and also on transportation strategies, as it would not be able to take advantage of the planning measures. The latter measures would seem to be the most effective and are a fundamental in determining the energy demand of anthropogenic systems, energy use remaining in the shadow of land use policy due to the influence of the latter on constructed and natural environments [58, 59]. However, these measures alone cannot attain the goal of reducing service sector GHG emissions by half. Consequently, there is an urgent need to implement combined strategies to tackle GHG emissions in the sector, with regard to both planning and buildings.

4.6. Conclusions

The paramount role of energy in the study of anthropogenic systems is evident. In the RP service sector, the inclusion of employee and customer transportation is crucial in defining its function, as this strongly conditions EFA results. Our analysis of a Spanish case study RP indicates that the role of transportation must be highlighted due to the fact that it represents three quarters of total energy consumption for the service system, a subsystem that has been neglected to date. However, GWP assessment in relation to energy consumption reveals a new picture in which electricity consumption in buildings is also prominent, contributing 39.9% of emissions compared with 57.9% for customer transportation.

Energy-intensity indicators, which have to date focused on energy consumption in buildings, have been further defined to provide coherence with actual energetic metabolism. The energy and GHG emission intensity of a purchase in the RP object of study, estimated to be 1.64 KOE and 9.26 kg CO_2eq per purchase in the year 2006, enhance the role of service systems in the struggle to reduce GHG and global climate change. The scenarios described show that relatively high potential exists for the reduction of carbon emissions in employing combined strategies under an integrative approach. In this respect, reducing service system emissions by more than 50% is feasible in the case of a new RP. However, if the strategies are to be applied to an existing RP, GHG emissions could be reduced to a lesser extent, by up to 27%. Although it has been widely recognized that planning strategies are fundamental in determining the energy consumption of urban systems, any attempt to focus on planning alone could not attain the goal of reducing emissions by half, and it should certainly be complemented by the implementation of other strategies such as energy efficiency, conservation and increased supply. The combined implementation of these strategies could contribute significantly to stimulating the government and companies' responsiveness to the threat of global climate change on a local scale.

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PART IV

Water Flows and
Indicators in Urban Areas.
A Focus on Rainwater Harvesting

As earlier introduced, quantifying the water balance of the whole urban water cycle is a way of moving towards the goal of IUWM by providing greater understanding of the various inputs of water into, and outputs of water from, an urban catchment [1]. Thus, it is necessary to identify the water flows into and out of urban systems. Among these, the role of rainwater is highlighted as a resource that has been generally neglected in most urban areas.

A response to the urban metabolism approach is the deployment of localized or regional-scale, decentralized environmental technologies, as opposed to large-scale, highly centralized systems [2]. The overall aim of such environmental technologies is to maximize the possibility that cities can meet their needs from the natural capital of their own bio-regions in a renewable way and to move to closed loop infrastructure systems that recycle and re-sue their own waste, so that the absorptive capacities of natural systems are not overwhelmed with the waste loads from urban areas [2].

In this context, infrastructures for RWH are necessary in order to prevent water scarcity, which is becoming an imminent problem in many regions worldwide. In the case of Sothern Europe, climate change is projected to worsen conditions (high temperatures and drought) in a region already vulnerable to climate variability, and to reduce water availability [3]. For this reason, RWH seems to be a necessary strategy to alleviate water stress on water-scarce areas. However, there is a need to study some aspects in depth, such as the RWH potential of the most common urban catchment areas (roofs) both in terms of quality and quantity; and to assess the economic performance of RWH infrastructures in urban areas.

Part IV is composed of three chapters:

- Chapter 5 (Indicators for sustainable water management in urban systems: case studies of retail parks in Spain and Brazil) assesses two commercial service neighbourhoods in terms of water flows. The study of their metabolism brings up the matter of rainwater management in urban areas.
- Chapter 6 (Roof selection for rainwater harvesting: quantity and quality assessment) provides criteria for urban planning regarding RWH strategies and catchment areas.
- Chapter 7 (Cost-efficiency of Rainwater Harvesting Strategies in Dense Mediterranean Neighbourhoods) provides economic criteria for urban planning regarding the most cost-efficient RWH strategy.

Chapter 5.

INDICATORS FOR SUSTAINABLE WATER MANAGEMENT IN URBAN SYSTEMS: CASE STUDIES OF RETAIL PARKS IN SPAIN AND BRAZIL

This chapter is based on the following paper:

Farreny R, Rieradevall J, Barbassa AP, Teixeira B, Gabarrell X. Indicators for sustainable water management in urban systems: case studies of retail parks in Spain and Brazil. Accepted with revisions in *Water and Environment Journal*.

Abstract

The use of planning and management tools for water management in urban environments is a promising area. This paper focuses on the description of two indicators, Water Intensity of a Purchase (WIP) and PWSS from RWH, for the expanding sector of RP. These tools have been checked in two case studies in Spain and Brazil. The results show a WIP of 8.0 and 22.9 litres, respectively, which measures the (in)efficiency of water use. This water demand, mainly of low quality, is met with the potable water supply network, while stormwater runoff is lost to sewage. The PWSS results, 3.0 for Spain and 1.4 for Brazil, indicate that RP could satisfy their needs with rainwater and even have a surplus of water. The combined use of both WIP and PWSS can be useful for the planning, design, evaluation and monitoring of RP.

Keywords: rainwater harvesting, sustainability, retail park, urban environments, water consumption.

5.1. Introduction

Urban water demand is escalating as the world population is increasing and more and more urbanisation is taking place worldwide [4]. As a consequence, many areas are facing water scarcity, not only arid regions but also areas with abundant resources where local demand often exceeds local availability. The increasing demand reduces fresh water supplies [5] and is followed by the use of more distant or inferior-quality sources [6]. Therefore, water scarcity can lead to dependence on water imports. This need to import water mostly affects urban areas, which concentrate 50% of the world's population and more than 70% in America, Europe and Oceania [7].

In this context, RWH has been presented as a strategy entailing many benefits -it may reduce a city's external water demand, alleviate water stress on the area, reduce non-point source pollutant loads and prevent flooding [4, 6, 8-11], furthermore it may prevent some of the hydrologic impacts of urbanization [12].

In industrialised economies the contribution of the services sector to the economy has come to represent more than 70% of the gross domestic product [13]. One of these expanding activities is the RP sector. The great expansion of RP, their worldwide ubiquity and their nature as something between an urban system and an industrial estate highlight the need, and also the opportunity, for providing these urban service systems with environmental management tools. The need for sustainable development indicators has been widely expressed [14], as they can allow us to better organise, synthesise and use information and to provide performance measurement, reporting and communication to stakeholders in order to move towards sustainability. Indicators have most often been applied to manufacturing industries and tangible products [15], but it has been broadly accepted that there is a need to go further and address their application to services [16]. The lack of suitable metrics and approaches for measuring the environmental impacts of a service is part of the reason why the relationships between service industries and the environment have been overlooked for many years with very little attention given to the service sector [17, 18].

The objectives of this research are threefold: firstly, to describe the water metabolism of two RP service systems considering not only the buildings but also the outdoor areas; secondly, to quantify their water intensity of a purchase (WIP); and thirdly, to determine their PWSS through RWH.

5.2. Case study areas[1]

Two RP case studies have been selected in Spain and Brazil, countries that have distinct climatic and socio-economic characteristics.

[1] Case study areas previously introduced in section 2.1 (Figures 2.2 and 2.3) and section 4.2.

5.2.1. Spanish case study

The selection of this case study area meets two determining criteria. Firstly, it is representative of this kind of service activities all over Europe in terms of structural characteristics and dimensions [19] (Figure 5.1). Secondly, it is located in Spain, a country which is not only rapidly facing a substantial increase of the number of RP [20] but it is also experiencing a high risk of water scarcity that could worsen over the forthcoming years [21].

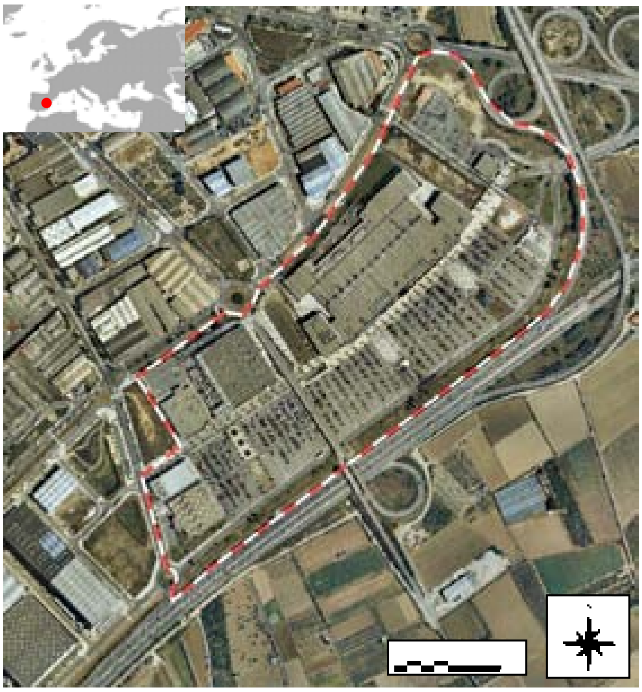

Figure 5.1. Spanish case study RP. The line shows the limits of the system.

The average annual rainfall is of 628 mm according to the period from 1971 to 2000, with August to December being the wettest period of the year and July the driest [22]. 2006 was a drier year, with only 476 mm of rain [23].

5.2.2. Brazilian case study

The selection of this case study area meets two determining criteria. First of all, it is located in a country where the RP phenomenon is increasing in popularity: it is experiencing an annual increase of around 4% in the number of RP reaching figures of 411 parks in 2010 [24]. Moreover, Brazil faces water-use conflicts and consumption restrictions. Secondly, the RP is representative of the sector in the country since one third of the Brazilian RP are situated in medium sized cities such as São Carlos.

The Brazilian RP case study is located in São Carlos, about 230 km inland from the city of São Paulo, on an area of 70 000 m^2 (Figure 5.2). It includes several buildings under a single roof which covers all the RP facilities. There is one supermarket and one superstore, 3 cinemas and 71 shops.

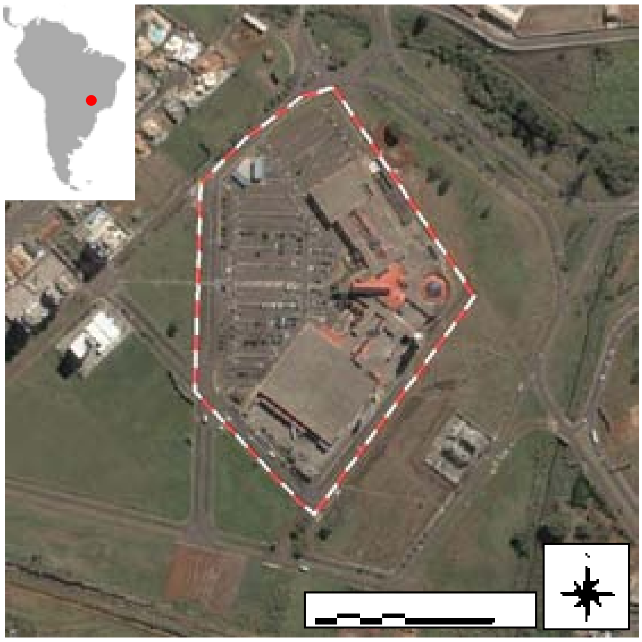

Figure 5.2. Brazilian case study RP. The line shows the limits of the system.

The climate in the study area is subtropical humid and the average annual temperature is 20.6 ºC [25]. The average annual rainfall in the local area is 1515 mm according to the period from 1978 to 2007, with December to March being the wettest period of the year and June to August the driest. The total rainfall in 2006 was 1297 mm [25].

5.3. Methodology

The methodology is divided into three stages. The first stage consists of the description of the water metabolism of the RP through Water Input and Use Accounting (WIUA), the second one consists of a description of the WIP indicator, and the third one consists of the description of the PWSS indicator

5.3.1. Water Input and Use Accounting

WIUA is conceived as an adaptation of a MFA, which is a widespread and standardised method of assessing the flows and stocks of materials within a system defined in space and time [26] (see section 2.3.1 for further details). In this study, MFA methodology is adapted to describe the water inputs (inflows) and uses. The system is defined by obtaining water from the environment (natural flows which consist of rainfall and artificial flows which consist of potable water from the mains water supply) and also by the administrative borders of the RP with the surrounding areas. The study period is year 2006 due to the availability of data.

Artificial flows

Data about the artificial water inputs and uses can be obtained directly from field work by compiling invoices and reports provided by local agents – park managers, representatives from the retail warehouses, the gardening company and the local council. If water consumed in outdoor areas (i.e. for street cleaning and garden irrigation) is not accounted for in the invoices, it has to be estimated according to the water consuming activities carried out.

Street cleaning water was not included in the Spanish RP invoices and has consequently been estimated from the daily cleaning of the RP roads, car park and paved pedestrian areas with a hydro-sweeper that consumes 0.04 L/m^2 of water. Field work indicated that street cleaning water consumption in the Brazilian RP is negligible.

In the Spanish case study, garden watering was included with indoor water consumption on invoices. However, a rough estimate of its magnitude has been made by considering a local average garden consumption of 0.38 $m^3/m^2 \cdot year$ [27]. In the Brazilian case study there was no garden irrigation.

The use of water for employees' drinking is supplied either by mains water or by bottled water. However, it is not accounted for as its magnitude seems to be small compared to the other flows.

Natural flows

In order to calculate the natural inputs to the system (total amount of rainfall falling on it), it is necessary to carry out a land cover analysis, which is also useful to estimate some variables such as street cleaning or irrigation water consumption.

The land cover analysis is carried out using TNTmips software (version 2005:71) in order to create maps based on the most recent aerial photographs available and validated and updated with field work. The land cover is divided into two subsystems: the built-up subsystem – which includes (1) the buildings, (2) RP roads, car park, and logistics and paved pedestrian areas (from here on referred to as Paved Covers at Ground Surface, PCGS) and (3) areas under construction (still with no roof and unpaved)-; and the vegetation subsystem –which includes (1) gardens (trees, bushes and small lawned areas) and (2) neglected/degraded open areas.

The analysis provides the area of each category and also the total impervious fraction [1].

Once the area of each subsystem is obtained, the natural water inputs to each subsystem are calculated as follows (equation 4):

$$\text{Rainfall water inputs} = \text{Average rainfall} \times \text{Subsystem area} \qquad [m^3/\text{year}] \qquad \text{[Eq. 4]}$$

It is assumed that water that falls on built-up areas runs off to combined sewage systems while water that falls on the vegetation subsystem is incorporated to the natural water cycle.

5.3.2. Water intensity of a purchase

The WIP is defined as the ratio between total water consumption used in the operation of a RP and the amount of *total-RP shopping baskets* purchased in the RP (see equation 5). One unit of a total-RP shopping basket is assumed to be purchased by one customer. A customer is defined as each trip that a person or group takes together to the RP to satisfy his purchasing needs. Once a customer leaves the RP they are said to have purchased one unit of a total-RP shopping basket regardless of the number of separate purchases or individual establishments that were visited. Thus, the number of total-RP shopping basket purchases (from now on, purchases) is equivalent to the number of customers.

$$\mathrm{WIP} = \frac{\text{Water Consumption}}{\text{Total - RP shopping baskets purchased}} \quad [\text{L/purchase}] \qquad [\text{Eq. 5}]$$

Data concerning water consumption is obtained from the WIUA and it consists of the sum of the water flows that fulfil the necessities of the RP operation (indoor consumption, outdoor cleaning and irrigation).

The number of customers in the Spanish RP is calculated by Farreny et al. [16]. Data from the Brazilian case study is obtained from the RP manager, who has electronic vehicle controls installed throughout the year and has a rigorous monitoring of entrance and exit of passenger vehicles to and from the car park. This accounting provided the total number of passenger vehicles that travelled to the RP. To discern the number of customer vehicles from these transport flows, employee's automobiles are subtracted. It is assumed that each customer vehicle corresponds to a customer. The number of employees' cars was obtained considering 978 employees, 22% of them travelling by car to work [28] and a local average occupancy of 1 person/car. Beside this, there is an amount of customers that get to the RP using public transportation (bus). This amount is estimated using the database of São Carlos City Hall, which contains the number of public transportation users during every day of the week, and by dividing the amount of people that get off at the RP by 2.5, which is the general customer profile in the Brazilian RP (2.5 people/customer).

5.3.3. Potential water self-sufficiency

The PWSS indicator is defined as the ratio of the system's annual Water Harvesting Potential (WHP) to its total water consumption (equation 6).

$$\mathrm{PWSS} = \frac{\mathrm{WHP}}{\text{Total water consumption}} = \frac{\mathrm{P} \times \sum(\mathrm{A_i} \times \mathrm{RC_i})}{\text{Total water consumption}} \quad [-] \qquad [\text{Eq. 6}]$$

The WHP of a system is defined as the amount of water that could be potentially harvested, taking into account the annual average precipitations (P), the impervious catchment areas (A_i) and the losses due to different kinds of surfaces (RC_i). The RC_i is the ratio of the volume of water that runs off a surface to the volume of rainfall that falls on the surface. RC is assumed to be equal to 0.9 and 0.7 for roofs and PCGS respectively [11, 29].

The only local renewable water resource considered is the rainwater that falls on the built-up areas of the system and that is potentially usable after storage, assuming that the system has proper regulatory and water storage infrastructures. Thus, the WHP is calculated in the RP case studies considering two catchment alternatives: roofs only or both roofs and PCGS. Rainwater falling on the vegetation subsystem is directly used by nature through infiltration and runoff and is included in the natural water cycle, whose study is beyond the scope of this paper.

A value of the PWSS greater than one means that the WHP is in excess, and can theoretically cover water demand of the system, suggesting potential self-sufficiency. The contrary case implies dependence on water imports and/or domestic extraction.

5.4. Results

The results are divided into three parts, according to the methodology section.

5.4.1. Retail park water metabolism

The land cover results are shown in Table 5.1. The total impervious fraction is 0.80 and 0.92 in Spain and Brazil, respectively.

Table 5.1. Land cover analysis carried out in the two case studies for 2006 using TNTmips software and local cartographic sources.

Subsystem	Land cover		Spanish RP		Brazilian RP	
			Area (m²)	Area (%)	Area (m²)	Area (%)
Built	Buildings		73 512	24.3	24 861	35.5
	PCGS	Roads	31 386	10.4	10 279	14.7
		Open air car park	78 888	26.1	16 272	23.2
		Logistic areas	10 571	3.5	6160	8.8
		Pedestrian areas	28 360	9.4	4557	6.5
	Under construction		17 607	5.8	2000	2.9
Vegetation	Gardens		47 698	15.8	5871	8.4
	Neglected/degraded open areas		14 036	4.7	0	0.0
TOTAL			302 058	100.0	70 000	100.0

Table 5.2 shows the water inputs to the system. Natural flows (rainfall) amount to 80% of total water inputs in the Spanish case study and to 63% in the Brazilian one. The input of potable mains water (artificial flow) per area of RP is more than 6 times higher in the Brazilian case study (0.75 $m^3/m^2 \cdot year$) than in the Spanish one (0.12 $m^3/m^2 \cdot year$). This water serves mostly non-drinking uses such as garden irrigation, outdoor cleaning and indoor uses (cleaning, toilet flushing, heating and refrigeration). The demand for drinking-water, which is limited to certain activities related to cooking or drinking, and for street cleaning consumption is negligible compared to the other water uses

Table 5.2. Water input and use accounting results for the two case studies in 2006.

CASE STUDY	WATER INFLOWS	WATER USE FLOWS ($10^3 m^3$/year)					
		Rain on gardens	*Irrigation*	*Runoff from built areas*	*Indoor consumption*	*Outdoor cleaning*	*Total*
Spanish RP	*Rainfall*	29.4		114.4			143.8 [80%]
	Mains water		18.1		17.0	0.7	35.8 [20%]
Brazilian RP	*Rainfall*	7.6		83.2			90.8 [63%]
	Mains water		0		52.7	0	52.7 [37%]
		Natural water		Sewage			

5.4.2. Water Intensity of a purchase

The Spanish and Brazilian RP have accounted for 4 498 037 and 2 299 099 customers or purchases in 2006, which results in WIP of 8.0 and 22.9 litres, respectively. According to the WIUA, nearly half of the water intensity in the Spanish RP is estimated to be for gardens irrigation, an activity that does not take place in the Brazilian case study.

5.4.3. Potential Water Self-Sufficiency

The PWSS values for the case studies are shown in Table 5.3. If all impervious catchment areas were used, the WHP would be higher than the mains water inputs to the systems even in view of drier-than-average weather conditions. Therefore, both systems might have a surplus of water, particularly in the case of the Spanish RP.

If catchment areas were reduced to only roof areas, the WHP would not be enough to cope with the RP water demand (PWSS<1) in dry years (i.e. in 2006 the complete self-sufficiency would not be possible, although between 60 and 90% of the RP' water needs could be satisfied).

Table 5.3. PWSS indicator applied to the two case studies considering two catchment areas alternatives: roof only, and both roof & PCGS, and two rainfall periods (average 30-year rainfall and 2006 rainfall).

Case study	Annual rainfall (mm)			Only roofs		Roofs & PCGS	
				WHP (m^3)	PWSS	WHP (m^3)	PWSS
Spanish RP	Rainfall period	1971-2000	628	41 549	**1.2**	107 140	**3.0**
		2006	476	31 493	**0.9**	81 208	**2.3**
Brazilian RP	Rainfall period	1978-2007	1515	33 898	**0.6**	73 421	**1.4**
		2006	1297	29 013	**0.6**	62 841	**1.2**

5.5. Discussion

The analysis of the water metabolism of a system through the WIUA can be useful not only to detect which are the most water-demanding points but also to assess in which uses water is spent. The latter aspect is particularly relevant in order to evaluate whether the quality of water is right for its uses. It becomes evident that most uses in RP do not require drinking water standards. Therefore, they could be partially or totally supplied by means of RWH instead of potable mains water, since it has been widely recognised that RWH can provide water of sufficient quality to be used for street cleaning, irrigation, toilet flushing or heating and air conditioning systems.

On the other hand, WIUA provides data for the subsequent calculation of WIP and PWSS indicators.

The WIP is thought to be an environmental indicator with the purpose of evaluating resource use efficiency in the retail sector, which can be useful for park managers and local authorities in identifying potential improvements and informing water policy decisions. The existing indicators, developed by government or industry, are mostly input-based indicators (i.e. L/m^2) developed in order to check the buildings' performance. Thus, they fail to consider the function provided by the system. For instance, a RP with low water consumption per m^2 but without customers would be extremely inefficient. In contrast, the WIP is an output-based efficiency indicator which tries to relate water consumption to the output of the whole system, that is to say, the number of purchases.

The results indicate that the WIP in Brazil is almost three times larger than in Spain, even though it does not have irrigation. This can be partly explained because water consuming devices (i.e. toilet flushing, taps) in the Brazilian RP are inefficient and rational water use is incipient, in contrast with the Spanish RP. In addition, the Brazilian RP has fifteen fast-food restaurants, one of them is responsible for 10% of annual water consumption, while in the Spanish RP there are only two. The fact that rainfall on the Brazilian case study is relatively abundant should not induce the consideration of such high WIP as acceptable. The local and/or temporary availability of a resource does not justify its waste, particularly in a context of global scarcity.

If the shopping basket were the same in both RP, the WIP would be a measure of the inefficiency of water consumption in the Brazilian park compared to the Spanish one. However, comparison between different RP is somewhat impeded by differences in the shopping basket composition. For this reason, a more detailed analysis establishment by establishment would be necessary. Nonetheless, for a given system, the WIP can be useful to evaluate water use efficiency as well as the effects of water conservation strategies applied to RP.

On the other hand, the PWSS is conceived as a tool whose aim is to detect which systems are potentially able to achieve the goal of water self-sufficiency by means of RWH. According to the results, RP are service systems that seem to be likely to be water self-sufficient in diverse conditions, both in Mediterranean conditions such as in Barcelona, and in conditions of relatively high water consumption such as in São Carlos. These results can be explained because (1) RP are extensive in terms of land consumption, as they expand on the outskirts of cities horizontally, (2) they show high total impervious fractions so they can harvest large amounts of rainwater, and (3) they have relatively low water consumption per m^2 particularly compared to residential areas. These results could be further improved with an increase in the efficiency of water use (reducing WIP). Furthermore, RWH strategies are appropriate in RP since they have a demand for low-quality water and there is a park manager which enhances the possibility of applying strategies at the system level. Besides, RWH systems for buildings with large catchment areas and high non-potable water use are potentially more financially viable due to economies of scale [30].

In some RP it might be possible to achieve water self-sufficiency using only roof areas, as happens in the Spanish case study. This would be preferable since rooftop runoff quality is better [31]. However, the reduction of the catchment area may lead to water scarcity in dry years and failure to meet water demand, as it would have happened in the year 2006 (Table 5.3).

When the PWSS takes values much higher than one, the possibility of offering their surplus of water to nearby areas of the city (industrial estates, other service areas or periurban agricultural land) should be explored.

The application of the PWSS assumes rainwater as the only local renewable water resource available. However, relying solely on RWH supplies shows some limitations such as the variability and uncertainty of rainfall, which may reduce the efficiency of RWH systems if tank capacity has not sufficient storage capacity to store recovered water through the rainy months to meet peak period demand for water. Hence, there may be an unbalance between water demand and rainfall. However, the simplicity of the indicator of potential self-sufficiency is preferred to the complexity of a more sophisticated means of calculation. It has to be kept in mind that the PWSS indicator tries to highlight rainwater resources and their role in water management in urban areas through an understandable and easy-to-calculate indicator, by detecting at a first glance which systems have a potential of water self-reliance.

Once the preliminary PWSS is evaluated, the design of the necessary infrastructures should be assessed through more sophisticated methods, such as continuous simulation models for tank sizing [30]. Furthermore, the different technical alternatives before being implemented should be evaluated with economic and environmental tools and methods under a life cycle approach (as done in Chapter 7 for the economic assessment of RWH systems and by Oliver-Solà [32-34] for the environmental assessment of urban infrastructures) in order to suggest and assess future "sustainable solutions".

The application of PWSS is of particular interest for planning policies and strategies at a local level. The indicator can be applied not only to RP but also to other urban systems. In the case of RP, local authorities and governments could demand RP to be water self-sufficient to a certain extent according to their PWSS. Then, RP could be planned and designed in order to favour RWH (i.e. by means of maximising the RC of catchment areas). In no case, should it be at the expense of an increase in the impervious fraction justified by RWH motivations. Another strategy to achieve water self-sufficiency would be reducing their water consumption (lower WIP) through, for instance, more efficient water consumption. Then, the proposed indicators become tools for planning, design, redesign, evaluation and also monitoring of RP and, can be useful for decision-making, particularly when combined and complemented with other criteria and tools.

5.6. Conclusions

(1) RP are large land consumers sprawling horizontally across the territory with high total impervious fractions. They have a relatively reduced demand of water per unit of area, mostly of low-quality, that is met using mains water. Meanwhile, stormwater runoff is lost to the sewage system without any use. These aspects favour the implementation of RWH strategies in RP, altogether with the many benefits associated with RWH practices.

(2) The WIP is an indicator that evaluates water use efficiency in RP, relating water consumption to the number of purchases. This paper sets up a methodology for monitoring the intensity at which water is spent in the sector. The Spanish and Brazilian case studies show a WIP of 8.0 and 22.9 litres/purchase, respectively. The extended use of WIP across the sector could set up a benchmark for the establishment of forthcoming water conservation strategies.

(3) The PWSS indicator expands the vision of resources to one of resources-consumption. Its great value is to demonstrate the capacity of rainwater resources in urban areas at the microscale. RWH is often overlooked as a non-potable water resource. Therefore, the indicator tries to highlight its role in urban water management through an understandable and easy-to-calculate methodology. The PWSS results, 3.0 and 1.4 for the Spanish and Brazilian RP respectively, show that they potentially have enough available local renewable water resources from rainfall to cope with their water demand.

(4) The combined use of both WIP and PWSS can be useful for the planning, design, evaluation and monitoring of RP. These systems can evaluate their water consumption according to WIP, meanwhile local authorities and governments can demand the RP to be water self-sufficient to a certain extent according to their PWSS.

(5) Based on these conclusions, forthcoming research is expected to focus on the environmental, social and economic repercussions of RWH techniques, by comparing its impacts related to those of the mains water supply.

Chapter 6.

ROOF SELECTION FOR RAINWATER HARVESTING: QUANTITY AND QUALITY ASSESSMENT IN SPAIN

This chapter is based on the following paper, currently submitted for review:

Farreny R, Guisasola A, Morales-Pinzón T, Tayà C, Rieradevall J, Gabarrell X. Roof selection for rainwater harvesting: quantity and quality assessment. Submitted in September 2010 to *Water Research*.

Abstract

Roofs are the first candidate for RWH in urban areas. This research integrates quantitative and qualitative data of rooftop stormwater runoff in an urban Mediterranean-climate environment. The objective of this paper is to provide criteria for the roof selection in order to maximise the availability and quality of rainwater. Four roofs have been selected and monitored over a period of 2 years (2008-2010): three sloping roofs –CT, M and P roofs- and one flat roof –FG roof-. The authors offer a model for the estimation of the runoff volume and the initial abstraction of each roof, and assess the physicochemical contamination of roof runoff. Great differences in the RC are observed, depending mostly on the slope and the roughness of the roof. Thus, sloping smooth roofs (RC>0.90) may harvest up to about 50% more rainwater than flat rough roofs (RC=0.62). Physicochemical runoff quality appears to be acceptable or good among all roofs (EC: 85.03 ± 9.98 μS/cm, TSS: 5.98 ± 0.95 mg/L, TOC: 11.56 ± 1.72 mg/L, pH: 7.59 ± 0.07 upH). However, statistically significant differences are found between sloping and flat rough roofs for some parameters (EC, TOC, total carbonates system and TAN), with the former presenting better quality in all parameters (except for TAN). The results have an important significance for local governments and urban planners in the (re)design of buildings and cities from the perspective of sustainable rainwater management. The inclusion of criteria related to the roof's slope and roughness in city planning may be useful to promote rainwater as an alternative water supply while preventing flooding and water scarcity.

Keywords: city ecodesign, runoff coefficient, sustainable urbanism, stormwater runoff, urban environment, water management

6.1. Introduction

RWH in urban areas is a strategy that brings many benefits and may serve to cope with current water shortages, urban stream degradation and flooding [6, 11, 35]. In this context, the assessment of the quantitative potential of RWH and the quality of stormwater runoff from several types of roofs is essential in order to set up criteria for the (re)design of cities from the perspective of sustainable rainwater management. Both aspects (quantity and quality) are necessary in order to select the most adequate roof for RWH. Since roofs represent approximately half of the total sealed surface in cities, they contribute to the most important urban stormwater runoff flow. As a consequence, they offer a significant possibility for RWH [10], which makes it relevant to have criteria for roof selection at one's disposal.

6.1.1. Quantity

The WHP (in L/year) of a roof can be estimated based on the local precipitations (P, in mm/year), the catchment area (A, in m^2) and the RC (adimensional), as shown in equation 7:

$$WHP = P \cdot A \cdot RC \qquad \text{[Eq. 7]}$$

Equation 7 draws inspiration from the rational method, which has traditionally been used in order to estimate the peak runoff rate of any watershed [36, 37]. The RC is a dimensionless value that estimates the portion of rainfall that becomes runoff, taking into account losses due to spillage, leakage, catchment surface wetting and evaporation [38]. Thus, the RC is useful for predicting the potential water running off a surface, which can be conveyed to a rainwater storage system. Since water shortage is recognised as an emerging problem which is becoming the number one problem in the world today [5], and many cities are facing water restrictions due to an increasing pressure on water resources [35], it is essential to consider the RC in the selection of roofs in order to maximise their RWH potential.

The value of the RC has usually been selected from generic lists based on the degree of imperviousness and infiltration capacity of the drainage surface. Estimates so far consider that roof RCs are within the range of 0.7 to 0.95 for relatively frequent storms (see Table 6.1 for details). This broad range is the result of the interaction of many factors, both climatic (size and intensity of the rain event, antecedent moisture, prevailing winds) and architectural (slope, roof material, surface depressions, leaks/infiltration, roughness). For this reason, it seems urgent to solve the lack of specific RC for different roof types under diverse environmental climatic conditions in the context of RWH.

6.1.2. Quality

On the other hand, an increased interest in the monitoring of roof runoff quality has been observed recently [39]. Roofs are the first candidate for RWH systems because their runoff is often regarded to be unpolluted [40] or, at least, it presents relatively good quality standards compared to the rainwater from surface catchment areas [31]. Despite this, there is still some disagreement about the quality of roof runoff water: the assessment or rooftop runoff quality ranges from good or acceptable (for example, [41-43]) to severely polluted (for example, [44-46]).

Table 6.1. Review of RC estimates.

Roof	RC	Reference
Roofs (in general)	0.7-0.9	[29]
	0.75-0.95	[36-38, 47, 48]
	0.85	[49]
	0.8-0.9	[50]
	0.8	[51]
	0.8-0.95	[52]
Sloping roofs		
Concrete/asphalt	0.9	[52]
Metal	0.95	[52]
	0.81-0.84	[53]
Aluminium	0.7	[54]
Flat roofs		
Bituminous	0.7	[54]
Gravel	0.8-0.85	[52]
Level cement	0.81	[53]

Rooftop runoff quality is dependent on both the roof type and the environmental conditions (not only the local climate but also the atmosphere pollution). Most research on the quality of rainwater roof runoff has been carried out in East Asia (for example: [55-57]), in Central, Eastern and Northern Europe (for example: [40, 45, 54, 58-62]), in the United States (for example: [44, 63]) and in Oceania (for example: [46, 64-66]). However, there is scarce data from Southern Europe, in particular from Spain.

This research integrates quantitative and qualitative data of rooftop stormwater runoff in an urban Mediterranean-climate environment in order to select the best roof-type for RWH. The eventual purpose of this is to maximise the availability and quality of rainwater supplies as a measure of adaptation to water scarcity and of climate change effects mitigation.

The main objective of this paper is to provide criteria for roof selection when (re)designing buildings and cities. The specific objectives are, first, to develop a model for the estimation of the runoff and the initial abstraction of each roof; second, to estimate the global RC for the different roofs in Mediterranean-climate conditions; third, to estimate the physicochemical contamination of roof runoff; fourth, to determine the degree of association between water quality parameters and storm characteristics and between water quality parameters themselves; and, fifth, to assess the differences in runoff quality between the different roofs.

6.2. Material and methods

6.2.1. Case study area[1]

Four different roofs have been selected in the UAB University Campus, in Cerdanyola del Vallès (metropolitan region of Barcelona, NE Spain). The climate in the area can be characterised as semi-wet Mediterranean and the average annual temperature and rainfall are 15.5 ºC and 568 mm, respectively.

The selection of roofs, the main characteristics of which are shown in Table 6.2, includes: clay tiles (CT), metal sheet (M), polycarbonate plastic (P) and flat gravel (FG). This set of roofs presents two extreme positions regarding slope and roughness: the M and P roofs present high slope (30º) and smooth surfaces, whereas the FG roof is flat and presents a rough surface. The CT roof, which is a well-known trademark of the constructed Mediterranean landscape, presents characteristics similar to the M and P roofs but with a slightly rougher surface. Our research hypothesis is that these two parameters (slope and roughness) are fundamental for the assessment of the quantity and quality of roof runoff.

Table 6.2. Characteristics of the roof catchments.

Roof	Roof type (slope)	Roughness	Orientation	Roof footprint (m^2)	Environment	UTM Coord.
Clay tiles	Hip sloping roof (30º)	Rather smooth	None prevailing	120.0	Surrounded by forest. A few trees overhanging the roof	424482.6 E 4594896.6 N
Metal sheet	Single pitch sloping roof (30º)	Smooth	50º NE	40.6	Urban environment (no trees nearby)	425349.6 E 4594851.4 N
Polycarbonate Plastic	Single pitch sloping roof (30º)	Smooth	230º SW	40.6	Urban environment (no trees nearby)	425347.1 E 4594848.6 N
Flat Gravel[a]	Flat Roof (1º)	Rough	None prevailing	56.6	Urban environment (some trees nearby)	425476.6 E 4594733.4 N

[a]Particle diameter: ~5 mm, gravel depth 15-20 mm

All roofs are located between 0.5 and 1 km from a motorway with dense traffic, and at less than 4 km from some industrial states (light industry), both of which are located to the E, NE or SE of the campus. Predominant winds in this area come from westerly directions.

[1] Case study previously introduced in section 2.1 (Figure 2.4).

6.2.2. Experimental design[2]

A one-way design with four levels -where the factor was the type of roof and the levels were CT, M, P and FG- was applied. The assessed variables were the runoff volume and the physical-chemical parameters; and rainfall height, predominant wind orientation and antecedent dry weather period (ADWP) were included as covariates.

A rainwater conveyance and storage system was installed in each roof. The experimental design consisted of connecting the building's gutters and downpipes to one or more polyethylene rainwater tanks with a capacity of 1 m^3 (Figure 6.1), without first flush diversion system. No special maintenance of the roofs was carried out.

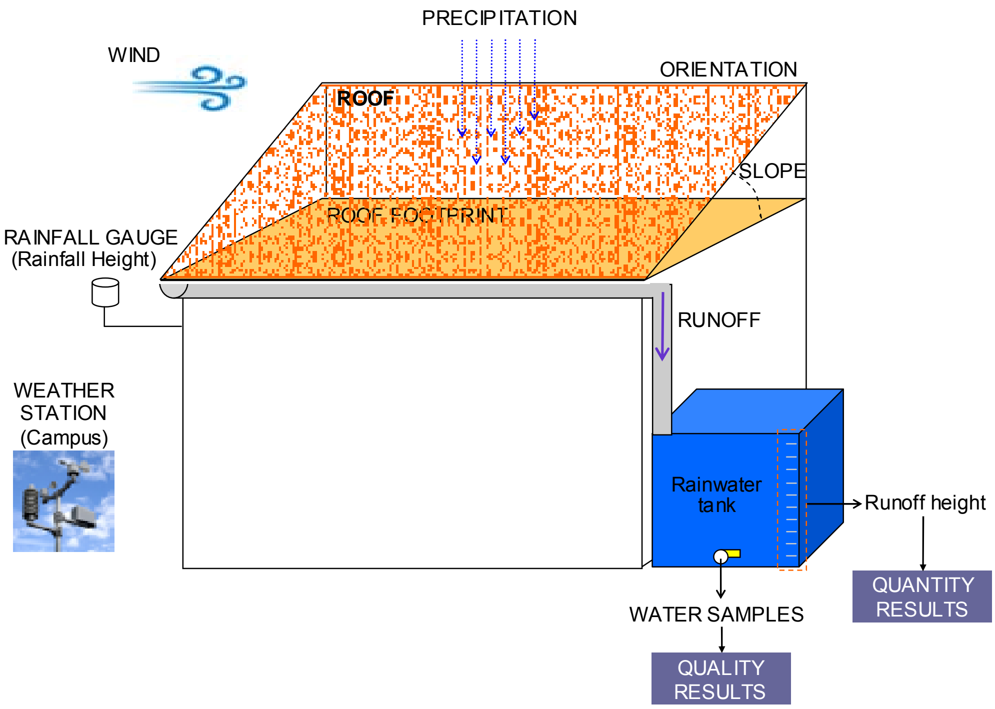

Figure 6.1. Diagram of the experimental design.

Data for the calculation of RC and/or water samples for the quality analysis were collected after several rainfall events during the experimental campaign between June 2008 and September 2010. A rain event was defined as a rainfall of a total height of at least 1 mm and separated one from another by an ADWP of at least 2 hours. The amounts of rainfall were monitored using a rainwater gauge on each roof.

6.2.3. Quantity assessment

Data collection

After the rain events, the rainfall height and the amount of water collected were registered and the tank was emptied (rain events that did not generate runoff

[2] See section 2.4 for further details.

were not included). Several precipitation events were selected, the rainfall and ADWP range of which is shown in Table 6.3. The prevailing wind direction during the rain event was also recorded. Rainfall events that exceeded rainwater tank capacity were excluded.

Table 6.3. Rain events considered in the determination of the RC and the samples for quality analysis.

Roof	QUANTITY ASSESSMENT			QUALITY ASSESSMENT	
	# monitored events	ADWP range (days)	Rainfall range (mm)	# monitored events	Rainfall range (mm)
Clay Tiles	25	0.1 - 37.9	1 - 14	14	1.2 - 68
Metal	22	0.5 - 28	1 - 49	14	1 - 62
Plastic	23	0.5 - 28	1 - 49	15	2.5 - 31.2
Flat Gravel	22	0.2 - 37.9	2 - 21	12	1 - 62

Data analysis. Determination of runoff coefficient

In order to develop a model to estimate the runoff of each roof, a statistical analysis has been conducted with the aid of PASW Statistics 17, from the Statistical Package for the Social Sciences (SPSS) software. This analysis included a correlation analysis followed by linear regression model, considering the amount of runoff depending on several independent variables (rainfall, ADWP and wind direction). In all cases the assumptions were verified.

The technique of cross-validation [67] is used to assess how the results of the regression models will generalise to an independent data set. Therefore, it is used to estimate how accurately the predictive model will perform in practice. The sample of data is divided into two complementary subsets (half and half at random division): the calibration and the validation sets. If the reduction in the cross-validation gives numbers smaller than 0.1, it is assumed that the model will accurately predict the volume of runoff.

Then, the regression model is used in order to estimate the initial abstraction, defined as the amount of rainfall that occurs prior to the start of direct runoff [36].

The global RC for the different roofs is estimated by means of the obtained runoff model, taking into account the local rainfall profile. Data from the weather station of Cerdanyola del Vallès (provided by the Meteorological Service of Catalonia, unpublished), where the roofs are located, has been used for the period 1999-2009. The calculation consists of, first, estimating the runoff of each rain event, and second, dividing the total runoff per year by the annual rainfall, according to equation 8:

$$RC = R / P \qquad \text{[Eq. 8]}$$

where R is the total height of runoff (L) and P is the total height of precipitations (L) in a yearly basis for each roof.

6.2.4. Quality assessment

Sample collection and physical-chemical analysis

A composite sample (V=0.6L) of the content of the rainwater tank was taken after each monitored rain event (n=55). Several precipitation events were selected, with a rainfall which varied depending on the roof (Table 6.3) and an ADWP between 0.1 and 37.9 days for all roofs. The concentration of the composite sample represents the Event Mean Concentration (EMC) of that event. The EMC can be defined as the total mass load of a pollutant from a site during a storm divided by the total runoff water volume discharged during the storm [68].

After obtaining the composite sample, the tank was emptied. Then, samples were immediately prepared for analyses and taken to the laboratory. Electrical conductivity (EC) and pH were measured using a Crison probe (mod. 401/L K1 and 5202, respectively). Phosphate (PO_4^{3-}), sulphate (SO_4^{2-}), chloride (Cl^-), nitrate (NO_3^-) and nitrite (NO_2^-) in filtered samples were measured with ionic chromatography (DIONEX ICS-2000 Integrated Reagent-Free IC System with an auto-sampler AS40). Mixed liquor total suspended solids (TSS) were analysed according to standard procedures [69]. Total ammonium nitrogen (TAN) was analysed using Lange LCK302, LCK303 and LCK304 ammonium kits. Finally, Total Inorganic Carbon (TIC) and Total Organic Carbon (TOC) were measured using a 1020A O-I-Analytical TOC analyser. Bicarbonates (HCO_3^-), carbonates (CO_3^{2-}) and carbon acid (H_2CO_3) were calculated based on TIC and pH results.

Data analysis

Descriptive statistics were obtained with the aid of PASW Statistics 17, from the SPSS software. Average values were expressed both in means (with standard error) and in medians, since some parameters do not have a lognormal distribution [31].

The data generated was subjected to appropriate statistical analyses including variance and correlation analysis. Variance analyses were used to determine if the differences in the mean/median concentration of the roofs were statistically significant. Whenever possible, the one-way ANOVA test was the preferred option. For this reason, data about water quality were transformed with the aid of the power estimation procedure in order to meet the requirements of the ANOVA test (in particular, the normal distribution and the assumption of homogeneity of variance). When this was not possible, the Kruskall-Wallis test was used. Pairwise comparisons were carried out by means of either the Bonferroni method or the Mann-Whitney U test using Bonferroni correction method, respectively.

Correlation analyses were used to determine the degree of association between water quality parameters and storm characteristics (total rainfall height and ADWP) and between water quality parameters themselves, for the whole set of roofs and also for each particular roof (Spearman Rho correlation coefficient).

6.3. Results and discussion

6.3.1. Quantity assessment

The correlation between runoff and rainfall is high (Pearson coefficient >0.95 and p<0.001 for all roofs). The regression model (R=mP+n) between roof runoff (R) and precipitation height (P) for each roof is presented in Figure 6.2. All the regression parameters are statistically significant (p<0.05), except for the y-intercept (n) in the equations for M and P roofs. The regression model has been successfully cross-validated, with reductions in the cross-validation in the range of 0.005 and 0.039. Therefore, it can be assumed that the inferences of these regression models to the whole population are valid.

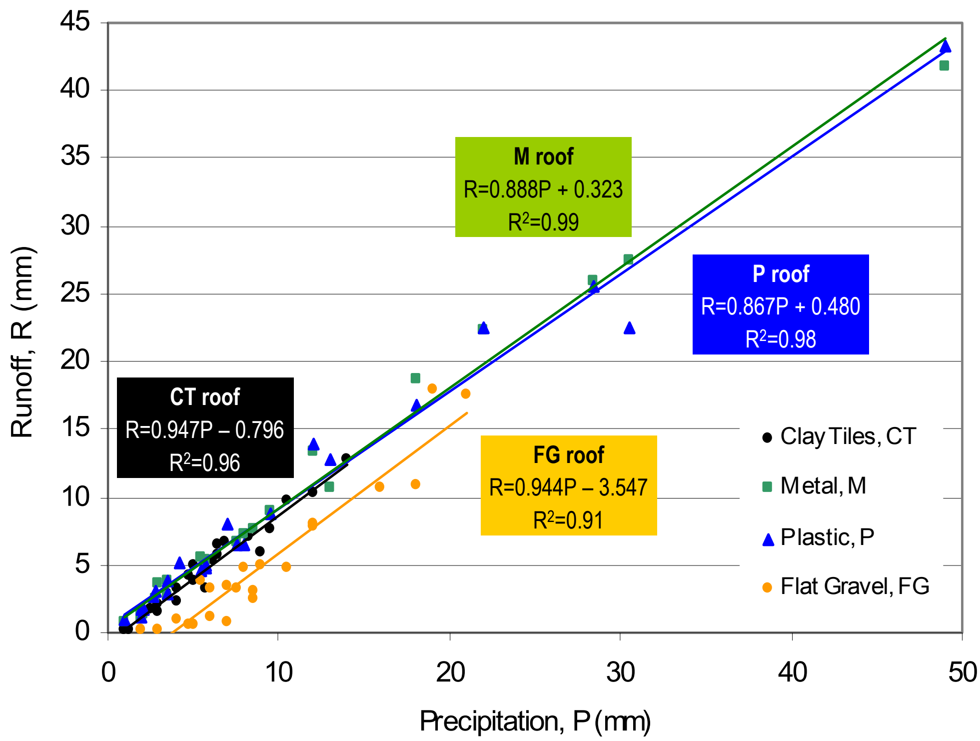

Figure 6.2. Regression model for roof runoff and rainfall height. Regression equations and corrected R^2 are also shown. Each point represents a monitored rain event.

Initial abstraction

The texture of different roof materials causes different retention, different runoff behaviour and different weathering processes [31]. Therefore, each roof has its own characteristic initial abstraction volume, mostly explained by its slope and materials (roughness). The most important abstraction is interception, which can be defined as the rainfall that wets and sticks to aboveground objects until it is returned to the atmosphere through evaporation [70].

The initial abstraction is estimated as the value of the x-intercept (-n/m) from the regression model (see Figure 6.2). Thus, the estimates of the initial abstraction are 0.8 and 3.8 mm for CT and FG, respectively. Since the estimation of the y-intercept (n) is not significant (p>0.05) for M and P roofs, which means that it cannot be asserted that n ≠ 0, it is assumed that their initial abstraction is also zero. Although it may be argued that there must be a certain amount of initial abstraction, it is so close to zero that it has not been possible to estimate it with the available data (despite us having included small rain events in the analysis).

The highest initial abstraction of the FG roof is explained by the fact that the more porous or rough the roof surface, the more likely it will retain or absorb rainwater [52]. Therefore, the gravel intercepts the first litres of water due to its high water retention capacity (greater interstitial pore space) together with the lack of slope in the roof. The results for the FG roof coincide with the predictions from Wright-McLaughlin Engineers [70] who affirm that typical depression and detention values for flat roofs are between 2.5 and 7.5 mm. However, the results for the sloping roofs differ from their predictions since Wright-McLaughlin Engineers assume that the initial abstraction for sloping roofs is between 1.3 and 2.5 mm.

Global runoff coefficient

Regression models are used to calculate the runoff for those rain events that exceed the initial abstraction. In the case of M and P roofs, it is considered that runoff never exceeds the event rainfall height (which would happen according to the runoff-rain function for the smaller rain events due to the positive y-intercept). Then, equation 8 is used to calculate the global RC. Depending on the local rainfall profile (either predominance of small or large rain events), the total annual losses related to initial abstraction will vary.

The average global RC (period 1999-2009) for CT, M, P and FG roofs is 0.84 ± 0.01, 0.92 ± 0.00, 0.91 ± 0.01 and 0.62 ± 0.04, respectively. The lowest RC for FG roof is explained because of its high initial abstraction. This is relevant for stormwater management and, particularly, for flood prevention. Many cities are facing problems with the management of combined sewer overflows during and after rain events. As a solution to this problem, combined sewer overflow tanks are being constructed to reduce the runoff peak flows, which might be alternatively attained by having roofs with low RC instead.

Since the rainfall profile affects the RC, the application of the model to other climatic characteristics would lead to different results. The greatest differences in roof RC between the set of roofs are found when the size of rain events is small (e.g. if all rain events were of 5mm, the RC would be 0.79, 0.95, 0.96 and 0.23 for CT, M, P and FG roofs, respectively). However, if the size of rain events were greater, differences would be much smaller (e.g. if all rain events were of 15mm, the RC would be of 0.89, 0.91, 0.90 and 0.71 for CT, M, P and FG roofs, respectively).

The effect of antecedent dry weather period and wind direction on the regression model

Since the effective collection area of each roof depends on factors such as the direction of prevailing winds and orientation [10], particularly for sloping roofs, it is suggested that wind direction could affect the runoff from M and P roofs (the only single pitch sloping roofs). However, statistical analyses show that there is no significant ($p>0.05$) relationship between runoff and wind direction for any of the roofs. However, we suggest that the effect of wind could partially explain the lack of significance of the y-intercept for M and P.

Another variable that could affect runoff is the ADWP. Although there is no significant ($p>0.05$) correlation between runoff and ADWP for any roof, its incorporation in the regression model provides a more adjusted regression model (corrected $R^2=0.92$) in the case of FG roof:

$$R = 0.937\ P - 0.083\ ADWP - 2.901 \qquad \text{[Eq. 9]}$$

The negative coefficient that accompanies the variable ADWP indicates that the longer the ADWP, the smaller the roof runoff. This is explained by the accumulation of water over longer periods in FG roofs, which is linked to their higher initial abstraction.

6.3.2. Quality assessment

Descriptive statistics including minimum, maximum, mean and median concentration of the water quality variables for the whole set of roofs are presented in Table 6.4. Nitrites and phosphates were not detected at all in most samples (35 and 41 out of 55, respectively), for which a concentration of 0 mg/L was considered for further statistical analyses. Table 6.4 also compares the water quality results to the values from a review of rooftop runoff quality of data expressed in EMCs [31, 42, 44, 64]. The variety and quantity of individual pollutants present in roof runoff are affected by a number of factors [5, 10, 39, 44, 46], namely, characteristics of the surface, atmosphere conditions and properties of pollutants.

In order to allow for comparisons, the water guidelines from the Drinking Water Directive 98/83/EC on the quality of water intended for human consumption [71] are shown for the legislated parameters. Furthermore, the pollution levels of the currently used raw water sources for drinking purposes in the region -either surface or groundwater-, previous to water purification are shown.

General assessment of the runoff quality for the whole set of roofs

EC, which represents the samples' total ion content, can be identified as a leading parameter [31] and may be regarded, to a certain extent, as a measure of the concentration of dissolved matter [72]. All roofs are within a low range of EC (Table 6.4), particularly compared to current surface and groundwater sources.

Generally, the pH of rainwater ranges from 4.5 to 6.5 but increases slightly after falling on the roof and during storage in tanks [31, 73]. However, our results indicate higher pH values, in the range of 6.54 and 8.25. These results are consistent with those obtained by Melidis et al. [42] in several roofs in Greece (among which there were CT and M roofs). This pH can be explained as a result of the neutralisation which takes place mainly because of high values of alkalinity and base cations in African rains, which are common in the region, compared to the rains of European origin [74]. The limited amounts of nitrates and sulphates also explain these high pH values.

Table 6.4. Rooftop runoff quality results and review of literature results.

Parameter	Units	Case study roofs				Roof Review			DWG [b]	Surface and groundwater sources[c]		
										1	2	3
		min	max	mean ± S.E.	med	min	max	med[a]	Limit	mean	mean	mean
Physical-chemical parameters												
Conductivity	μS/cm	15.35	456	85.03 ± 9.98	59.25	2.2	269	141	2500	1439.3	481.0	3169.5
pH	upH	6.54	8.85	7.59 ± 0.07	7.61	3.3	8.25	5.7	6.5-9.5	8.11	7.91	7.52
Sum parameters												
TSS	mg/L	0	38.5	5.98 ± 0.95	3.63	13	120	43	-	n.a.	n.a.	n.a.
TOC	mg/L	0.65	53.60	11.56 ± 1.72	6.4	n.a.	n.a.	n.a.	-	4.04	1.76	4.04
TIC	mg/L	1.36	19.02	7.37 ± 0.66	5.78	n.a.	n.a.	n.a.	-	n.a.	n.a.	n.a.
Nutrients												
PO_4^{3-}	mg/L	0.00	6.60	0.32 ± 0.14	0.00	n.a.	n.a.	n.a.	-	0.51	0.11	
TAN	mg/L	0.04	2.42	0.50 ± 0.07	0.42	0.1	6.2	3.39	0.5	0.91	0.15	0.18
NO_3^-	mg/L	0.01	9.34	1.75 ± 0.26	1.16	0.1	5.73	2.78	50	9.23	7.84	4.89
NO_2^-	mg/L	0.00	3.45	0.13 ± 0.05	0.00	n.a.	n.a.	n.a.	0.1	0.55	0.13	0.05
Main ions												
SO_4^{2-}	mg/L	0	11.5	3.54 ± 0.39	2.59	0.01	19.7	46.71	250	173.5	58.8	244.2
Cl^-	mg/L	0.15	119	8.86 ± 2.38	3.38	5.73	40.5	7.74	250	292.2	47.1	977.7
Total Carbonates	mmol/L	0.12	1.62	0.63 ± 0.06	0.49	n.a.	n.a.	n.a.	-	n.a.	n.a.	n.a.

[a]Medians are based on the review made by Göbel et al. [31].

[b]Drinking Water guidelines [71].

[c]Source 1, 2 and 3 correspond to quality data from Llobregat river, Ter river and Llobregat Delta Aquifer, respectively [75].

The measurement of the TSS contents in urban runoff is of major concern with respect to the transport of anthropogenic pollutants, since pollutants are dominantly bound to particles [60]. The amount of TSS is small in all roofs (median TSS < 5mg/L), particularly compared to the review. There is no guideline for TSS for drinking purposes. However, a content below 25 mg TSS/L is associated with excellent water quality [76].

The TOC content, which is not legislated for drinking purposes, is slightly higher than that in surface and groundwater (Table 6.4). However, it is considered that concentrations below 20 mg/L correspond to good water quality [76].

Inorganic nitrogen occurred mainly as nitrate (between 0.01 and 9.34 mg/L) and ammonium (between 0.04 and 2.42 mg/L) while nitrite occurred in smaller proportions (although some samples achieved concentrations of 3.45 mg/L). Because nitrate is a transformation product, it shows a reversed behaviour and increases in concentration as the ammonium concentration decreases [31].

Sulphates and nitrates together represent the major ionic derivatives of industrial and traffic emissions [64], as a result of fossil fuels combustion [77]. Despite the proximity to a major highway, the concentrations of these pollutants are in the low range, compared to the review of roofs (Table 6.4). This can be partly explained by the relative position of the predominant direction of winds in the area and the highway (preventing the pollution from reaching the roofs). Ammonium concentrations are normally of natural origin –fermentation of nitrogenised products such as bird faeces- in areas with low industrial activity [42]. Therefore, bird excrements together with moss and lichens on the roofs can cause an increase in ammonium as well as phosphorus levels [31].

The runoff quality data is affected by the first flush phenomena (see [65, 78]), since the experimental design does not consider first flush diversion. However, a practical implementation of a RWH strategy would divert the very dirty runoff from the first few millimetres of rainfall away from the tanks to avoid contamination [10], which is a practice followed globally [5]. Thus, the water quality of the RW collected in the tank would be significantly improved [65].

Comparing the quality (expressed in medians) of runoff from the case study roofs to the review made by Göbel et al. [31] (Table 6.4), who reviews more than 300 references providing about 1300 pieces of data for different pollutants, the quality in the case study area is, in general, better for the parameters under study and with available data.

The violations in water quality standards were most severe for nitrites and TAN (18% and 24% of samples exceeded the European drinking water standards, respectively (Table 6.4)). However, the nitrite concentration should not be considered a concern since American and Australian legislations establish a limit of 1 and 3 mg/L, respectively [79, 80]. On the other hand, median TAN concentration was within the guidelines.

On the other hand, it can be stated that the physicochemical quality of the collected roof runoff is, in general, superior to the sources of surface and groundwater in the region. This can be partly explained by the degradation of current water sources in the region. This is consistent with van Roon [6], who stated that the physical and chemical properties of rainwater are usually superior to sources of groundwater that may have been subjected to contamination.

The effect of rainfall height and antecedent dry weather period on runoff quality

The wide distribution of EMCs depends on total rainfall because of the dilution effect during a storm [81]. Our results show that, in general (for the whole set of roofs), the higher the rainfall height, the smaller the pollution loads in the samples. The correlation is significant ($p<0.05$) and negative between rainfall height and the following parameters: EC, TIC, TOC, TC, total carbonates system, chlorides, nitrates and sulphates (Spearman correlation coefficient between -0.301 and -0.642). If the correlation analysis distinguishes between roofs, the highest significant correlation is found between rain and EC (coefficient between -0.843 and -0.940 among the several roofs), TC (between -0.564 and -0.814 among the several roofs), total carbonates system (-0.723 for M roof), nitrates (-0.591, -0.771 and -0.789 for CT, M and P roofs) and sulphates (-0.618, -0.656 and -0.629 for CT, M and P roofs).

On the other hand, it has been previously observed that ADWP can markedly affect the quality of runoff water [82]. However, no significant ($p>0.05$) correlations are found between ADWP and the quality parameters, except for NO_2^- (Spearman correlation coefficient = 0.439). These results are consistent with those obtained by Kim et al. [83] who were disappointed because of a lack of correlation between water quality (from highways) and storm characteristics (such as ADWP).

Correlation analyses between the water quality parameters show that the highest correlations are found between any combinations of the following parameters: TIC, TOC, TC and total carbonates system (Table 6.5). The negative significant ($p<0.001$) correlation between TAN and some parameters (i.e. pH and TIC) can be explained by the fact that alkaline mediums foster ammonia volatilisation and also because aerobic conditions encourage oxidation processes –which result in CO_2, measured indirectly by means of TIC- and nitrification, both of which result in less amounts of TAN.

Table 6.5. Spearman Rho correlation coefficients between the water quality parameters for the whole set of roofs.

	pH	EC	TIC	TOC	TC	Carb[a]	Cl^-	NO_2^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	TAN	TSS
pH		.290*	.346**	.223	.302*	.368**	.260	.009	.156	.506**	-.202	-.453**	.547**
EC			.830**	.755**	.833**	.825**	.599**	.237	.424**	.656**	.057	-.346**	.119
TIC				.818**	.938**	.999**	.526**	.303*	.336*	.588**	.098	-.465**	.224
TOC					.954**	.818**	.440**	.275*	.321*	.501**	.121	-.500**	.180
TC						.939**	.524**	.311*	.376**	.576**	.091	-.491**	.226
Carb[a]							.520**	.297*	.340*	.593**	.087	-.477**	.247
Cl^-								.416**	.469**	.546**	-.011	-.101	.283*
NO_2^-									.226	.080	.287*	-.120	.121
NO_3^-										.639**	-.252	-.032	.137
SO_4^-											-.266*	-.377**	.190
PO_4^{3-}												-.093	.043
TAN													-.158
SST													

[a]Carb stands for total carbonates

*$p<0.05$; **$p<0.01$. The colour-shaded cells indicate the degree of correlation (light grey : $|r|<0.5$, dark grey: $0.5<|r|<0.9$ and black: $|r|>0.9$)

Differences in water quality between roofs

The water quality results for the runoff collected during the study period in each roof are shown in Figure 6.3 for the following parameters: pH, EC, TSS, TOC, sulphates, nitrates, TAN and total carbonates system (HCO_3^-, CO_3^{2-} and H_2CO_3).

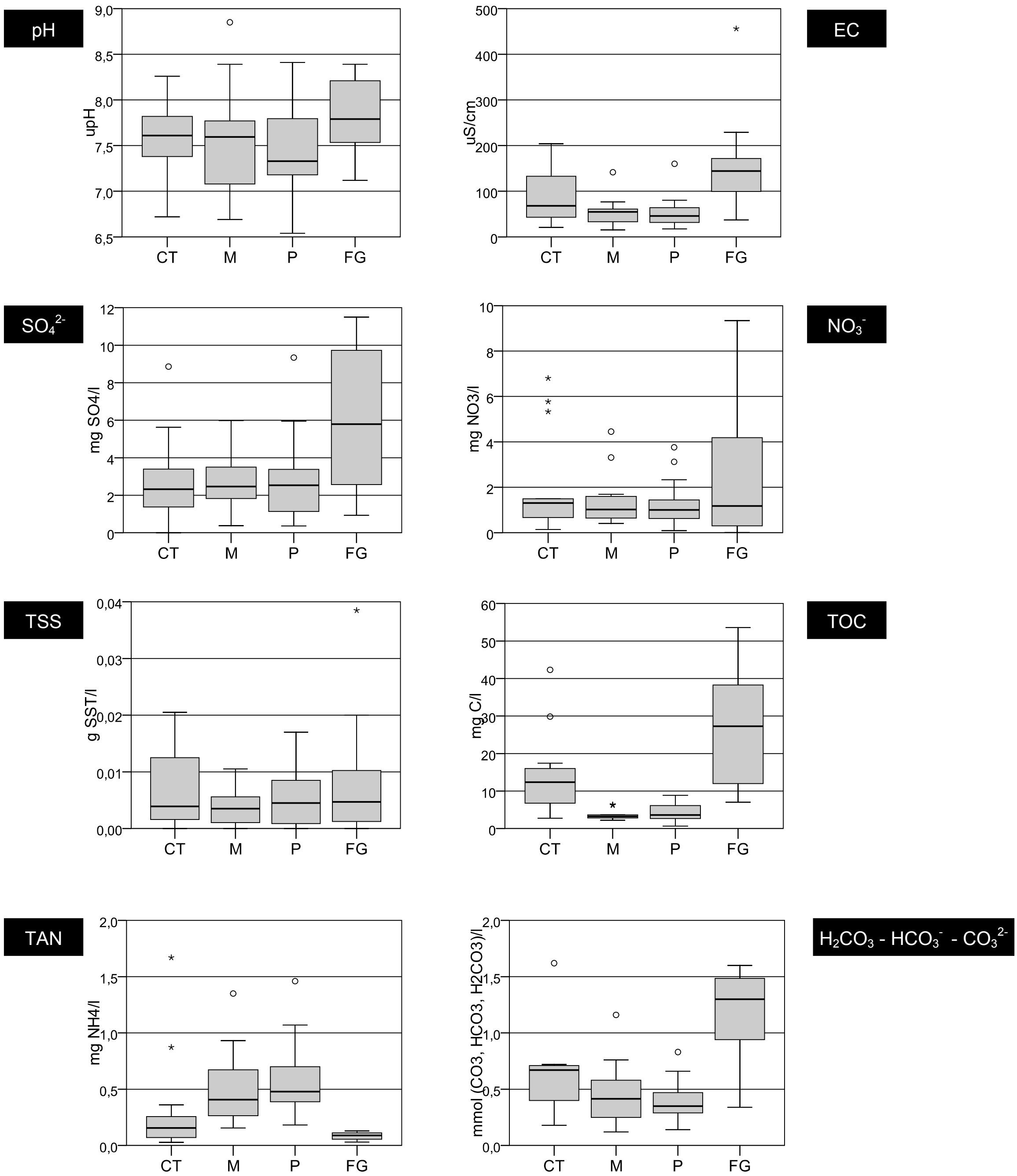

Figure 6.3. Box plot diagram of rooftop runoff water quality for each roof. ***Abbreviations:*** **CT = Clay tiles; M = Metal; P = Plastic; FG = Flat Gravel.**

Statistical analyses of variances indicate that the differences in water quality within the whole roof set are not significant ($p>0.05$) for the following parameters: pH, chlorides, nitrates, sulphates and TSS. However, significant differences were found ($p<0.05$) between the quality in FG roof and the three pitched roofs for EC, TIC, TOC, TC, total carbonates system and TAN, presenting higher pollution levels for all parameters except for TAN.

The higher pollution load in FG roof can be explained by the weathering of the roof materials (gravels) and the accumulated deposits of particulates and associated flora on them. FG roofs are more predisposed to being colonised by a wide range of plants, notably mosses, algal crust and lichens. Besides this, the lack of slope aids the development of these processes. In contrast, lower levels of TAN in FG roof may be explained by the higher alkalinity and the greater oxidation processes (indirectly measured by means of TIC). Nevertheless, it is believed that other flat roofs with different materials other than gravel (such as concrete, asphalt, hot tar or tiles) would present different pollution results.

On the other hand, M and P roofs do not show significant differences ($p>0.05$) for any of the parameters. This can be explained by the similarity of the hydraulic behaviour of both catchments (sloping smooth materials). The two studied roofs are actually the opposite sides of the same roof (although made of different material) but there are no differences in concentrations since neither side receives a distinctly higher net precipitation than the other. These results agree with those obtained by Chang et al. [44] for similar roof materials (painted aluminium, galvanised iron and composite shingles), in which the orientation of the roof had no effect on the runoff water quality.

In contrast, M and P roofs present differences with the CT roof for TOC, TC and TAN. The higher amount of TOC in CT roofs can be explained by the relatively high porosity of clay tiles, for which the material is exposed to greater physical, chemical and biological degradation. Besides this, the lichen's presence and growth can cause several additional deterioration problems [84].

From these results, one can affirm that runoff from M and P roofs is of the same or better quality than the other roofs for all parameters, except for TAN. On the other hand, runoff from FG roofs presents the best quality in terms of TAN but the worst in terms of EC, TOC and the system of carbonates. The runoff from CT roofs presents an in-between quality.

6.4. Conclusions

The linear regression model developed for each roof (CT, M, P and FG) shows that runoff depends greatly on the rainfall height. The initial abstraction, which depends on the roof's slope and roughness, is highest in flat rough roofs (e.g. 3.8 mm for FG) while sloping roofs present much smaller abstractions (≤0.8mm)

The selection of sloping smooth roofs (e.g. M and P roofs, with a RC>0.9) implies a global RWH potential approximately 50% greater than flat rough roofs (e.g. FG roof, with RC=0.62). The promotion of roofs with low RC may be advisable in order to reduce peak flows and minimise the problem of combined sewer overflows.

Quality analyses indicate that rainwater runoff samples are in the low range for EC (85.03 ± 9.98 μS/cm), TSS (5.98 ± 0.95 mg/L) and TOC (11.56 ± 1.72 mg/L); and their pH is basic (7.59 ± 0.07 upH). Thus, the quality of rainwater runoff in the case study area (north-eastern Spain) appears to be generally better than the average quality found for roof runoff in the literature review.

Differences in runoff water quality are relevant between sloping smooth and flat rough roofs. The FG roof presents higher levels of all pollutants (except for TAN) because of the processes of particle deposition, roof weathering and plant colonisation. In contrast, sloping roofs (such as CT, M and P roofs) present better quality.

These results have an important significance for local governments and urban planners in the design and planning of cities. With city planning policies that could establish guidelines regarding the slope and roughness of roofs (both for the existing city and for new developments), stormwater roof runoff could be promoted both in terms of resource availability and quality. Thus, sloping smooth roofs, which have proved to perform best, may be preferable in order to foster RWH.

Chapter 7.

Cost-Efficiency of Rainwater Harvesting in the (Re)Design of Mediterranean Neighbourhoods

This chapter is based on the following paper, currently submitted for review:

Farreny R, Gabarrell X, Rieradevall J. Cost-efficiency of Rainwater Harvesting Strategies in Dense Mediterranean Neighbourhoods. Submitted in September 2010 to *Resources, Conservation and Recycling.*

Abstract

RWH presents many benefits for urban sustainability and it is emerging as a key strategy in order to cope with water scarcity in cities. However, there is still a lack of knowledge regarding the most adequate scale in financial terms for RWH infrastructures particularly in dense areas. The aim of this research is to answer this question by analysing the cost-efficiency of several RWH strategies in urban environments. The research is based on a case study consisting of a neighbourhood of dense social housing (600 inhabitants/Ha) with multi-storey buildings. The neighbourhood is located in the city of Granollers (Spain), which has a Mediterranean climate (average 650 mm/year). The four strategies are defined according to the spatial scale of implementation and the moment of RWH infrastructure construction (building / neighbourhood scale and retrofit action vs. new construction). Two scenarios of water prices have been considered (current water prices and future increased water prices under the EU Water Framework Directive). In order to evaluate the cost-efficiency of these strategies, the necessary rainwater conveyance, storage and distribution systems have been designed and assessed in economic terms through the NPV. The pipe water price that makes RWH cost-efficient for each strategy has been obtained, ranging from 1.86 to 6.42€/m^3. The results indicate that RWH strategies in dense urban areas under Mediterranean conditions appear to be economically advantageous only if carried out at the appropriate scale in order to enable economies of scale, and considering the expected evolution of water prices. However, not all strategies are considered cost-efficient. Thus, it is necessary to choose the appropriate scale for rainwater infrastructures in order to make them economically feasible.

Keywords: Ecocities; Net Present Value; Rainwater infrastructures; Urban Retrofit

7.1. Introduction

Water management in cities is crucial since their present water usage is far from being sustainable [5], the main problems related to it being water shortage, stream degradation and flooding. Pressure on water resources in urban areas is increasing, with growing demand and limited water sources [35]. This increasing demand reduces fresh water reservoirs [5] and is followed by the use of more distant or inferior-quality sources [6]. For this reason water restrictions are becoming a fact of life in many cities [35]. Furthermore, observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems. Specifically, it seems that current water management practices may not be robust enough to cope with the impacts of climate change on water supply reliability and flood risk, among others [85].

RWH is presented as a sustainable strategy to be included in urban water cycle management. It presents many benefits, i.e. it may reduce a city's external water demand, alleviate water stress on the area, reduce non-point source pollutant loads, reduce treatable urban runoff volume, prevent flooding and help to alleviate climate change [6, 10, 11, 57, 86, 87]. Despite of this, until recently the collection of rainwater has all too often been ignored [53]. Nevertheless, in recent years there has been increasing interest in the use of water resources generated within the urban boundary for potable supply substitution, as a means of augmenting current supply capacity [88]. This interest has grown particularly rapidly in semi-arid areas due to water scarcity and vulnerability, such as in the Mediterranean-weather areas (namely Mediterranean Sea basin, California, Cape Province in South Africa, central Chile and Southern Australia).

In this context, it is necessary to provide criteria for the spreading of RWH systems, bearing in mind that the proper application of economic principles to environmental problems is essential in order to identify and implement the most cost-effective solutions [70] and move towards sustainable strategies for urban water management. Tam et al. [89] suggested that the most important consideration in the decision whether to install a RWH system lies in terms of financial costs and benefits. For this reason, it is particularly important to determine the economic feasibility of RWH systems.

Some light has been shone on this issue by several authors. Table 7.1 summarizes the research carried out so far, identifying the scale of RWH infrastructures, their location, annual rainfall, the time in which the infrastructures are implemented (new construction or retrofit action), the approach of the research and two economic parameters (r, discount rate; t, discount period).

Table 7.1. Review of the research on the economic feasibility of RWH systems.

Scale[a]	Location (average rain, mm/year)	Time[b]	Approach of the research	r (%)	t (years)	Ref.
S	3 cities in Taiwan (range from 1755 to 3350)	R	Determination of the optimum storage volume of rainwater tanks, considering economic aspects	5	15	[53]
S	West Yorkshire, UK (~700)	N	Life cycle costs of RWH	3.5 5 10 15	5 10 25 50	[90]
S	7 cities in Australia (range from 520 to 1597)	N	Costs of RWH compared to other water supply alternatives	3	20	[89]
S	Florianopolis, Brazil (1706)	R	Combination of greywater and RWH systems	1 5 10		[91]
S, Nb	Melbourne, Australia (800)	N	Role of stormwater as a substitute of potable water	5.2	50	[88]
M	4 cities in Australia (range from 800 to 1600)	N	Feasibility of RWH in high-rise buildings (payback period)	6.5		[92]
M	Sydney, Australia (1200)	N	Determination of the most sustainable RWH scenario for multi-storey buildings	5 7.5 10	60	[49]
M	Florianopolis, Brazil (1706)	N	Combination of greywater and RWH systems (payback period)			[93]

[a] Scale of infrastructures: S = Single-family building, M = Multistorey building, Nb = Neighbourhood level

[b] Time of implementation: N = New construction, R = Retrofit action

From this review, it follows that most research is based on the single-family building level, which may be explained because most RWH have traditionally been installed in this kind of buildings due to their availability of wide catchment areas for RWH and space for rainwater storage systems. As a consequence, the studies on multi-storey residential buildings have been more limited [49]. To date, there is only one preliminary study on a scale larger than the building one, which considers a neighbourhood consisting of single-family houses in a low density layout (between 15 and 40 households per hectare) [88]. One of the findings of this research was that the spatial scale of the stormwater harvesting systems implemented to date has generally been determined by opportunistic drivers rather than strategic considerations such as the relationship between scale and cost [88].

Since access to information is crucial to the decision-making process of urban ecodesign [34] in order to improve the sustainability of our cities, it is necessary to establish the most adequate scale for RWH systems (either at the building level or at the neighbourhood level). This is particularly important for dense urban areas, which generally suffer from most of the problems related to urban water management (external water dependence, flooding, stream degradation, etc.). However, to our knowledge there is no research on the economic feasibility of RWH infrastructures for neighbourhoods made up of multi-storey buildings. On the other hand, there is a lack of research on the differences in the financial implications of the implementation of RWH systems in new neighbourhoods compared to retrofit actions within existing urban developments.

The goal of this research is to evaluate the cost-efficiency of several strategies for urban RWH in Mediterranean weather conditions, comparing different spatial scales (RWH infrastructures at the building or at the neighbourhood level) and two implementation times (RWH infrastructures in new construction areas or in existing urban developments as a retrofit action).

7.2. Material and methods

This section presents the case study area, which is a dense neighbourhood located in Spain, and the methods and approaches followed in this project.

7.2.1. Dense Mediterranean neighbourhood case study[1]

The case study area is a 2.6 Ha neighbourhood of social housing located in Granollers, 30 km north of Barcelona, Catalonia, Spain (Figure 7.1). According to the land cover analysis developed with the aid of the software TNTMips [94] based on the most recent aerial photographs [95], 44.5% of the neighbourhood is covered by pedestrian areas, 29.0% buildings, 14.7% green areas (mostly grass but also trees and shrubs) and 11.8% roads.

The two main criteria for the selection of this neighbourhood are its location in a water scarce region and its urban density. On one hand, the climate in this area (with an average annual rainfall of around 650 mm, representative of the average precipitation in Mediterranean climate areas [96]) together with high water demand result in water scarcity and droughts. On the other hand, the neighbourhood comprises a total of 43 multi-storey buildings (558 dwellings; 2.83 inhabitants/household) which results in a high net density (more than 600 inhabitants/Ha).

[1] Case study previously introduced in section 2.1 (Figure 2.5).

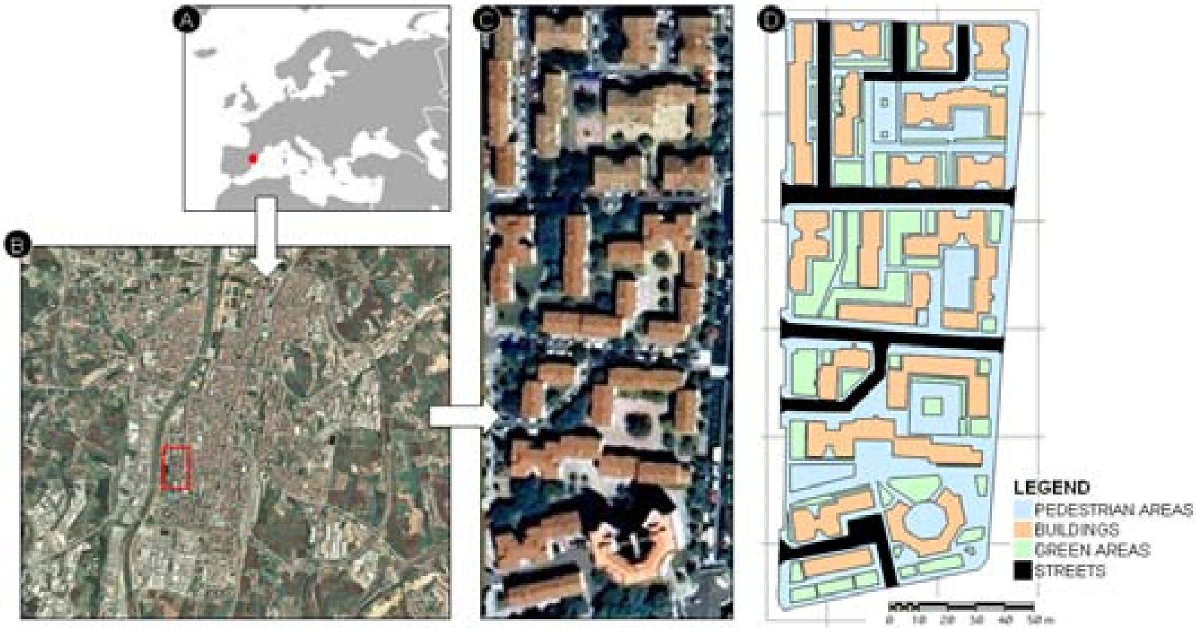

Figure 7.1. (a) Location of the area of study in Europe; (b) aerial photograph of the city of Granollers; (c) aerial photograph of the neighbourhood; (d) land cover map.

7.2.2. Methods and approaches

Definition of strategies

Four RWH strategies (Table 7.2) have been defined based on the neighbourhood case study. All of them assume that stormwater runoff from roofs would be collected, since roofs are the most common type of catchment used for harvesting rainfall [89, 97]. This runoff would be accumulated in rainwater tanks for its consumption for non-potable uses. These tanks would be connected to a mains back-up supply system in order to increase the reliability of this alternative water supply system. Street stormwater runoff reuse has not been considered, mostly because it is expected to be of lower quality [31].

Table 7.2. Definition of RWH strategies.

Strategy		**Spatial scale**	
		Single-Building	Neighbourhood
Temporal scale	Renewal	1	3
	New construction	2	4

The proposed strategies differ on the spatial scale of construction of RWH infrastructures and on the time of construction. The spatial scale means differentiating between the construction of RWH infrastructures at either the building or the neighbourhood level. For the building level, the most common type of building in the neighbourhood has been considered: a five-storey building (ten dwellings) with a projected roof area of 125 m². Thus, a strategy would be to install a rainwater conveyance, storage and distribution system in each building (strategies 1 and 2) and another one would be to build it up at the neighbourhood level, with a shared rainwater conveyance, storage and distribution system for all the buildings (strategies 3 and 4).

The time of construction differentiates between retrofit actions and new construction. Then, a strategy would be to install these infrastructures in the current neighbourhood, that is to say, as a retrofit operation (strategies 1 and 3), and another one would be in a greenfield development consisting of a new neighbourhood that would have the same characteristics as the case study (strategies 2 and 4).

Neighbourhood rainwater demand

The most publicly accepted non-potable applications for harvested rainwater are toilet flushing, garden irrigation and use in washing machines [90]. In this case study, the first of them was not considered since it was expected that greywater systems (from showers) would be in place to provide water for that purpose. The second use was also excluded since irrigation water demands were very small because xerogardening practices were in place.

For these reasons, it was considered that the most appropriate use for rainwater would be for laundry. Besides, the laundry water demand is very high (compared to the RWH potential) and regular throughout the year. This implies that a smaller rainwater tank is necessary [51] and maximizes the benefits [49]. Secondly, using harvested rainwater for washing purposes has the additional benefit of reducing washing powder consumption, as rainwater is often softer than drinking water from the tap [98].

In strategy 1, water is distributed to each dwelling for consumption by individual washing machines. This water demand is assumed as high as 20% of the neighbourhood's domestic water demand, based on general domestic water consumption facts. Domestic water consumption, which has been accounted for through a monitoring control of water meters over a period of 1 year in a sample set of dwellings, is estimated at 57 231 m^3/year based on meter readings (281 L/dwelling). Thus, laundry water consumption is estimated at 20.5 m^3/household per year.

In strategies 2, 3 and 4, it is proposed that water be utilized in a public laundry room next to the storage rainwater tank. This assumption is made since it is believed that this is an advisable option for neighbourhoods with small apartments, such as is the case in this social housing neighbourhood, because it saves space in the apartments and the inhabitants do not need to purchase a washing machine. This option represents an important saving in terms of global environmental impact related to the space occupied by a washing machine in the dwelling and also the improvements in the efficiency of machines [99]. Therefore, laundry water demand in strategies 2, 3 and 4 is expected to be reduced by a 30% in respect to the individual laundry water demand in strategy 1. Thus, water demand is estimated at 14.3 m^3/household per year.

Design of the rainwater harvesting infrastructures

The conceptual design of infrastructures has been executed with the aid of expert companies in the field. For each strategy, the inventory of materials and works has been obtained and divided into three subsystems: harvesting, storage and distribution (Figure 7.2). The sizing of piping systems (pipe diameters, valves, etc.) has followed well-known conventional procedures based on the most common hydraulic engineering principles. Pipe materials selected for the water supply system were based on the local water authority's adopted practice.

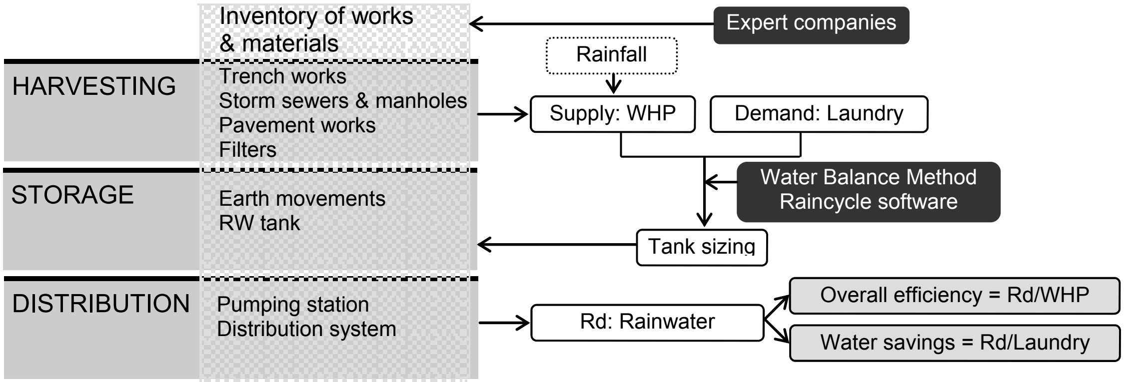

Figure 7.2. Methodology for the design of infrastructures and calculation of performance of indicators.

The rainwater tank storage capacity (tank sizing) has been calculated according to the Water Balance Method using monthly demand and supply data [100]. The results have been compared with those obtained on a daily basis with the software RainCycle [101], which is a computer-based modelling tool based on the yield after spillage algorithm in the form of a continuous simulation. For these methods, rainfall and demand time series need to be known. Average monthly rainfall data is obtained from meteorological records for a period over 30 years [102], while daily rainfall data has been obtained for year 2008 based on data from the Catalan Meteorological Service. The RC has been assumed to be 0.9 [37]. The losses related to the filters are estimated at 5%.

Two performance indicators have been calculated as a measure of the hydrological performance of the infrastructures: overall efficiency and water savings. The expected overall efficiency of the system is calculated as the ratio between the net amount of rainwater collected and delivered (Rd) and the volume of rainwater that potentially could have entered the system (WHP) [103]. Water savings have been calculated as the percentage of water demand in the laundry covered by rainwater.

Economic assessment of the rainwater harvesting infrastructures

The conducted conceptual design is the base for the estimation of the financial costs along the life span of the infrastructures. The economic assessment has been carried out by means of the calculation of the NPV and the PP (see section 2.3.3 for further details).

The NPV analysis method is one of the most commonly used tools to determine the current value of future investments to compare alternative water system options [104]. In this analysis, the associated costs of RWH systems, such as capital, operational and maintenance expenses, are balanced against any revenues/benefits (such as reduction in mains supply charges). The NPV analysis requires a rate at which costs and benefits are reduced over time, known as the discount rate [105]. The case study consists of a social neighbourhood promoted by local/regional governments. In general, public analysis is often conducted at discount rates lower than those required by private investment to reflect the social time value of money rather than the investment value. For this reason, two possibilities have been considered: 0 and 3% discount rate. The choice of 3% is similar to the one proposed by other authors [89, 90]. The selected discount period was 60 years, taking into account the lifespan of the proposed infrastructures [49]. Inflation has not been considered.

The PP, which is the time that a project is expected to take in order to earn net revenue equal to the capital cost of the project, has also been calculated within the discount period. It is measured as the ratio between total capital costs and the difference between annual revenue and annual expenditures, taking into account two possible discount rates (0 –no discount rate, simple PP- and 3% -discounted PP).

Costs

Capital costs have been accounted for in 2009 with the Metabase ITeC [106], a database from the Catalan Institute of Construction Technology that provides information on prices, technical details, companies and, certificates of generic building elements and products. The costs in this database include both materials/equipment and installation costs (labour). Information from local RWH systems suppliers has been used to complement it.

Whilst capital costs can be predicted with a fair degree of accuracy, long-term costs (operating and maintenance costs) are harder to forecast [107]. These long-term costs are accounted for under the following considerations:

- pumping electricity costs (16.84 c€/kWh, based on the average domestic electricity price in Spain for the second semester 2009, which is very similar to the average price in EU-27 -16.38 c€/kWh- [108]),
- maintenance costs (150€ and 300€ every 2 years in strategies at the building and at the neighbourhood scale, respectively),
- pump replacement every 15 years,
- replacement of half of the filters every 15 years,
- pre-fabricated rainwater tank replacement every 30 years,
- the remaining infrastructures (concrete rainwater tank, piping…) are assumed to have a life span equal to the discount period, that is to say, 60 years.

Benefits

The primary financial benefit will be a reduction in the annual water bill from local water authorities. This annual revenue is calculated as the savings related to the substitution of mains water for rainwater. Thus, the price of pipe water supply and the amount of rainwater delivered (Rd) are considered. It needs to be highlighted that only the costs related to water supply (but not to the sewage system) are considered, since once the water is used it will end up to the sewage system (independent of the original supply source).

With respect to the pipe water price, two scenarios are considered:

- *Scenario 1*. It considers the current domestic water price of water supply in the region: 1.12 €/m^3 [109].
- *Scenario 2*. It considers that water supply prices in the case study region will achieve the price of 4 €/m^3 in the coming years, particularly because of water scarcity and increasing water costs related to more expensive water sources (i.e. desalination). The adoption of the current average cost of mains water as an indicator of savings is an underestimate, given the 'full cost' of water is likely to be higher than currently priced [88]. Actually, prices of water in Spain have increased along the past years at a annual rate over 5% [109] and it is expected that these prices will go on increasing. This is mostly explained because water prices will have to move to full-price water recovery under EU Water Framework Directive of which Spain is a signatory [110]. As a consequence, there will be some sort of homogenisation of prices throughout Europe, where there is currently a big disparity among countries (current water supply prices in some European cities ascend to as much as 3.68 €/m^3 in Copenhaguen, 2.89 €/m^3 in Brussels, 2.41 €/m^3 in Luxembourg or 2.18 €/m^3 in Berlin for a monthly consumption of 16 m^3/household [111]).

7.3. Results

Table 7.3 shows the size of the tank for each strategy, as well as the water savings and the overall efficiency, according to the water balance on a daily basis.

Table 7.3. Performance indicators and other variables for each strategy.

	Strategy			
	1	**2**	**3**	**4**
Tank capacity (m^3)	8	6	275	275
Demand (m^3/year)	205	143	8030	8030
Water savings (%)	35.7	43.9	43.4	43.4
Overall efficiency (%)	100	86	78	78
Overflows (% of water entering the tank)	0	14	22	22
Tank empty (days/year)	256	223	226	226

Table 7.4 shows the inventory of elements for the RWH infrastructures. The main difference between strategies 1 and 2 lies in the distribution of water (in new construction water is used in a common laundry room, so fewer pipes, bypasses and valves are necessary). The difference between strategies 3 and 4 lies in the demolition and repositioning of paving.

Table 7.4. Elements included in the design of the infrastructures for RWH. The dash indicates that this item does not apply for the strategy.

	Item [units of measurement in brackets]	Strategy			
		1	2	3	4
Harvesting	*Trench works*				
	Trenching [m³]	20		4110	
	Filling with sand and excavation materials [m³]	19.8		4054	
	Storm sewers				
	PVC building derivations [m]	20 (D125)		1290 (D160)	
	PVC general storm sewer [m]	-	-	765 (D315)	
	Manholes				
	Downpipe drain (non-syphonic) [u]	2		86	
	Inspection chamber [u]	3		94	
	Pavement works				
	Bituminous pavement demolition [m²]	-	-	2055	-
	Pavement reposition (40 cm aggregates, 8 cm bitumen weighting, 1kg/m² prime coat) [m²]	-	-	2055	-
	Filter				
	Filter [u]	-	-	43	
Storage	*Earth movements*				
	Excavation [m³]	-	-	500	
	Earth transportation to landfill [m³]	-	-	429	
	Rainwater tank (built in-situ)				
	Cleaning and ground levelling with concrete HL-150/P/20 (0,2m thickness) [m²]	-	-	66	
	Floor & ceiling slabs of concrete HA-30/B/20/IIb (0.5m thick) [m³]	-	-	66	
	Floor slab reinforcements with corrugated rod steel B500S (50kg/m³) [kg]	-	-	1650	
	Ceiling slab reinforcements with corrugated rod steel B500S (120kg/m³) [kg]	-	-	3960	
	Floor slab shuttering with pine wood boards [m²]	-	-	20	
	Ceiling slabs shuttering over scaffold [m²]	-	-	86	
	Walls made of concrete HA-30/B/20/IIa (0.5m thickness) with Repellent additive [m³]	-	-	88	
	Wall reinforcement with corrugated rod steel B500S (80kg/m³) [kg]	-	-	7040	
	Wall shuttering with pine wood [m²]	-	-	416	
	Sealing with polymer in aqueous dispersion for waterproofing (1.3 kg/m²) [m²]	-	-	614	
	Pre-fabricated tank				
	Polyester tank with filter (including excavation)	1 (8m³)	1 (6m³)	-	-
Distribution	*Pumping station*				
	Submersible pump (2.2kw) [u]	1		2	
	Distribution system				
	Polypropylene bypass (D20) [m]	110	10	50	
	Polypropylene copolymer PP-R pressure pipe [m]	52 (D20/25)	20 (D20/25)	80 (D20/50)	
	Ball stopckock (polypropylene copolymer PP-R), (D20)	14	10	50	
	Solitude manual valve tap with screw type [u]	4 (D19)	1 (D19)	1 (D25)	
	Retention valve [u]	4 (D20)	1 (D25)	1 (D50)	
	Reducing valve [u]	1 (D19)		1 (D51)	
	Gate valve with manual clamps, 16 bar [u]	1 (D25)		1 (D50)	
	Manhole of prefabricated concrete placed on a concrete sill HM-20/P/40/I 15cm thick [u]	1			

Table 7.5 shows the capital costs related to the main items of the inventory. The costs are concentrated in the storage subsystem for strategies at the building scale, while they are largely attributed to the harvesting subsystem for the strategies at the neighbourhood scale. The capital costs per household are within the range of 648-650 € for strategies in new construction and between 759 and 790 € for retrofit actions.

Table 7.5. Capital costs of the infrastructures for RWH.

<table>
<tr><th colspan="2" rowspan="2">Item [costs expressed in €]</th><th colspan="4">Strategy</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td rowspan="6">Harvesting</td><td>Trench works</td><td colspan="2">600</td><td colspan="2">123 411</td></tr>
<tr><td>Storm sewers</td><td colspan="2">627</td><td colspan="2">133 315</td></tr>
<tr><td>Manholes</td><td colspan="2">820</td><td colspan="2">29 917</td></tr>
<tr><td>Pavement works</td><td>-[a]</td><td>-</td><td>62 161</td><td>-</td></tr>
<tr><td>Filter</td><td>-</td><td>-</td><td colspan="2">4687</td></tr>
<tr><td>Total
(relative contribution in parentheses)</td><td>2047
(25.9%)</td><td>2047
(31.5%)</td><td>348 804
(82.4%)</td><td>286 643
(79.3%)</td></tr>
<tr><td rowspan="4">Storage</td><td>Earth movements</td><td>-</td><td>-</td><td colspan="2">3496</td></tr>
<tr><td>Rainwater tank structures (made-to-measure)</td><td>-</td><td>-</td><td colspan="2">67 549</td></tr>
<tr><td>Pre-fabricated tank</td><td>3650</td><td>3000</td><td>-</td><td>-</td></tr>
<tr><td>Total
(relative contribution in parentheses)</td><td>3650
(46.2%)</td><td>3000
(46.1%)</td><td>71 045
(16.8%)</td><td>71 045
(19.7%)</td></tr>
<tr><td rowspan="3">Distribution</td><td>Pumping station</td><td colspan="2">1006</td><td colspan="2">2012</td></tr>
<tr><td>Distribution system</td><td>1200</td><td>452</td><td colspan="2">1652</td></tr>
<tr><td>Total
(relative contribution in parentheses)</td><td>2206
(27.9%)</td><td>1458
(22.4%)</td><td>3664
(0.9%)</td><td>3664
(1.0%)</td></tr>
<tr><td colspan="2">Total infrastructures</td><td>7903</td><td>6505</td><td>423 513</td><td>361 352</td></tr>
</table>

[a]The dash indicates that this item does not apply for the strategy.

Table 7.6 shows the NPV of each strategy considering the two variables: pipe water price (scenario 1 and 2) and discount rate (r=0% and r=3%). The payback period is shown in the cases that it falls within the discount period (t=60 years). A positive value of the NPV is an indication of benefits outweighing costs. The NPV values for strategies at a different spatial scale (building level -1 and 2- and neighbourhood level -3 and 4-) are not directly comparable, precisely due to reasons of scale. To aid comparison, the metrics have been scaled for strategies 1 and 2 (RWH at building level), so that they are applicable to the whole neighbourhood. Thus, the NPV of strategies 1 and 2 are also expressed at the neighbourhood scale, that is to say, considering the RWH system at the building level reproduced in each building (Table 7.6).

Table 7.6. Financial results for the RWH strategies. The shadowed cells show the positive NPV.

Scenario		Strategy 1	Strategy 2	Strategy 3	Strategy 4	Building strategies (1,2) the neighbourhood level 1'	Building strategies (1,2) the neighbourhood level 2'
(1) Current water price (1.12 €/m³)	NPV at r[a] = 0% (€)	-15 561	-14 076	-217 046	-154 885	-868 304	-785 441
	PP (years)	n.a.[b]	n.a.	n.a.	n.a.	n.a.	n.a.
	NPV at r = 3% (€)	-10 909	-9511	-324 201	-262 040	-608 722	-530 714
	PP (years)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
(2) Future water price (4 €/m³)	NPV at r = 0% (€)	-2922	-3192	385 438	447 599	-163 048	-178 114
	PP (years)	n.a.	n.a.	31	27	n.a.	n.a.
	NPV at r = 3% (€)	-4905	-4350	-37 962	24 199	-273 699	-242 730
	PP (years)	n.a.	n.a.	n.a.	51	n.a.	n.a.

[a] 'r' stands for 'discount rate'
[b] 'n.a.' stands for 'not available'

Figure 7.3 represents the dependence of the NPV on the price of pipe water for the whole set of strategies, considering two discount rates (0 and 3%). From these functions, the price of mains water that results in a NPV=0 is obtained (Figure 7.3). Prices of mains water higher than this will entail cost-efficient RWH strategies.

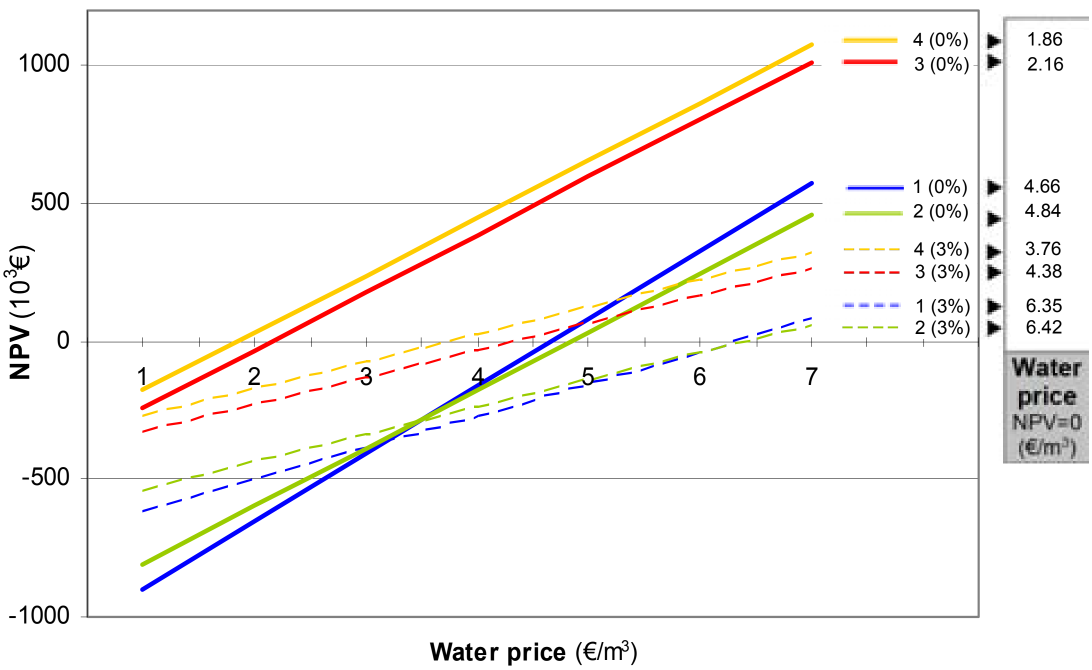

Figure 7.3. NPV function depending on the pipe water price.

7.4. Discussion

In general, no strategy is cost-efficient if average domestic regional water prices are considered (scenario 1). This is consistent with most previous studies, which have found RWH systems to be financially unrewarding under the current water price regime where water is supplied to urban residents at a subsidized rate [49].

The economic performance of RWH strategies is the least interesting at the building scale, where revenues never compensate costs (no PP available; negative NPV) independent of the water price (within the considered scenarios) (Table 7.6). The differences in the financial performance of strategies at the two spatial scales are evident if the NPV is extended to the whole neighbourhood. This results agree with other authors [90], who state that domestic RWH 'at the building scale' is unlikely to be cost effective for all reasonably foreseeable scenarios.

Nevertheless, the strategies at the neighbourhood level seem to be more favourable, in particular in scenario 2 (increase in local water prices). This is consistent with the findings from Fletcher et al. [35] and Mitchell et al. [35, 88], who estimate that costs of RWH systems are inversely related to their scale. The most cost-efficient strategy is the one at the neighbourhood level and under new construction (strategy 4). In this case, the PP is reduced to 27 years, which might be acceptable from the point of view of the Public Administration. Therefore, strategies at the neighbourhood level should be preferable, although it has to be kept in mind that distributed RWH infrastructures are relatively untried and unproven [112]. Furthermore, the retrofit of RWH into existing urban areas is proving to be a challenge [35].

The RWH economic feasibility in the case of the neighbourhood studied is strongly conditioned by the small catchment area per dwelling. This residential neighbourhood presents a high urban density although only 29% of its land is occupied by buildings. Consequently, a small portion of catchment area (less than 14 m^2 of roof per dwelling) corresponds to each household, and, therefore, the ratio 'rainfall per inhabitant' is small. This contrasts with the catchment area availability per dwelling in other parts of the city of Granollers (e.g. if we consider a neighbourhood with semi-detached houses, each household has around 80 m^2 of roof) or the ones considered in other studies [88]. Tam et al. [89] indicated that a factor that may limit the appropriateness of rainwater catchment systems is the shortage of space and high cost of land, which is generally the case for dense urban areas. Furthermore, not only is the neighbourhood located in an area with limited rainfall, but also regional water prices are lower than average European prices [111]. For all these reasons, water savings (benefits) from the projected rainwater systems in this dense Mediterranean neighbourhood are limited.

In order to enhance RWH strategies -at any spatial scale- it would be necessary to consider discount rates being as low as possible (Table 7.6, Figure 7.3). As an example, strategy 3 is only profitable for a 0% discount rate (in scenario 2). At the same time, increased water pricing regimes are necessary to foster RWH, which is incidentally a feasible trend taking into account the implementation of the Water Framework Directive, as well as the increase in water demand. The water prices that should be achieved so that RWH would be cost-efficient largely differ between the strategies -from 1.86 €/m^3 for strategy 4 (r=0%) to 6.42 €/m^3 for strategy 2 (r=3%) **(**Figure 7.3). Therefore, it seems realistic that the neighbourhood strategies will be cost-efficient in the short term, but it is more difficult to expect that strategies at the building level to show favourable economic performances.

Another consideration is that water companies already price water based on block tariffs, with rising prices as the consumption of water increases. Thus, the considered water prices so far correspond to average water prices. However, the mains water that would be first substituted by rainwater would correspond to the highest block tariff, that is to say, the one with the most expensive water. Consequently, the substituted water price is higher than the average one, which would result in increased benefits and a better economic performance for all considered RWH systems.

In any case, however, the decision of rejecting RWH infrastructures should not be based only on economic criteria. Taking into account the scarcity of water resources, together with the expected increase in water demand; and considering that capital costs are less than 800 €/dwelling, it would not be acceptable that public policies underutilize or overlook rainwater resources. RWH systems, even in dense areas and in Mediterranean conditions, can satisfy between 35.7 and 43.9% of the laundry demand as in the case study neighbourhood (Table 7.3). This would be enough to defer the need of new supply infrastructures to satisfy growing water demands.

These results need to be considered as a first step in the financial assessment of the infrastructures for RWH and use in urban areas, since a major shortcoming of the cost-benefit analysis is that, by definition, it ignores non-monetised impacts. The analysis of financial benefits purely in terms of potable water savings provides an incomplete picture because it excludes externalities [113], because of the difficulties in their quantification [35]. However, it is evident that the inclusion of environmental and social aspects in financial analysis would present an improved economic performance [114].

This cost-benefit analysis considers the savings of mains water as the only benefit of RWH systems. However, it is well-known that there are many other benefits of RWH in urban areas. Among these we highlight, due to their financial and environmental repercussions, the reduction (or deferring the need) of the following water infrastructures:

- downstream storm water conveyance and treatment systems,
- alternative water supply infrastructures (such as new dams, desalination plants or water transfers), as well as a reduction in the water supply infrastructures in new neighbourhoods,
- flood-prevention infrastructures.

In addition, there are other less tangible benefits which can also be relevant, such as the value that households may attach to the added insurance that rainwater tanks provide against impacts of water restrictions [89] or the improved environmental outcomes for surrounding rivers and streams [105].

If all these multiple benefits were taken into account, the financial benefits would increase and, consequently, the payback period would be reduced. Some steps into this direction are being taken. Many countries, such as Germany, the United Kingdom and Australia, are charging households a rainwater fee (also named surface water charge) for the buildings whose stormwater runoff is connected to the sewerage system [115, 116]. However, if no connection to the sewer exists because there is a RWH system, the house owner may be entitled to a rebate on the bill from the sewerage company. In addition, some state governments and local councils have offered cash rebates to support the installation of rainwater tanks in households [89]. Therefore, some financial mechanisms which take into account the externalities of RWH strategies are being developed, which may eventually foster the development of RWH systems.

7.5. Conclusions

Current urban water management practices have lead to water shortages, stream degradation and flooding. In this context, RWH may be helpful, particularly in water-scarce areas.

This research evaluates which is the most cost-efficient RWH strategy in a dense urban neighbourhood in Mediterranean conditions in Spain. Based on the economic analysis, the cost-efficiency of the presented RWH strategies may be put in doubt in dry areas in Spain, as in many other countries, if current local water prices are still so low. However, the application of the EU Framework Water Directive will increase local water prices so as to include the real costs of supplying water. As a consequence, this may foster the interest on RWH strategies from an economic point of view.

Despite some strategies seeming not to be economically cost-efficient, the small capital costs (<800€/dwelling) and the expected decrease in water availability (which will result in increasing reticulated water supply costs) make it advisable to promote RWH infrastructures.

The results of this research indicate that RWH strategies should be preferably installed at the neighbourhood level, since it enables economies of scale, and that they should take place at the moment of the settlement construction. Considering a 0% discount rate, a water price of 1.86 €/m^3 would be enough to make RWH cost-efficient for this option. On the other hand, considering an increase in the local water price (up to 4€/m^3) and a discount rate of 3%, the PP would be 51 years. If no discount rate were considered, the payback period would be reduced to 27 years. Therefore, this strategy is more cost-efficient than the one at the building level.

Future research will focus, on one hand, on the expansion of the economic analysis in order to include the externalities caused by RWH. On the other hand, it will focus on the environmental analysis of the proposed infrastructures, through a LCA -as our research group has been doing in the analysis of several urban infrastructures [32-34]. These analyses should be compared with current conventional water supply systems and with alternative ones (desalination, reclaimed waters). Finally, it will be necessary to study the administrative obstacles that will arise so as to promote RWH at the neighbourhood level, as well as to study planning procedures in order to incorporate RWH into current and future urbanisation schemes.

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PART V

Transfer of knowledge

Chapter 8.

TOWARDS A TRANSITION

In parallel with the production of the dissertation, the occasion has been given to participate in several ecoinnovation projects within the framework of urban sustainability. This has presented an opportunity to apply the concepts, strategies and tools arisen along this research, and also to integrate its outcomes, in several projects at different spatial scales. This aids a better understanding and an enhanced knowledge of the practical implementation of urban sustainability.

Hence, the main aim of Chapter 8 is to contribute to the general knowledge about urban sustainability by providing some methodological key ideas to make a transition towards this.

This chapter is organized into four sections (8.1 to 8.4), each presenting a ***methodological key idea*** and how this idea is transferred or applied into several practical projects:

- Acting at an early stage of the design of urban systems and monitoring the performance along their life cycle.
- Interdisciplinary team and sufficient understanding of the local context.
- Mixed land uses, high-density of the built-up area and self-sufficiency.
- Availability of data and criteria for urban ecodesign.

Towards a transition

Figure 8.1 shows the four methodological key ideas, taken from chapters 3 to 7, and how they should be integrated throughout the urban ecodesign process. Although the reader might find that these ideas are obvious or trivial, we believe that it is useful to state that *these* are **methodological key ideas for a transition towards urban sustainability.**

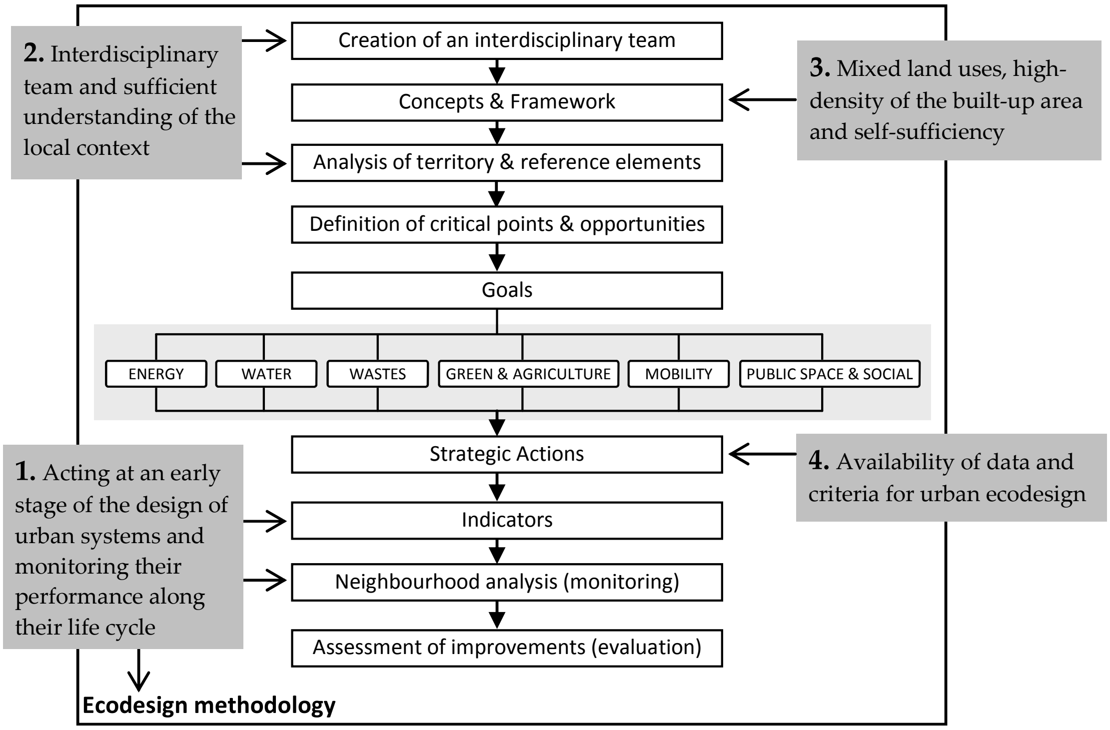


Figure 8.1. The four methodological key ideas should be integrated in the ecodesign methodology.

First, being able to design from the early stages (instead of redesigning) can make a difference in assuring a sustainable settlement. In addition, it is necessary to define a system of indicators to undertake neighbourhood analysis and evaluation of improvements. Second, the interdisciplinary team needs to have sufficient understanding of the local context, which facilitates and improves the analysis of the territory. Third, land use mixticity, a high-density in the built-up area and self-sufficiency are concepts that need to be present from the conceptual stage and throughout the whole ecodesign framework. Fourth, the definition of strategic actions will need to be guided by objective criteria (environmental, social, economic) in order to define the best strategy to achieve the previously defined goals.

Figure 8.2 presents a diagram showing which chapter/s cover these methodological key ideas, and the ecoinnovation projects to which they have been applied or integrated. These projects can be grouped into three levels of action: conceptual design, planning proposal and retrofit action.

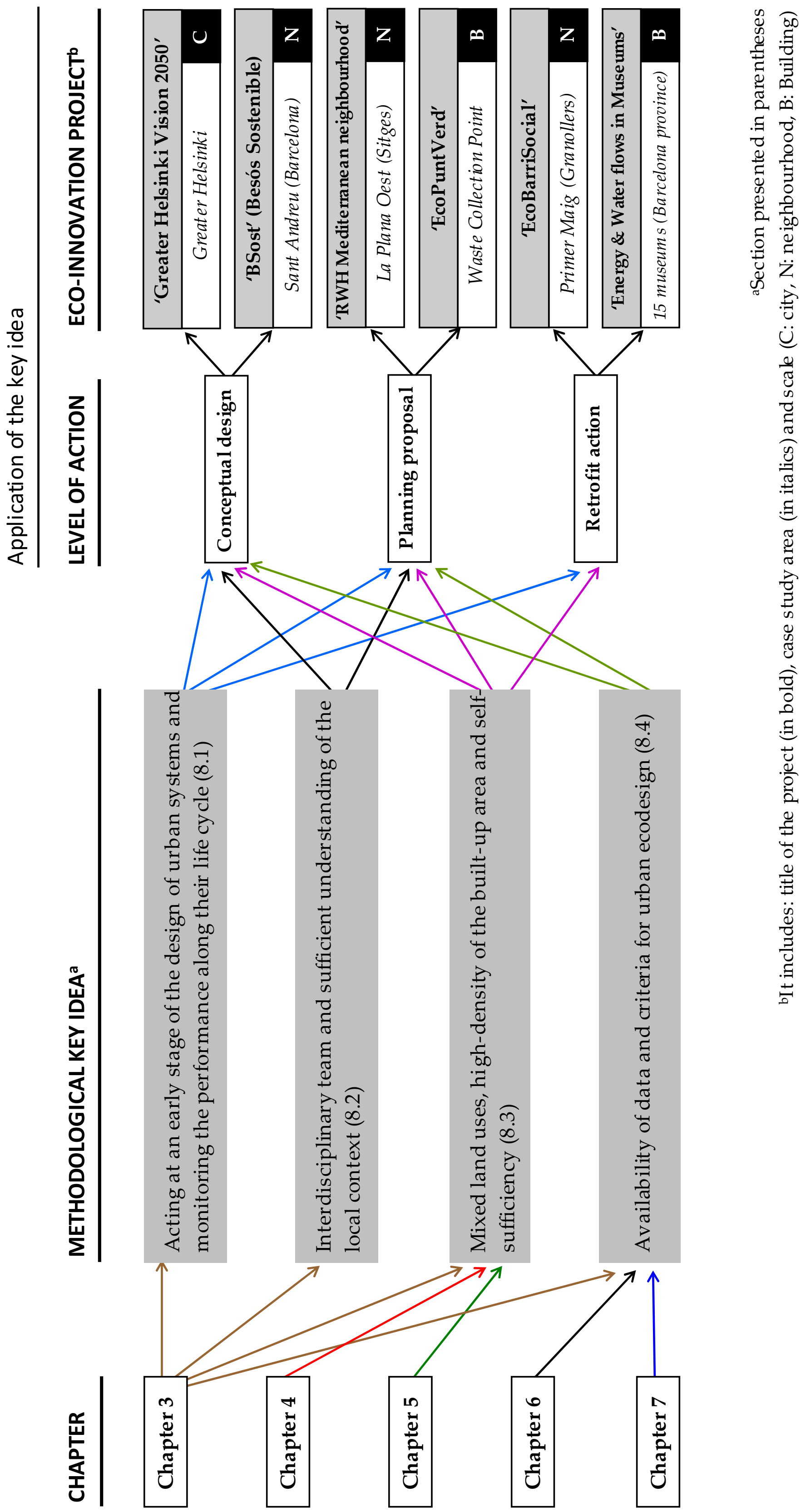


Figure 8.2. Interrelationships between the chapters, key messages and ecoinnovation projects.

Ecoinnovation projects

The key ideas are applied to or integrated into different projects. The main characteristics of these projects are summarized next, in a series of schemata that consists of the following parts:

- **Description** (brief presentation of the project; the case study area is shown in bold and underlined).
- **Aims** (brief description of the aims of the project).
- **Urban scale** (the scale of the project: metropolitan region, city, neighbourhood, building).
- **Duration** of the project (in months).
- **Location** of the case study system (region or municipality, with the country in parentheses) and **area.**
- **Outcomes of the project** (summary of the main results and conclusions of the project).
- **Main tools** used during the project (for more information about the tools, see Chapter 2).
- **Participating entities,** institutions or individuals that have been directly involved in the realization of the project.
- **Motivation** of the project (i.e. commissioned by a client, academic purposes, etc.).
- **Role of the author** of this dissertation in the project.

After the series of schemata, the different sections will describe each key methodological idea in detail.

1 Greater Helsinki Vision 2050

Description
Helsinki Greater Vision 2050 was an open, international planning competition for the design of the future **Greater Helsinki**. It became the perfect excuse to create a multidisciplinary team and set up a framework for the development of ideas and concepts for the cities of the future.

Aims
To find new and open-minded residential, land use, and transport solutions for developing the Greater Helsinki region.

Urban scale: Metropolitan region

Duration (months): 6

Location and Area
Greater Helsinki [Finland]
7000 ha of new housing

Outcomes of the project
(1) Obtaining ideas and concepts useful for the cities of the future (Figure 8.4a):

- **Self-sufficiency of resources** (to reduce the external dependence on resources such as food, water, energy, materials…).
- **Mixture of uses** (in order to reduce the need for transport and enhance interactions within the urban system).
- **Urban density** (in order to avoid urban sprawl and reduce transportation demands).
- **Multifunctionality** (so as to provide the maximum services with the minimum infrastructures, increasing their utility and deferring the need for new ones).

(2) Incorporation of the **metabolism concept** into the design and planning of urban settlements, useful to search for strategies to increase self-sufficiency of resources and to exploit the multiple synergies that may exist in cities (Figure 8.4b).

Main tools*

ED	MEFA	LCA	Ind	EA	FLW
☒	☐	☐	☐	☐	☐

Participating entities
Interdisciplinary team (architects, engineers, health experts, farmers, environmentalists...)

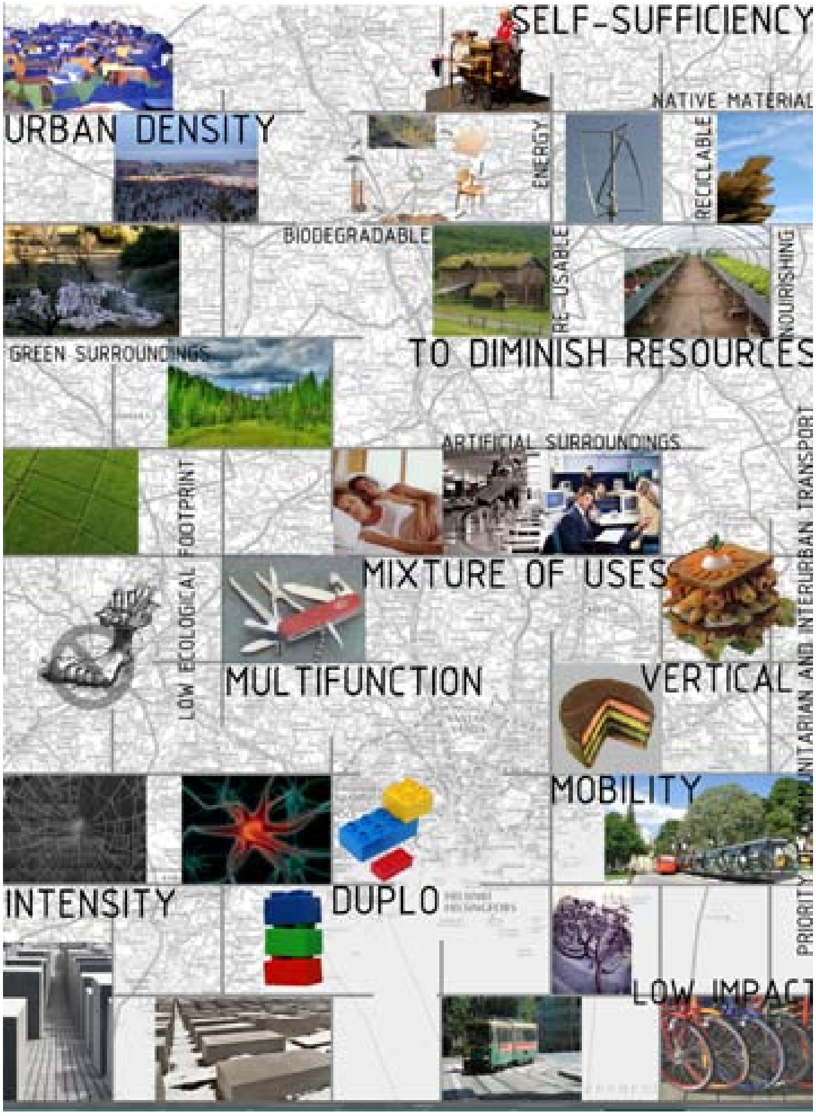
Motivation
International competition

Role of the author
Participation in team meetings and discussions

ED:* *Ecodesign;* ***MEFA: Material and Energy Flow Accounting,* ***LCA**: Life Cycle Assessment;* ***Ind:** Indicators;* ***EA**: Economic Assessment;* ***FLW:** Field and Laboratory Work*

Figure 8.3. Main characteristics of the Greater Helsinki Vision 2050 project. ***Source*****: Adapted from [1].**

(a) Presentation of the concepts underlying the team proposal



(b) Qualitative flows of energy and materials for the proposed city.

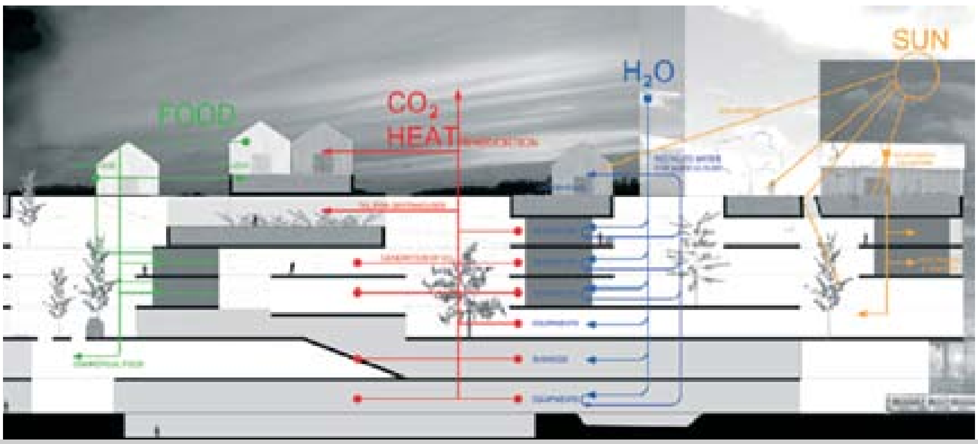


Figure 8.4. Greater Helsinki Vision 2050 project (figure). ***Source:*** **[1].**

2 BSost (Besós Sostenible)

Description

This project proposed the conceptual implementation of a new neighbourhood in the city of Barcelona, in **Sant Andreu** (Figure 8.6a), an area of industrial land and degraded building stock currently in transformation without a strong criterion of coherence.

Aims

To undergo a theoretical exercise to define concepts for a sustainable district, with the pursuit of the maximum level of self-sufficiency in the provision of water, energy and basic foods and in the management of emissions and wastes.

Urban scale: Neighbourhood

Duration (months): 12

Location and Area

Barcelona [Spain]

166.4 ha

Outcomes of the project

(1) An architectonical proposal (Figure 8.6b) based on the following concepts:

- Integration of agriculture in people's lives and within the urban form,
- Minimization of energy consumption
- Reduction in water dependency
- Revalorization of wastes
- Low environmental impact mobility
- Facilitation of social inclusion and healthy lifestyles.

(2) Quantification of the possibilities of closing loops within the district, from a metabolic point of view. The demand of energy, water, and food of the whole neighbourhood was quantified, whereas the potential for endogenous resources was examined.

Main tools*

ED	MEFA	LCA	Ind	EA	FLW
✕	✕		✕		

Participating entities

Interdisciplinary team (architects, engineers, doctors, farmers, environmentalists...)

Motivation

Team enrichment

Role of the author

Participation in team meetings, calculation of metabolism

ED: *Ecodesign;* ***MEFA****: Material and Energy Flow Accounting,* ***LCA****: Life Cycle Assessment;* ***Ind:*** *Indicators;* ***EA****: Economic Assessment;* ***FLW:*** *Field and Laboratory Work*

Figure 8.5. Main characteristics of the BSost project. ***Source:*** **Adapted from [2-4].**

(a) Proposal of distribution of the Sant Andreu neighbourhood area into three main subsystems: agriculture, built area and roads; and green spaces.

(b) General section of the neighbourhood. Parking buildings at the entries prevent the flow of cars in the neighbourhood. Services and equipments are provided in the base floors and residential uses in the upper levels.

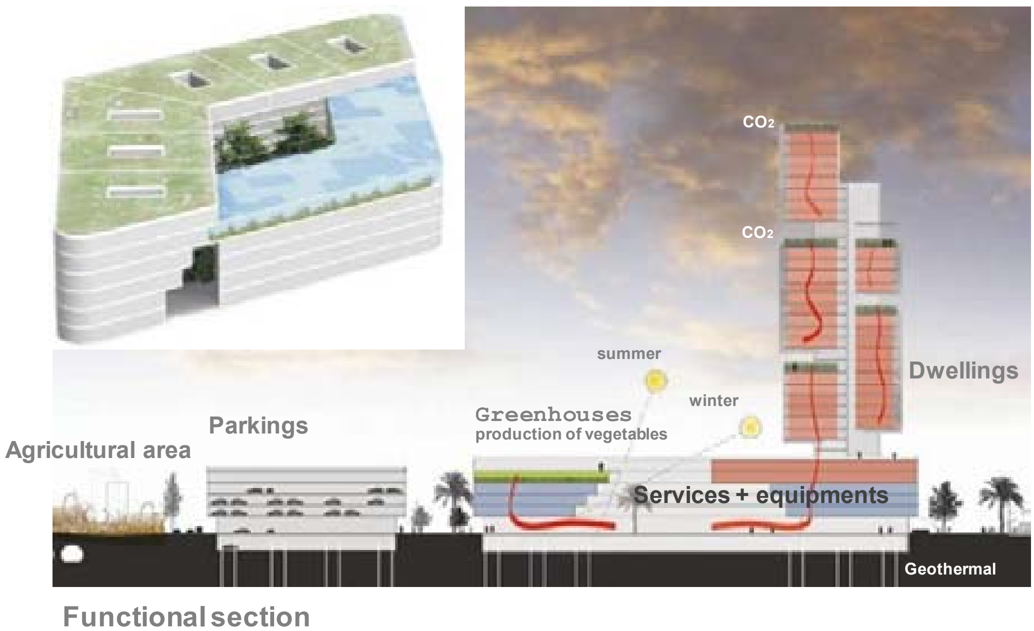


Figure 8.6. BSost project (figures). ***Source*****: [2].**

3 RWH Mediterranean neighbourhood

Description
The municipality of Sitges has planned a new residential neighbourhood (**La Plana Oest**), that will host 1664 households, several public facilities and green areas (Figures 8.8a and 8.8b). The local council is concerned about stormwater runoff management in this neighbourhood and the municipality as a whole.

Aims
To quantify the potential water self-sufficiency of this neighbourhood under several scenarios.

Urban scale: Neighbourhood

Duration (months): 10

Location and Area
Sitges [Spain]
78.4 ha

Outcomes of the project

(1) Obtention of a **matrix of water self-sufficiency potential** by means of RWH that considers different variables: neighbourhood water demand (eco-friendly, Sitges 'business-as-usual', average for the metropolitan region), rainfall pattern (dry, average and wet year) and architectural characteristics of roofs (sloping vs flat roofs). The resulting degree of neighbourhood potential self-sufficiency oscillated between 9 and 90%.

(2) Definition of a set of improvement strategies that can be applied in the planning proposal of the neighbourhood.

Main tools*

ED	MEFA	LCA	Ind	EA	FLW
☐	☒	☐	☒	☐	☐

Participating entities
SosteniPrA

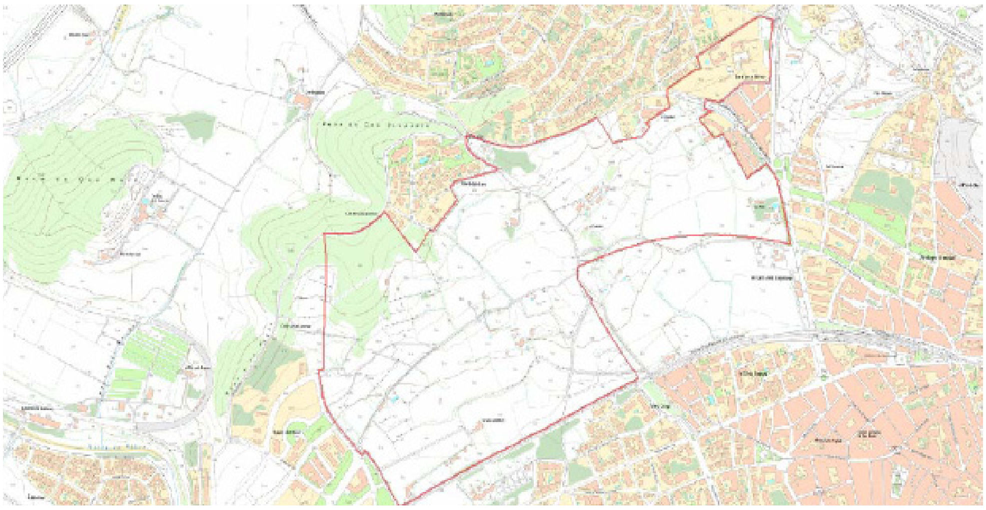
Motivation
Commissioned by Sitges town council

Role of the author
Co-supervision of a degree project

ED:** *Ecodesign;* ***MEFA*: Material and Energy Flow Accounting,* ***LCA****: Life Cycle Assessment;* ***Ind:*** *Indicators;* ***EA****: Economic Assessment;* ***FLW:*** *Field and Laboratory Work*

Figure 8.7. Main characteristics of the 'RWH Mediterranean neighbourhood' project. ***Source:*** **Adapted from [5].**

(a) Topographical map of La Plana neighbourhood (Sitges)



(b) Aerial view of La Plana neighbourhood (Sitges)

Figure 8.8. 'RWH Mediterranean neighbourhood' project (figures). ***Source:*** **[5].**

4 'EcoPuntVerd'

Description

Waste collection points themselves are generally not environmentally friendly enough. The city council of Barcelona commissioned the design of an ecodesigned **waste collection point** that would be an example of sustainability and that could be replicated throughout the city.

Aims

To ecodesign a waste collection point.

Urban scale: Building

Duration (months): 12

Location and Area

Barcelona [Spain]

50-140 m^2

Outcomes of the project

(1) Design of a new model of waste collection point (Figure 8.10). Some of its attributes are summarized next:

- More user-friendly, accessible and simple
- Use of local endogenous resources (rainwater, solar energy), aiming at self-sufficiency
- Use of recyclable materials
- Passive energy systems
- Pedagogic function
- Integrated with the urban environment
- Interactive with the users

Main tools*

ED	MEFA	LCA	Ind	EA	FLW
X					

Participating entities

Architects (Pich-Aguilera, Solanas), communicators (Gerona Group) and SosteniPrA

Motivation

Commissioned by the Barcelona city council

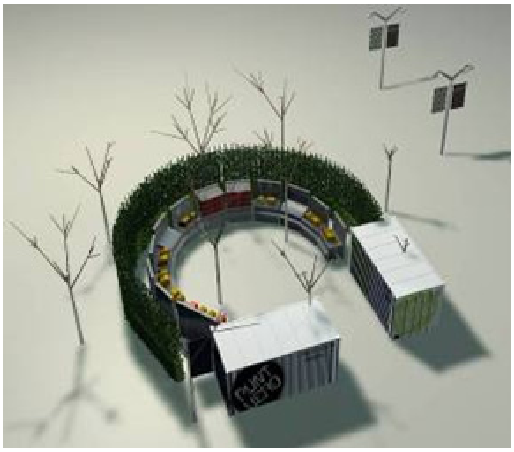
Role of the author

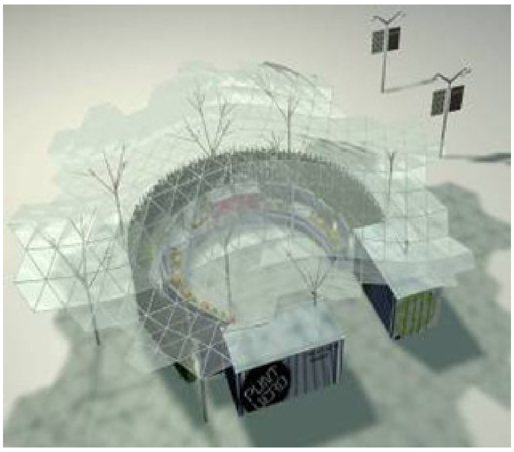
Participation in the ecodesign process

ED:** *Ecodesign;* ***MEFA*: Material and Energy Flow Accounting,* ***LCA****: Life Cycle Assessment;* ***Ind:*** *Indicators;* ***EA****: Economic Assessment;* ***FLW:*** *Field and Laboratory Work*

Figure 8.9. Main characteristics of the 'EcoPuntVerd' project. *Source*: Adapted from [6].

Different views of the waste collection point proposal.





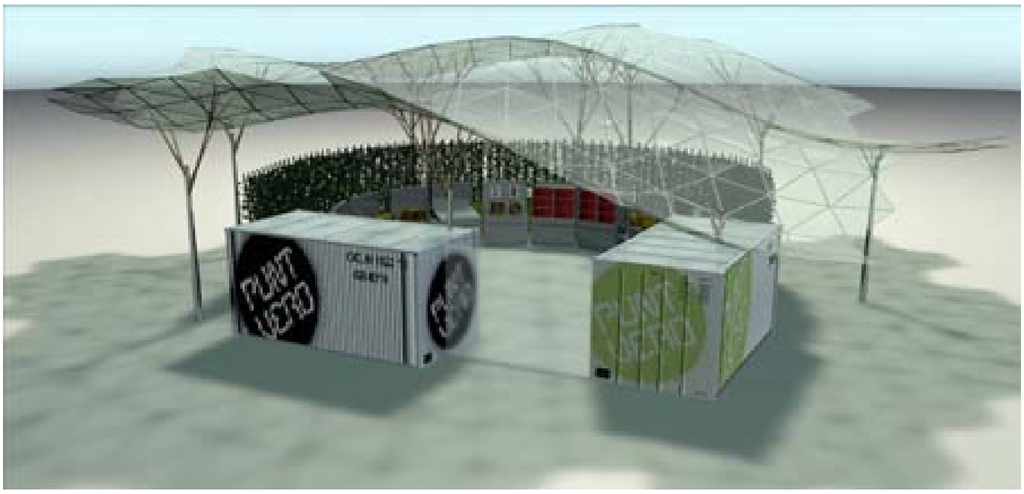


Figure 8.10. 'EcoPuntVerd' project (figures). ***Source:*** **[6].**

5 'EcoBarriSocial'

Description

This case study area, the **Primer de Maig neighbourhood,** has previously been introduced in chapters 2 and 7. Besides, this neighbourhood was selected as a representative social housing neighbourhood in order to carry out an enviornmental diagnosis and to elaborate a set of indicators to guide retrofit actions.

Aims

To make an environmental diagnosis of the neighbourhood and define a set of indicators to be used by Adigsa (the entity responsible for the social housing stock in Catalonia) for decision-making purposes in retrofit actions.

Urban scale: Neighbourhood

Duration (months): 24

Location and Area

Granollers [Spain]

2.6 ha

Outcomes of the project

(1) An environmental diagnosis of the neighbourhood, including aspects of energy, water, public space (pavements, green areas), mobility and waste generation. Besides, the potential of renewables was assessed. A set of strategies were proposed so as to reduce the environmental impacts of the neighbourhood, assessed from the technical, economic, social and environmental points of view. The potential solar energy self-sufficiency is estimated at at 24% while water self-sufficiency is at 9%.

(2) A set of indicators to aid in the process of retrofit of the social housing stock, divided into 6 different categories: water, wastes, energy and infrastructures, mobility, public spaces and social environment, and green spaces (Figure 8.12).

Main tools*

ED	MEFA	LCA	Ind	EA	FLW
☐	☒	☐	☒	☐	☒

Participating entities

SosteniPrA

Motivation

Commissioned by Adigsa, a public company belonging to the Catalan Government

Role of the author

Active participation in the whole project

ED:* *Ecodesign;* ***MEFA**: Material and Energy Flow Accounting,* ***LCA****: Life Cycle Assessment;* ***Ind:*** *Indicators;* ***EA****: Economic Assessment;* ***FLW:*** *Field and Laboratory Work*

Figure 8.11. Main characteristics of the 'EcoBarriSocial' project. ***Source:*** **Adapted from [7].**

Example of one indicator out of the set of 55 environmental indicators defined for the greening of existing residential neighbourhoods

Percentage of buildings that incorporate food production

Definition	It evaluates the percentage of buildings that incorporate any system of building integrated food production (green spaces category).
Variables	o Building with integrated food production systems (either with vegetable courtyards on the roof or balconies) o Total number of buildings
Calculus equation [unit]	$\frac{\text{Buildings with integrated food production systems}}{\text{Total number of buildings}}$ X100 [%]
Desired trend	↑ Ascending
Observations	Urban agriculture can provide food and, at the same time, can raise awareness of the inhabitants' links with nature. It also provides educative and social benefits.
Scope of application	New planning and retrofit actions
Data sources	Building projects (new construction or retrofit)
Scores	Priority: 5/5 (maximum priority) Complexity: 3/3 (minimum complexity) Interest of Adigsa: 1/5 (no interest on this indicator) *Result:* *Discarded*

Figure 8.12. 'EcoBarriSocial' project (figure). ***Source:*** **Adapted from [7].**

6 Energy & water flows in museums

Description
This project studied the energy and water flows in a selection of **15 museums** of different types (art, science and history), taking into account several variables (number of visitors, area of exposition, climatic conditions, opening hours, year of construction, efficiency of the installed equipments, etc.) (Figure 14a).

Aims
To assess the energy and water consumption patterns in museums (Figure 8.14b).

Urban scale: Building

Duration (months): 18

Location and Area
Barcelona province [Spain]
1300-33500 m² of built area

Outcomes of the project

(1) The average energy intensity (not including transportation) of a museum visit is 15.8 kWh. This energy consumption is associated with emissions that contribute to global warming valued at 2.02 kg of CO_2 per visit.

(2) The average water consumption per museum visit is 28.5 L.

(3) Energy and water consumption show a significative strong correlation. Their relationship has been modelled through a power function, which can be useful as a management tool for monitoring and controlling these flows.

Main tools

ED	MEFA	LCA	Ind	EA	FLW
	X		X		

Participating entities
SosteniPrA

Motivation
Commissioned by the Diputació de Barcelona (provincial government)

Role of the author
Co-supervision of a degree project

ED:** *Ecodesign;* ***MEFA*: Material and Energy Flow Accounting,* ***LCA****: Life Cycle Assessment;* ***Ind:*** *Indicators;* ***EA****: Economic Assessment;* ***FLW:*** *Field and Laboratory Work*

Figure 8.13. Main characteristics of the 'Energy and water flows in museums' project. Source: [8].

(a) Image of one of the art museums (MNAC) included in the set of musems under study.

(b) Diagram of the methodology followed for the assessment of energy and water flows in museums

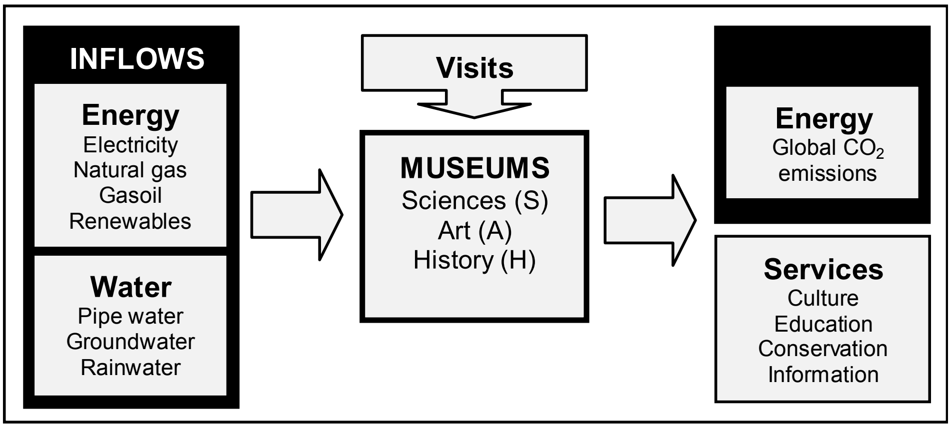


Figure 8.14. 'Energy and water flows in museums' project (figures). ***Source*****: [8].**

8.1. Acting at an early stage of the design of urban systems and monitoring the performance along their life cycle

The inclusion of sustainability criteria and the life cycle approach at an early stage of the design and planning of urban systems is the best strategy for environmental protection. This implies the recognition that each decision taken in the early stages of planning has consequences (social, economic and environmental) on the following urban stages along the life cycle of urban systems.

However, the design and planning of a sustainable neighbourhood does not necessarily mean that the resulting neighbourhood will actually be sustainable. Complementarily, it is necessary to monitor and follow-up the performance of the neighbourhood once it is in use and, when necessary, implement appropriate strategies and corrective measures (e.g. education programmes, efficiency in the use of resources).

[*Chapter 3*]

Planning projects vs retrofit actions

The participation in projects consisting of both the design/planning of new developments (i.e. '*Greater Helsinki Vision 2050*', '*BSost*', '*RWH Mediterranean neighbourhood*', '*EcoPuntVerd*') and retrofit actions in existing urban areas (i.e. '*EcoBarriSocial*') shows the **relevance of being able to act from the early stages of design**. By doing so, it is possible to condition the environmental, economic and social performance of urban systems, and to propose more ambitious strategies (e.g. integrating agriculture and green spaces into the city). Any neighbourhood designed to be correctly integrated with the environmental characteristics of its surroundings will certainly be more efficient and sustainable than another that has not been designed taking these criteria into account [9].

By contrast, **working with existing urban areas reduces the possibilities of action**. Thus, improving their environmental/economic performance is more challenging. All retrofit projects ('*EcoBarriSocial*', '*Energy and Water flows in museums*') lacked environmental protection at the design stage, which can be understood considering the lack of environmental awareness at the moment of their construction. For example, the project '*EcoBarriSocial*' shows that efficiency aspects (i.e. building insulation systems) were not considered when the neighbourhood was built. This was probably the most economical option in the short term, but over the years it has appeared to be more costly during the operation of the neighbourhood. For this reason, Adigsa has had to refurbish the building stock a few years ago in order to insulate façades and roofs.

It has also been observed that retrofitting is generally the result of small unconnected actions that focus on solving particular problems or inconveniences, focusing on short term results (e.g. improving buildings' insulation). However, maybe it would be better to implement a more ambitious general retrofit plan of greater magnitude, not only oriented to short-term results. In this sense, there is a lack of a framework for urban retrofit.

The fact that **Europe** is an old continent with a lot of retrofit to undergo and its limited population growth indicates that **efforts will need to be directed mostly towards retrofitting** (instead of constructing new developments). This supposes an important constraint to the implementation of urban sustainability in our continent, and entails that the possibilities of achieving urban sustainability in existing areas will greatly depend on past decisions beyond the reach of current planners. However, retrofitting with environmental criteria is generally environmentally preferable to deconstructing the whole urban system and building again albeit while considering environmental criteria.

The need to monitor and evaluate urban systems along their life cycle

Along the design and planning process of a neighbourhood, a set of **indicators** should be proposed as a **framework for monitoring and evaluation**. It is necessary to include mechanisms that help follow up the implementation of the planning proposal and that take care of the operation and maintenance of the elements of the urban systems. Monitoring and evaluation are both tools which help us to know when something is not working, and when circumstances have changed. Thus, they are useful for decision making.

However, indicators **are not only useful for monitoring the implementation of new urban settlements, but also for existing urban areas that need guidance in the process of urban redesign or retrofit**. Nevertheless, it has been observed that there is a lack of indicators for this purpose.

The *'EcoBarriSocial'* project**,** commissioned by Adigsa[1], tries to answer this demand by developing a set of indicators for the retrofit of existing social housing neighbourhoods to meet environmental criteria. From the environmental diagnosis of a representative neighbourhood (*Primer de Maig*) and a literature review, a list of potential indicators was developed for the following categories: energy, wastes, water, public spaces and social aspects, biodiversity/green areas and transport. In order to prioritize a reduced number of environmental indicators, each potential indicator was characterized and scored according to two main criteria:

- **priority** (which integrates reliability, understandability, appropriateness, relevance and selectiveness)

---

[1] Adigsa is the public company in charge of social housing in the region. Its housing stock ascends to 86 000 dwellings [10] Adigsa. Distribució comarcal del parc d'habitatges d'Adigsa. Unpublished. In: SosteniPrA, editor.2009.

- **complexity** (feasibility and cost-efficiency)

Then, Adigsa made a selection of indicators, considering the given scores and their own criteria. Although the scope of the project was at the neighbourhood scale, the approach of the client was mostly circumscribed to buildings, probably because its goal is to provide housing (but not green areas or public spaces, which tend to fall in the realm of local government). Besides, Adigsa prioritized the more conventional-looking indicators, mostly related to energy and water. Thus, indicators regarding green areas and public spaces were excluded from the selection (for example: percentage of buildings that incorporate food production, or percentage of buildings with communal spaces - meeting rooms, communal laundry, cycle storage room, etc…-) (see Figure 8.12 for an example of an indicator). This demonstrates that **it is costly to change the preconceived ideas and to open the opinions and attitudes of practitioners and, above all, policy-makers**, particularly when dealing with existing urban systems. For this reason, demonstration actions would be necessary to change the mind of the decision-makers and allay their fears.

The conventional approach in the selection of environmental indicators for neighbourhood retrofit actions constrained the scope of the final selection, losing the chance to include certain interesting strategies in the company's retrofit policies. However, it worth highlighting that Adigsa merits recognition for being aware of the need to establish a mechanism for decision making and for its audacity to incorporate a set of environmental indicators to guide its retrofit policies. This attitude may be also a sign that there is a political will to solve the problems and take actions towards sustainable urban policies.

Implementation of indicators

Indicators can be used to show progress over time and inform policy decisions. However, sometimes **the complexity of obtaining data makes their follow-up uneasy.**

A practical example of this difficulty is exemplified by the project '*Energy and water flows in museums*'. This project managed to quantify the energy and water intensities of a visit to a museum (following the steps from the research on RP, chapters 4 and 5). However, most facilities were not aware of their energy/water consumption since it is commonplace that energy/water invoices are managed by the department of finances, which may not be directly linked to the museum manager. In addition, it was necessary to collect data on the number of visits to the museums, since indicators need to be related to the function provided by the system (energy and water used to satisfy the needs of a visit to a museum).

Eventually, it was possible to assess energy and water flows for a selection of museums. This project brought in a very interesting result in the context of aiding the procurement of data. It was found that there was a significantly strong correlation between water and energy consumption in museums (Figure 8.15). Therefore, this regression model could be very useful to forecast the value of one of the variables should information only be available on the other. This is relevant since water consumption data is much more accessible than that of energy, especially when different energy carriers (electricity, natural gas, gasoil) are involved.

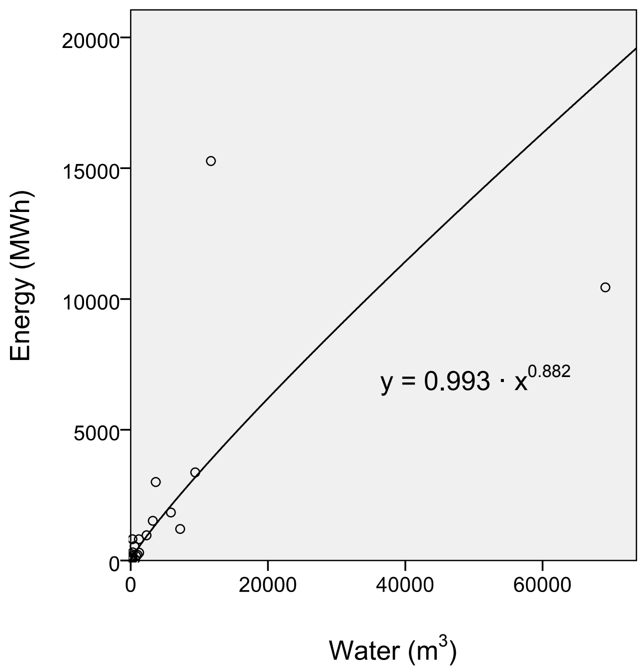


Figure 8.15. Regression model between energy and water for the selection of museums. ***Source*: [8].**

8.2. Interdisciplinary team and sufficient understanding of the local context

> An interdisciplinary design team is of great value and it is essential in urban planning. This team should have sufficient understanding of sustainable design practices, constraints, existing conditions and specifications. Thus, it is important to take into account the local context (site specific characteristics and given conditions) for the design and planning of sustainable settlements.
>
> [*Chapter 3*]

The collaboration in interdisciplinary teams has proved to be successful. It can be stated that the concepts, tools and strategies presented hereby have been understood and integrated by them. At the same time, we have been able to feedback the research in course, which is useful to facilitate its application and transference towards real projects.

The consensus was generally easier when working at the conceptual level (i.e. *'Greater Helsinki Vision 2050', 'BSost'*) **compared to the planning level** (i.e. *Vallbona neighbourhood, 'EcoPuntVerd'*). Although the projects developed at the conceptual level may not be actually put in practice, the process of team working was constructive for the whole team (architects, engineers, farmers, health practitioners, environmentalists, geographers…). From this, it is expected that each of the team members will introduce and reproduce these concepts in his/her day-to-day working activities.

However, it is clear that interdisciplinary team working alone does not always lead to favourable results. An example of this is the proposal for *Greater Helsinki*, which was inadequate according to the competition jury. Today, we would affirm that the **interdisciplinary team failed by not paying enough attention to the analysis of the territory and reference elements,** which is a basic step within the ecodesign methodology (see section 2.3.5). We lacked knowledge of the territory and this ignorance led to the failure to propose architectural solutions that did not suit the way of living in Finland.

By contrast, the projects *'EcoPuntVerd'* and *'BSost'* succeeded and are great examples of practical transition towards sustainability. One of the major assets of the teams was the familiarity with the local context. As a consequence, for instance, the conceptual proposal that was prepared within '*BSost'* for the *Sant Andreu neighbourhood*, which was similar in conceptual terms to the one in the competititon '*Greater Helsinki Vision 2050*' for *Greater Helsinki*, caused a positive impression on local authorities and local experts in the area, and was positively accepted in several forums of experts (e.g. in the two last Ecocity conferences, held in Melbourne [4] and in Istanbul [2]). The difference in acceptance of both proposals, similar in content, empirically demonstrates that sustainable urban development is a process which will necessarily vary between cities [11] since **there is not a uniform solution for sustainability** [12]. Thus, the design of sustainable neighbourhoods in different economic, social, technologic and geographical locations can have very disparate formal results, due to the different requirements and priorities of each site [9].

What professionals dominate the teams?

After working in several interdisciplinary teams, the general feeling is that environmentalists (a category in which I include myself) have been taken into account and their discourse has been considered seriously. However, there is a slight impression that **the neighbourhood and building scales are mostly the arena of architects and engineers**. This can be explained because these professions are the ones with competences to sign projects and are, ultimately, responsible for their contents. Therefore, society has transferred the responsibility to these professions. This situation may give them a capacity of leadership within interdisciplinary teams. As a result of this, in case of disagreement, they may have to take the final decision according to their preferences.

This can be exemplified with the design of a Waste Collection Point (WCP) (*'EcoPuntVerd'* project). This experience, which is a good example of ecodesign and interdisciplinary team working, presents some evidence of the leading role of architects in projects at the building scale. Within the team there were differences regarding the preferable size of the WCP. Smaller sizes (i.e. 50m^2) would facilitate its reproduction in many parts of the city, avoiding problems of availability of space; while bigger ones (i.e. 140m^2) would entail more leeway to incorporate all necessary services into the infrastructure and also make it more impressive. Eventually, this was a decision to be taken by architects, since they had the professional competence to present the proposal to the council.

8.3. Mixed land uses, high-density of the built-up area and self-sufficiency

Urban metabolism and mixed land uses: closing loops

> Urban metabolism has been established as an appropriate approach for assessing the sustainability of cities. The study of the flows of materials and energy makes it possible to move from a linear system to a more closed system.
>
> With this aim, the mixticity of uses is essential in order to foster synergies and close material and energy loops within neighbourhoods, and also to reduce the need to travel.
>
> [*Chapter 3*]

The ideas of urban metabolism and mixticity are the basis of the discipline of IE, which aims to study the 'flow' of all resources through an entire identified socioeconomic system with a view to strategically optimising their use [13, 14]. In this sense, it would be necessary that **urban systems integrate four central nodes** (the material extractor or grower –**agriculture**-, the materials processor or manufacturer –**industries/services**-, the consumer –**people**-, and the waste processor –**waste management facilities**-) to perform their operations within the nodes in a cyclic manner within the entire urban ecosystem (Figure 8.16) [15].

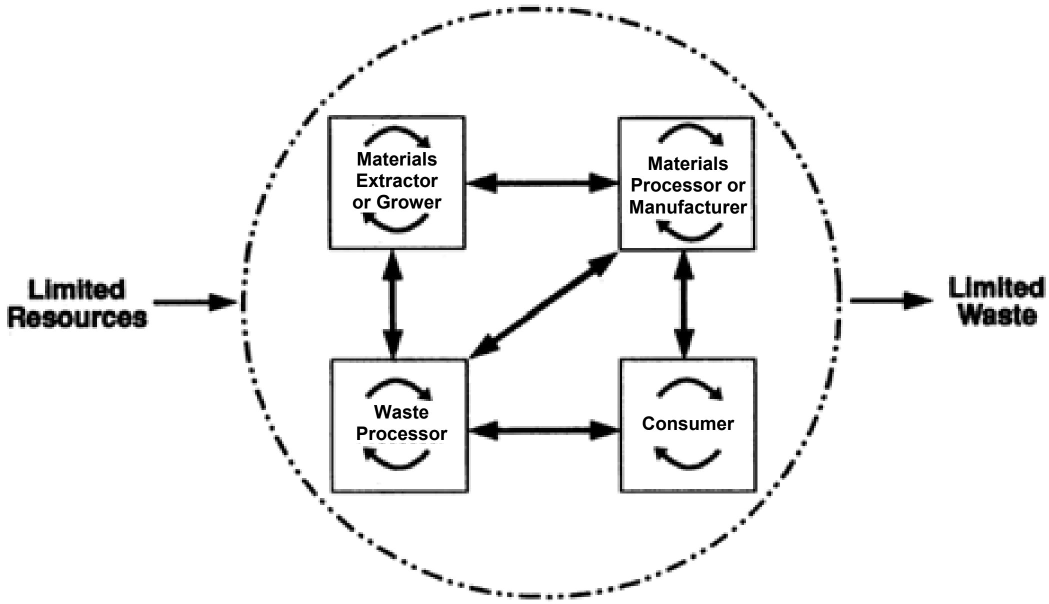


Figure 8.16. Mixed land uses, integrating the four central nodes, allows synergies within urban systems. ***Source*****: [15].**

Therefore, it would be useful to define a kind of strategic blueprint, which creates the right combinations of industries, infrastructure, technologies, skills, resources and legal frameworks to encourage IE to develop [16], the synergies of which should be fostered not only within the neighbourhood but also taking into consideration the vicinity. In addition, it is recommendable to foster the extensive use of environmental technologies for water, energy and waste management in order to have locally closed loop systems, which is one of the key principles for sustainable city development [17]. For this reason, **planning policies should move towards a mixticity of land uses**.

This approach was strongly present in the conceptual proposal for the *Sant Andreu neighbourhood* (*'BSost'* project). It has been useful as a team exercise to understand how the metabolism of neighbourhoods works. In this sense, it is encouraging how architects have introduced this concept in urban planning and design. Regarding the mixticity of land uses, for instance, agriculture was integrated within the city as a primary land use. This presented many benefits, among which: production of local food, absorbing the compost made with local organic wastes, employment of people, visualization of a tempo in the city (live landscape), enhancement of social values and pedagogy, and reduction in transport demands. However, it is not always possible to incorporate mixed uses of land. For example, in the design of Vallbona, legal constraints limited the leeway of planners (the restrictions of the SRA limited uses other than residential to 10% of the built area).

High density of the built-up area

Urban form (spatial pattern of land uses and their densities, and spatial design of transportation and communication infrastructures) is a determining factor in order to set up a sustainable settlement. It is accepted that sustainability in its broadest sense is much more difficult to imagine in a dispersed settlement than in a compact city. For this reason, it is important to achieve a high density of the built-up area.

[*Chapters 3 and 4*]

A high density of the built-up area is important since it means less land being devoted to sprawl and more land for open space, gardens, urban agriculture and forestry within the neighbourhood, fostering the mixticity of land uses. For example, the proposal in '*BSost*' project, which considered a density of 24 000 inhabitants/km^2 -similar to the average density in many districts in Barcelona-, concentrated the built-up area in 57% of the neighbourhood area. This made it possible to keep 22% and 21% of the area entirely for agriculture and parks, respectively (Figures 8.6 and 8.17).

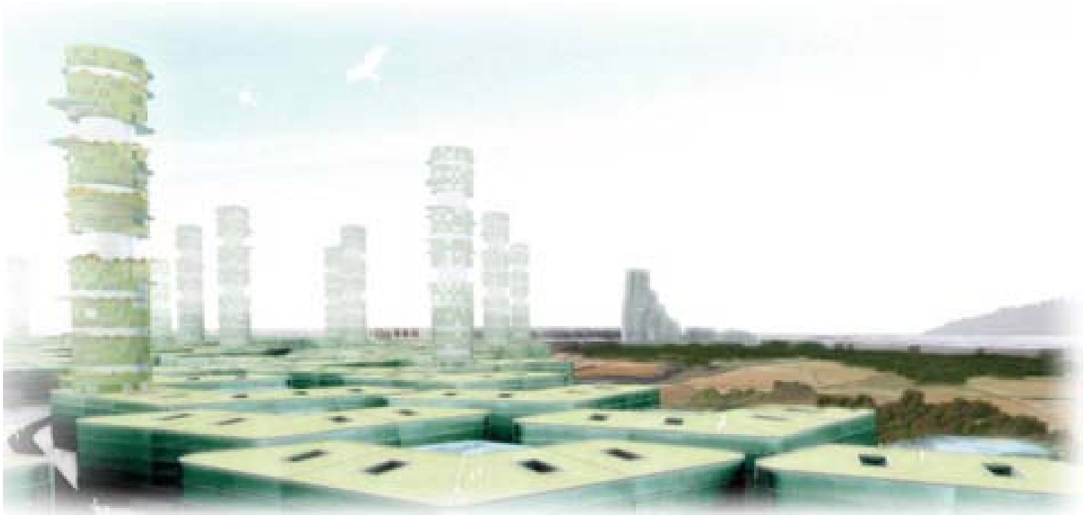


Figure 8.17. Render drawing of the Sant Andreu proposal. A dense occupation of the built area (on the left) makes possible to have vast areas for agricultural purposes (on the right). ***Source*****: [2].**

Both ideas (land use mixticity and dense occupation of the built area) have been useful in order to reduce transport demand, as observed in '*Greater Helsinki Vision 2050'* and *'BSost'* projects. Moreover, this reduction can be further enhanced if neighbourhoods are designed so as to facilitate access to public transport systems and to promote non motorized means of transport, and if the distribution of urban growth is located around existing and proposed transport networks.

Towards self-sufficiency

The desire of resources self-sufficiency in urban areas should be a premise for any sustainable settlement, understood as the ability to supply the neighbourhood with those local resources that have potential within the area. The use of environmental indicators can be helpful for the design and planning of urban systems aiming at self-sufficiency.

[*Chapters 3 and 5*]

The '*BSost*' project presents a great example of aiming at resource self-sufficiency, mostly thanks to the mixticity of uses. Although all balances and estimations were made at the conceptual level, it is heartening to see the **high degree of potential self-sufficiency** that could be achieved **by means of closing loops** within urban systems (Figures 8.18, 8.19 and 8.20). This potential self-sufficiency has been estimated with indicators of food, energy or waste management self-sufficiency, inspired in the PWSS indicator. All of them are understood as the ratio between the neighbourhood potential of provision of a resource or activity and its total demand.

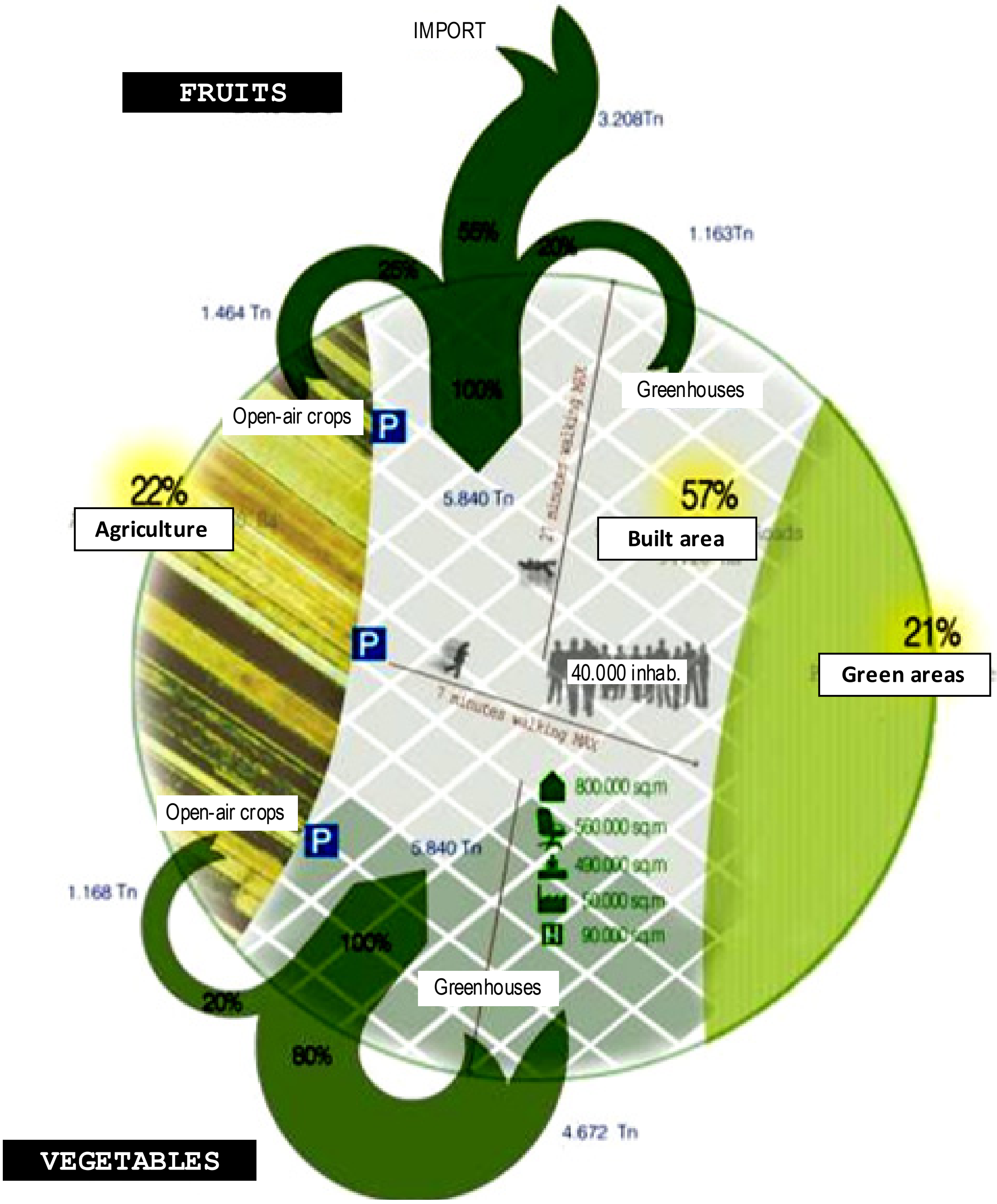


Figure 8.18. Food flows in the design of the *Sant Andreu* neighbourhood. Vegetables and fruit would be produced in the open-air and in greenhouses on top of the buildings. Vegetable and fruit self-sufficiency is estimated at 100 and 45 %, respectively. *Source*: [2].

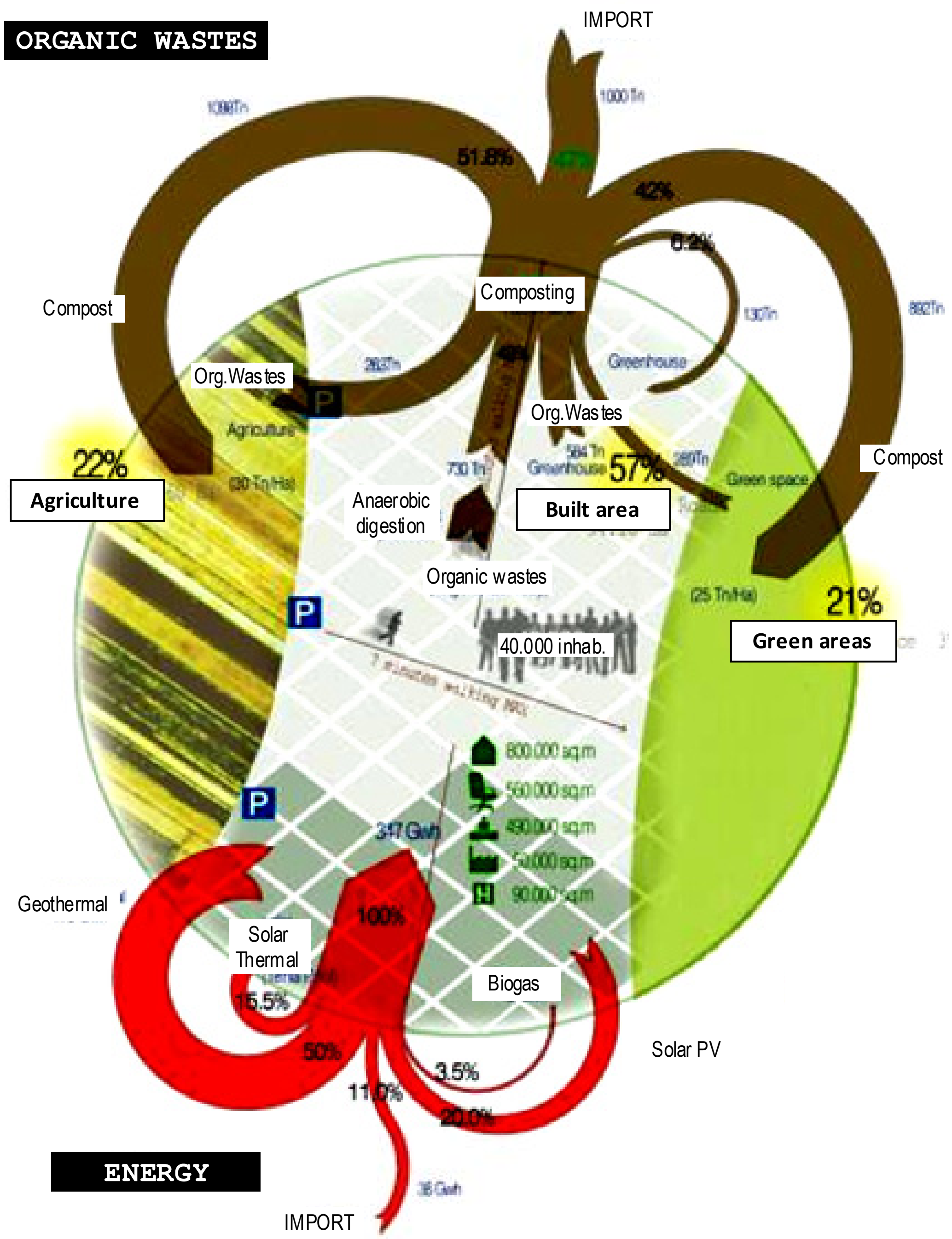


Figure 8.19. Organic waste and energy flows in the design of the *Sant Andreu* neighbourhood. Organic wastes would be composted and used in the green and agricultural areas. Geothermal energy would be the main supply, complemented with solar photovoltaic and solar thermal energy. Energy self-sufficiency is estimated at 89%. Compost self-sufficiency is estimated at 53%. *Source*: [2].

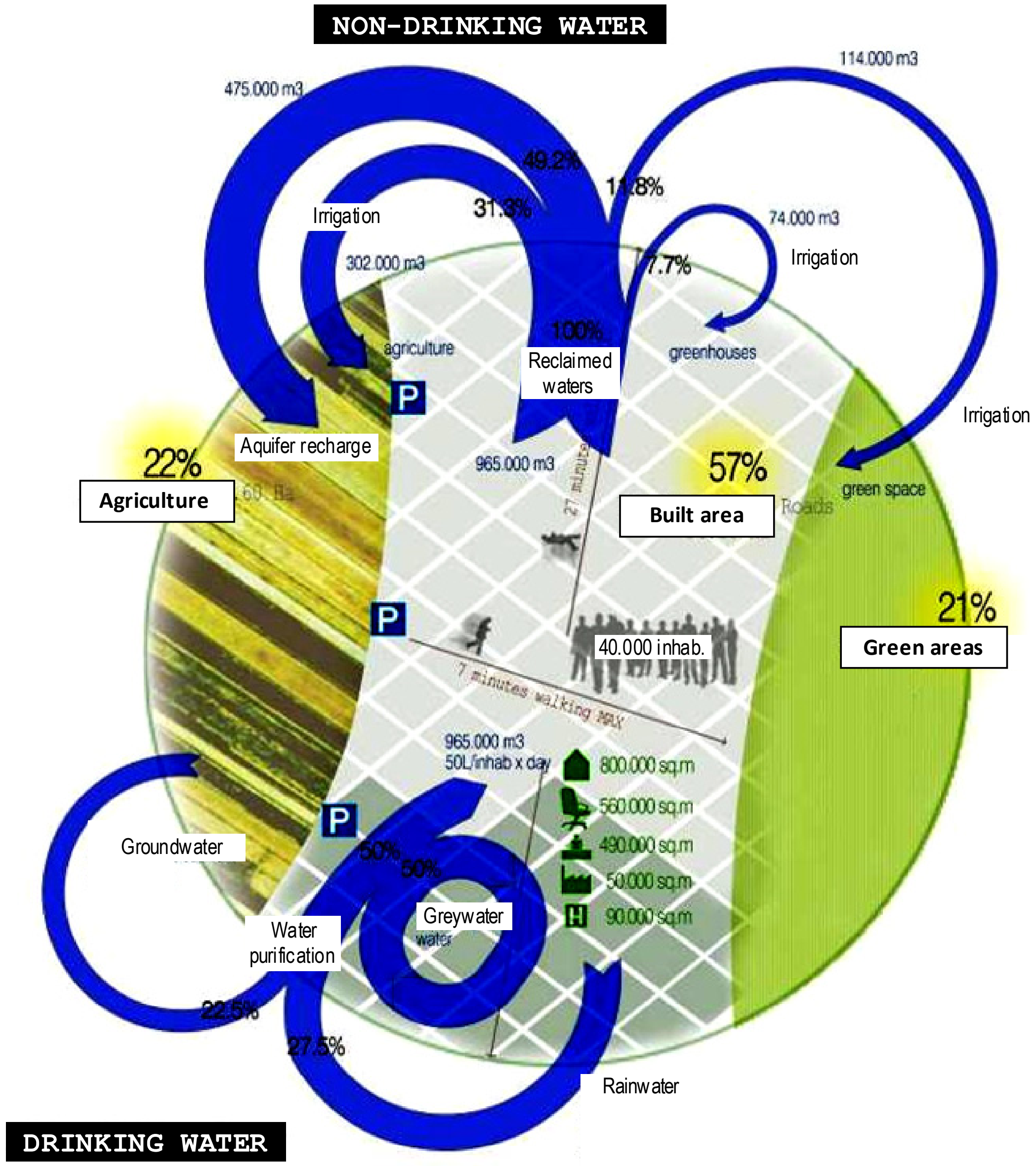


Figure 8.20. Water flows in the design of the *Sant Andreu* neighbourhood. Rainwater would be collected from roofs and paved areas, and used for outdoor and indoor purposes. Groundwater would be used to supply domestic needs. Greywater systems would be installed in all households. Water self-sufficiency is estimated at 100%. *Source*: [2].

Rainwater harvesting and water self-sufficiency

RWH has been proposed at many levels as a means of closing loops within the urban water cycle. The use of stormwater runoff can reduce external imports of pipe water and also outputs of sewage water. The PWWS is an indicator than can detect which systems have a potential of water self-sufficiency by means of RWH.

Once the potential is detected, it is necessary to foster the extensive use of environmental technologies for water, energy and waste management in order to have locally closed loop systems. These technologies should be assessed in environmental, economic and social terms.

[*Chapter 5*]

The strategy of RWH can achieve important reductions in the external dependency of urban systems, as a means of closing loops. In order to estimate it, the first step **is to assess the potential of RWH by means of the PWSS indicator, which is easy-to-calculate** since it only requires data about water consumption (invoices), catchment areas and rainfall pattern. The indicator has been applied on different scales (city, neighbourhood or building level) in the different projects (*'Helsinki, 'BSost', 'RWH Sitges', 'EcoBarriSocial', 'EcoPuntVerd'*). Among these, the project *'RWH potential of a Mediterranean neighbourhood'* has presented the most comprehensive opportunity to apply the PWSS indicator to the residential neighbourhood level. In this case, the city council commissioned the assessment of the PWSS under different scenarios of water demand, rainfall and architectonical features, resulting in a self-sufficiency matrix. The eventual planning proposal included RWH for irrigation purposes.

Once the self-sufficiency of a given system is estimated, the next step is **to design the necessary technologies to put these concepts into practice, and assess their feasibility (economic, social and environmental).** This would require the integration of objective quantitative assessment methods and tools (i.e. LCA, LCCA) into the design and planning of urban systems, in order to turn concepts into environmentally and financially feasible technological options.

8.4. Availability of data and criteria for urban ecodesign

> Access to information is crucial to the decision-making process. During the design and planning of a neighbourhood many decisions need to be taken according to certain prevalent criteria. Therefore, it is necessary to improve access to environmental, economic and social data, in order to manage global environmental threats under the "life-cycle thinking" approach.
>
> [*Chapter 3*]

During team work, architects, practitioners and policy-makers frequently asked us for criteria in order to justify their decisions regarding the 'sustainability' arena ahead of the community and society policy-making. Some examples of the questions raised, and which this dissertation tries to answer, are presented next. Many other questions were raised, but they are not presented here since they are out of the scope of this dissertation. Working together with architects, practitioners and policy-makers made it possible that our research results fed and enriched the discussion in which we were involved.

8.4.1. What is the rainwater harvesting potential of a system?

This question was raised in most projects ('*Vallbona*', '*BSost*', '*RWH Mediterranean neighbourhood*, '*EcoPuntVerd*', '*EcoBarriSocial*', '*Greater Helsinki Vision 2050*') when we exposed the need to harvest rainwater as a means of reducing water imports and increasing self-sufficiency.

One of the main worries in taking the decision of including RWH systems was the quality of stormwater runoff. Hence, it was necessary to demonstrate that runoff quality was acceptable for the uses in which it was intended for. This was particularly important since it was found that some local governments (i.e. the city council of Barcelona) disliked the idea of using rainwater for domestic uses because of the fear about its quality. This question set up the base of the research presented in Chapter 6, in which the quality of roof runoff is investigated.

On the other hand, no architect was worried about the selection of a certain slope having an effect on runoff. However, Chapter 6 demonstrates how the selection of sloping smooth roofs implies a global WHP approximately 50% greater than flat rough roofs. This idea was incorporated in the project '*RWH Mediterranean neighbourhood*', where the WHP was evaluated considering different types of roofs.

With city planning policies that could establish guidelines regarding the slope and roughness of roofs (both for the existing city and for new developments), stormwater roof runoff could be promoted both in terms of resource availability and quality. Thus, sloping smooth roofs, which have proved to perform best, may be preferable in order to foster RWH. This has an important significance for local governments and urban planners in the design and planning of cities.

[*Chapter 6*]

8.4.2. What is the preferable scale of implementation of RWH systems?

This question was raised in some of the discussion in interdisciplinary teams (e.g. *Vallbona*). Defining the most adequate scale for environmental technologies is quite challenging, since there are many alternatives to centralized systems.

This dissertation answers this question focusing on economic criteria, since economic studies regarding the design and implementation of policies for the efficient management of water resources are a necessity that is increasingly recognized [18]. Our experience shows that financial aspects are a limiting factor in the design of urban systems: budgets are limited and they are generally dimensioned for business as usual planning strategies, as observed in *Vallbona*, where the neighbourhood proposal had to be circumscribed within a traditional cost-benefit analysis. Given the importance of economic aspects, Chapter 7 deals with the cost-efficiency of RWH strategies.

RWH strategies should be preferably installed at the neighbourhood level, since it enables economies of scale. Besides, they should ideally take place at the moment of settlement construction.

[*Chapter 7*]

Chapter 7 also highlights the need to expand economic assessments in order to include the externalities created by the implemented technology. If not, there is greater risk to rule out options such as RWH because of financial criteria. However, **RWH strategies could be financially profitable if environmental externalities were included in the analysis**.

Nevertheless, it needs to be highlighted that more environmentally friendly urban systems (buildings, neighbourhoods, cities, etc.) are not necessarily more expensive to implement. The '*EcoPuntVerd*' project presents an example of a good environmentally-friendly design, without being more expensive, even in the short term.

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PART VI

General conclusions and future actions

Chapter 9.

CONCLUSIONS

This dissertation presents and develops strategies and tools that could aid in the transition towards urban sustainable settlements, with special attention paid to energy and water. We are now in a position to address the formulation of a list of general conclusions. Thus, Chapter 9 draws the general conclusions, based on the extended conclusions presented in Chapters 3 to 7 and the discussion presented in Chapter 8[1].

[1] The first time that an acronym or abbreviation appears in this chapter it is written in full in order to facilitate the reading of the chapter as a standing-alone document.

9.1. Energetic metabolism of a commercial service neighbourhood

- **It is crucial to consider transport in the energy assessment of the service sector.** It is argued that the environmental impacts of customer transport are not irrelevant and should be chargeable to the service activity**.** In the Spanish retail park (RP) case study, transport energy demand (based on private car) accounts for three quarters of total energy consumption and three fifths of greenhouse gas (GHG) emissions.

- **Energy and GHG emission intensity indicators highlight the role of service systems in the struggle to reduce GHG and global climate change.** The energy and GHG emission intensity of a purchase in the RP object of study is estimated to be 1.64 KOE and 9.26 kg equivalents of carbon dioxide (CO_2eq) per purchase in year 2006. Therefore, energy consumption and emissions from service systems are not irrelevant, despite being overlooked so far.

- **The establishment of indicators** of intensity of energy use, as well as of environmental impact, **can be useful as a mechanism for the monitoring of urban systems**. However, the complexity of obtaining data sometimes makes their follow-up difficult.

- There exists a **high potential for reduction of energy consumption and GHG emissions in RP**. Urban planning strategies alone, affecting the location of the service provider facilities and the mixticity of land uses, could reduce GHG emissions by approximately 40% in the case study RP. Furthermore, the combination of planning strategies with efficient equipment in buildings, renewable energies and behavioural changes affecting the transport modal split could reduce emissions further, to over 50% compared to the base case. Therefore, **the combined implementation of strategies at the planning and management levels** could contribute significantly to **improve the environmental performance of service and urban systems**.

9.2. Water metabolism of a commercial service neighbourhood and rainwater harvesting

- Many urban systems, characterized by high total impervious fractions, do not take advantage of stormwater runoff and convey it through sewage systems. However, **the use of rainwater resources could bring many benefits to urban systems**, among which highlighted the prevention of flooding, stream degradation and water scarcity, and climate change mitigation as well. Rainwater harvesting (RWH) is particularly advisable in urban systems such as RP, because they have wide availability of catchment areas and there is a park manager.

- Water consumption of urban systems should be measured not only in absolute terms but also in relative ones, in order **to allow for comparisons** between different systems. Understanding that **each urban system has a given function** -speaking in broad terms- (i.e. providing a place of residence in residential neighbourhoods, producing a unit of product in an industrial state, offering a purchase in a RP), **the efficiency in the use of resources can be measured with indicators of intensity of use**. In the case of retail systems, water demand is measured by means of the water intensity of a purchase (WIP) indicator. The obtained values (8.0 and 22.9 L/purchase in the Spanish and Brazilian case studies, respectively) indicate that the **water demand of commercial neighbourhoods is not irrelevant**.

- The **potential rainwater supply of urban systems** can be calculated by means of the water harvesting potential (WHP). In order to estimate it, it is necessary to take into account both the local rainfall pattern and the availability and characteristics of catchment areas (slope, roughness, runoff coefficient (RC)).

- **The Potential Water Self-Sufficiency (PWSS) indicator has a role in identifying the potential water self-reliance by means of RWH**. Its application in two RP case studies demonstrates the capacity of rainwater resources to supply the water demand of these systems, both in conditions of limited rainfall, as in the Spanish case study (PWSS=3.0), and in conditions of inefficient use of water, as in the Brazilian case study (PWSS=1.4).

- **The establishment of indicators** of intensity of water use, as well as of water self-sufficiency, **can be useful as a mechanism for the planning, design, evaluation and monitoring of urban systems**. However, sometimes the complexity of obtaining data makes their follow-up difficult.

- The results obtained in the **analysis of energy and water** consumption in the service sector are **useful for formulating environmental policies** in this urban subsystem.

9.3. Roof selection for rainwater harvesting: quantitative and qualitative assessment

Quantitative assessment

- **There is a lack of awareness of the implications of the selection of a roof on the potential for RWH**. However, its slope and smoothness affect its RC. Then, certain roof types (e.g. sloping smooth roofs) may harvest up to 50% more rainwater runoff than others (e.g. flat rough roofs). This can be useful in order to maximize rooftop runoff conveyance to rainwater tanks (by means of selecting sloping smooth roofs) or to minimize runoff and reduce peak flows (flat rough roofs). Therefore, **roofs are no longer only about providing shelter and building protection but also about rainwater collection and regulation of input flows to urban areas.**

Qualitative assessment

- **Rooftop runoff physical-chemical quality from the case study area (eastern Spain) is acceptable** (it is in the low range for Electrical Conductivity (EC) (85.03 ± 9.98 μS/cm), Total Suspended Solids (TSS) (5.98 ± 0.95 mg/L) and Total Organic Carbon (TOC) (11.56 ± 1.72 mg/L); it has basic pH (7.59 ± 0.07)) and appears to be generally better than the average quality found in the literature review from other regions.

- **Differences in runoff water quality are significant between sloping smooth and flat rough roofs,** the latter presenting higher levels of all pollutants (except for Total Ammonium Nitrogen, TAN) due to more accumulation of particles and greater interaction between rain and roof materials.

Urban design and planning

- These results provide **criteria for the design and planning of cities**, and are relevant to answer one of the main worries in taking the decision of including RWH systems, which is stormwater runoff quality. Besides, they may be helpful for reducing water dependence in water scarce areas by maximizing runoff availability. In this context, **the establishment of guidelines regarding the slope and roughness of roofs** could condition the possibilities for RWH, being sloping smooth roofs preferable both in terms of runoff quality and available quantity.

9.4. Cost-efficiency of rainwater harvesting strategies in dense neighbourhoods

- **The cost-efficiency of RWH strategies in dense Mediterranean neighbourhoods,** both at the building and neighbourhood levels, **may be put in doubt because current local water prices are so low** (i.e. 1.12€/m³ for domestic supply in Spain in 2010). However, it is expected that RWH strategies could be financially profitable if environmental and social externalities were included in the analysis.

- An **increase in mains water prices may foster the interest on RWH strategies from an economic point of view**, since the first economic incentive of RWH systems is the substitution of mains water consumption by rainwater. If the discount rate (r) is not considered (r=0%) is considered, a mains water price of 1.86 €/m³ would be enough to make RWH cost-efficient in the case study neighbourhood.

- **In the context of water scarcity** (which could worsen in future years not only because of climate change effects but also because of an increase in population and/or consumption per capita), and despite limited economic performances of RWH strategies, the small household capital costs make **it advisable to promote RWH infrastructures.**

- **RWH strategies should be preferably installed at the neighbourhood level** (particularly when compared to the building one), since it enables economies of scale. For this, it would be advisable to have a neighbourhood manager responsible for collective resources such as stormwater runoff.

- **Capital costs are further reduced if RWH infrastructures are incorporated at the design and planning stage** of urban systems. In the case study neighbourhood, it would imply an increase of the Net Present Value (NPV) of 16% at the neighbourhood scale over the lifespan of the infrastructures (0% discount rate, future water price 4€/m³) or it may be even determinant in making these infrastructures profitable or not (3% discount rate, future water price 4€/m³).

9.5. Opportunities and constraints in the design of neighbourhoods

- New approaches and tools for the design and planning of urban systems are necessary. The **ecodesign methodology,** initially conceived for the design of goods and products, **can be successfully applied to the design of neighbourhoods**. The major asset of this methodology is the **incorporation of environmental criteria along the whole life cycle** of the neighbourhood. Other aspects relevant to this methodology are the initial analysis of reference elements and the analysis and assessment of improvements of the final ecodesigned product (neighbourhood).

- The **incorporation of environmental principles in the design of neighbourhoods is important** because many of the problems encountered on the macro-city scale are in fact cumulative consequences of poor planning at the micro-neighbourhood level. Neighbourhoods represent an adequate intermediate scale for action. In addition, most of these **decisions are well within the reach of local governments** and leaders.

- **A list of territorial, financial, technical/methodological, political, legal and social-cultural determining factors in the ecodesign process** of the Vallbona neighbourhood case study has been obtained. These factors condition the possibilities of giving rise to a sustainable neighbourhood. Therefore, it is argued that **the design of neighbourhoods in different locations will lead to different results,** without the existence of a unique path to achieving urban sustainability or a uniform solution.

- **Several constraints in Vallbona** challenged the ecodesign process. Among these, the **set of regulatory determinants,** affecting the mixticity of land uses, **and economic factors** limited the leeway of the planners. In contrast, **several opportunities** were decisive to counteract the barriers, such as the **territorial factors** (availability of local resources; urban form, urban fabrics and density of the region) and to a lesser extent, the **political factors**.

9.6. Transfer of knowledge

- **The following key methodological ideas** should be considered along the eco(re)design of sustainable neighbourhoods and urban systems:
    - **Acting at an early stage** of the design makes a difference, but it is still **necessary to monitor and assess the performance of the neighbourhood** along its life cycle, for which indicators .
    - There is a need of an **interdisciplinary team** and of sufficient understanding of the local context.
    - The concepts **of land use mixticity**, **high-density of the built-up area**, urban metabolism and **self-sufficiency** should be incorporated in the design.
    - Access to information and **criteria for urban ecodesign** is crucial in order to take the most appropriate decisions.

- There is **greater leeway in planning than in urban retrofit**, since working with existing urban areas reduces the possibilities of action. On the other hand, the consensus within interdisciplinary teams is generally easier when working at the conceptual level compared to the planning level, since the **planning process generally takes place in a complex institutional frame** with a large number of public and private actors, each of them with their own interests and responsibilities.

- **A lack of practical experiences related to innovative solutions** (i.e. local composting plants, greenhouses on roofs, rainwater reuse systems) **scares planners** and particularly politicians into taking on innovative "risky" strategies. For this reason, **demonstration actions are** sometimes **necessary** to change the mind of the decision-makers and allay their fears.

Chapter 10.

FUTURE ACTIONS

Chapter 10 compiles some of the most general lines of action that could be followed after this dissertation, according to three main areas of attention. Each area presents future actions towards the implementation of some of the outcomes of the research and/or the expansion of the research to other aspects of interest (Figure 10.1).

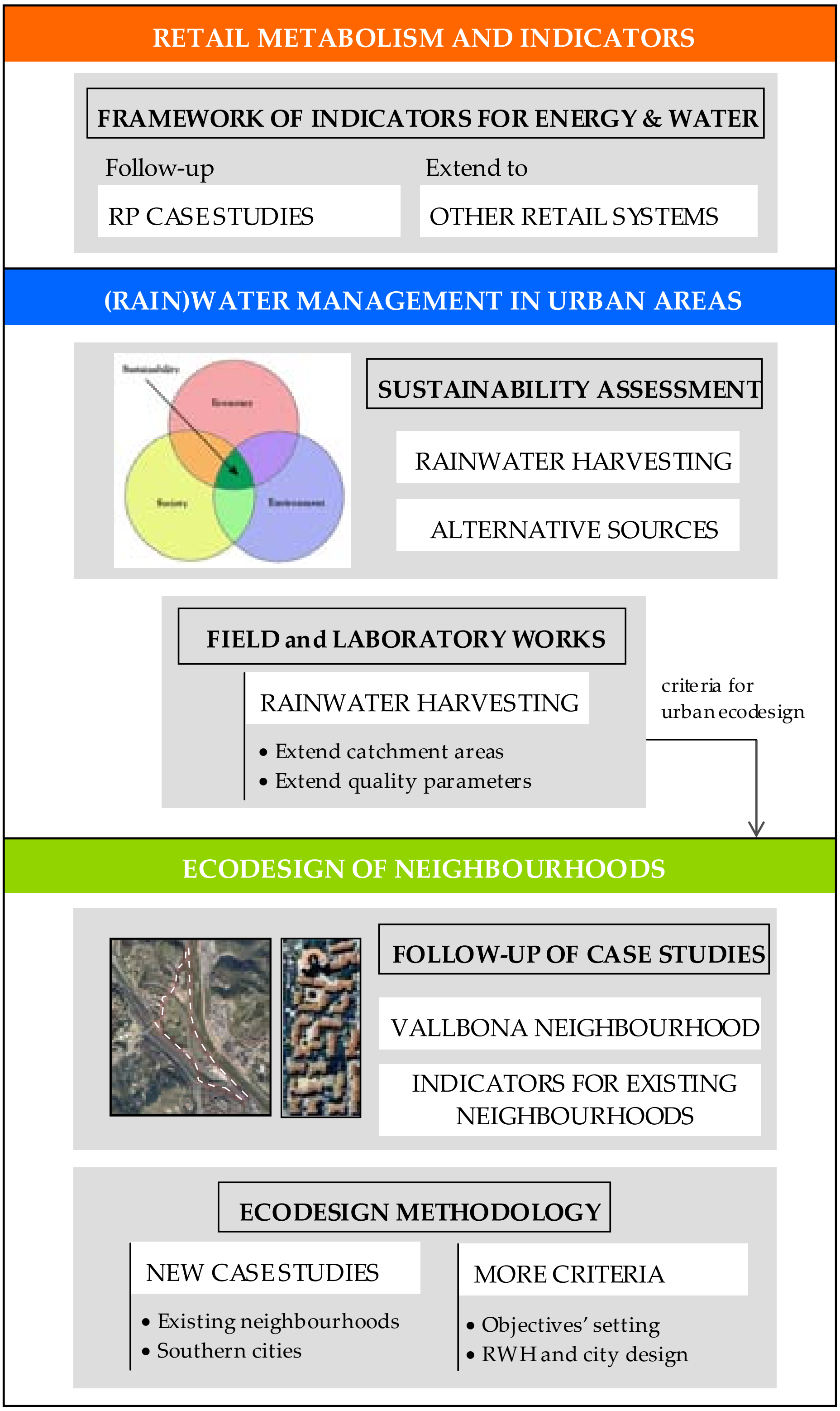

Figure 10.1. General diagram for the future actions after this dissertation.

10.1. Retail Metabolism and Indicators

- **Follow-up the framework of energy and water indicators** presented in chapters 4 and 5 in the RP case studies, and **apply it to other RP** in order to check the methodology and obtain values of water, energy and GHG emissions intensity for the sector, which will be useful for benchmarking.

- **Extend the framework** of indicators **to the several existing shopping formats** (i.e. RP, shopping centres, malls, markets, free-standing stores) in order to provide criteria for planning policies in relation to shopping and the retail sector. To do so, it would be necessary to define what the composition of an average total RP shopping basket is, since it might vary greatly between the various shopping formats.

- **Extend the methods, tools and approaches to other neighbourhoods**, and in particular, to service systems (i.e. business parks, public facilities parks, etc.), since there is a lack of environmental data for the sector. The environmental assessment of the service sector, although representing around 70% of gross domestic product in most developed countries, has been mostly overseen by the research literature.

10.2. (Rain)water management in urban areas

- **Assess the environmental, social and economic performance of RWH techniques**, in order to take into account the three sustainability pillars:

  - **Economic assessment.** Expand the economic analysis in order to include the externalities caused by RWH (i.e. flood prevention, diminution of stream degradation, extra water reliability, educational benefits). Include also the effects on the infrastructures of the whole urban water cycle (reduction of water supply infrastructures, downstream stormwater conveyance and treatment systems and alternative water supply infrastructures).

  - **Environmental assessment.** Assess the environmental performance of the proposed infrastructures, by means of the application of quantitative life-cycle objective methodologies, such as LCA. This approach has already proved to be useful in the assessment of the infrastructures for RWH in diffuse and compact urban areas.

  - **Social assessment**. Study, on one hand, the social acceptance of RWH technologies and, on the other, the administrative obstacles that will arise so as to promote RWH at the building and neighbourhood level and the planning procedures in order to incorporate it into current and future urbanisation schemes.

- **Link environmental and socioeconomic assessments** by means of novel approaches that aim to integrate tools. An example is the **combination of LCA and Data Envelopment Analysis (DEA)**, useful in order to identify which are the most eco-efficient options (eco-efficiency is a concept applied to judge the combined environmental and economic performance of product systems). Another example is the **MIVES (Integrated Value Model for a Sustainable Assessment)** methodology, which procures the integration of environmental, economic and social criteria by means of breaking up the different parameters of evaluation, defining a model that is able to be weighted for each of the alternatives, into a dimensionless quantity called value.

- **Compare** the environmental, social and economic impacts of **RWH** systems with the ones of current conventional water supply systems (**mains water**) and also to the **alternative non-conventional water supplies** (desalinated water, reclaimed water, greywater).

- **Extend field and laboratory works** to expand on the quantitative and qualitative assessment of RWH. Thus, future research will focus on the **quantitative and qualitative assessment of stormwater runoff from other**

types of roofs (i.e. wood shingles, composite shingles, corrugated fibrocement, slate roofs, flat concrete roof) as well as **different rainwater catchment areas** (pedestrianized streets, car parks, motorized streets, roads and motorways, ports and airports) in order to cover the most common potential catchment areas. It will also be of interest to incorporate the analysis of bulk rainwater quality, as well as an **extension of the water quality parameters** analysed, in order to incorporate microbial contamination as well as hydrocarbons and heavy metals.

10.3. Ecodesign of neighbourhoods

- Follow-up the implementation of the planning proposal in Vallbona. This includes the last stages of the ecodesign methodology; namely, the **neighbourhood analysis and the assessment of improvements**.

- Study how the several **barriers** identified in the Vallbona case study **can be overcome**, in order to turn them into opportunities.

- **Quantify the sustainable requirements for a satisfactory urban life -**energy, water, food, non-renewable resources, transport, housing, waste management…- in order to establish **quantitative objectives** for sustainable urban settlements in the process of ecodesign.

- **Implement the set of environmental indicators for the greening of existing neighbourhoods** to different case studies in order to validate it.

- **Implement the methodology of ecodesign to other urban systems** in different conditions (i.e. in developing countries) in order to check its feasibility.

- Strengthen the research in the area of **retrofit of existing urban areas.** Important efforts need to be addressed into this direction, since many regions with existing consolidated urban areas (e.g. Europe) **will need to redesign its urban environment** in order to make a transition towards urban sustainability. With this purpose, the methodology of urban ecodesign can still be applied since it remains conceptually valid. Besides, the many concepts regarding urban sustainability that have arisen throughout the dissertation should also be taken into account. However, it is expected that many obstacles will arise along the implementation of concepts and strategies, since dealing with existing urban environments is much more complex than planning and constructing a greenfield development.