



**Modeling a sustainable urban structure:
An application to the Metropolitan Area of Porto**

Luís Nuno Ferreira Pacheco Quental
(Licenciado)

Dissertação para obtenção do Grau de Doutor em Engenharia do Território

Orientadora: Doutora Júlia Maria Brandão Barbosa Lourenço

Co-orientador: Doutor Fernando José Silva e Nunes da Silva

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Cover artwork by Joana Quental.



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Acknowledgements

I would like to thank in the first place to my supervisors, Prof. Júlia Lourenço and Prof. Fernando Nunes da Silva. I am particularly grateful to Prof. Júlia, who has provided me with excellent logistical conditions. The first two years of this thesis were passed in the Catholic University, where I worked. I want to recognize and thank the prompt support given by my former professor and “boss” Margarida Silva.

I would also like to thank my family for everything, and – by the way – for the careful reading and correction of the manuscript and for the cover artwork. A special word for my friends Mafalda, Joaquim and Pedro for their dedication, and to Fernando Barbosa Rodrigues, with whom I have learned a lot. I do not also forget the precious help of Rosa Nunes, from Instituto Superior Técnico.

I have benefited from very interesting conversations with José Carlos Costa Marques, Bernardino Guimarães, José Alberto Rio Fernandes and Leonardo Costa. I held them in high esteem.

Various persons have either given me data or scientific support: Altino Castro (STCP), Álvaro Costa (TRENMO), Ana Moreira, Arminda Clara Poças (CM Valongo), Artur Duarte (Campo Aberto), Carina Picas, Cecília Silva (FEUP), Clara Patão (INE), Cláudia Guerreiro (INE), Cláudia Moreiras (TRENMO), Dulce Almeida (ARPPA), Eduardo Pereira (CCDR-N), Filipe Batista e Silva, Isabel Castel Branco (VWS Atkins), Isabel Cruz (CM Vila do Conde), Isabel Martins (ISEP), Iva Ferreira (CM Gondomar), João Abreu e Silva (IST), João Almeida (FCUP), Joaquim Pinto da Costa (FCUP), Joaquim Poças Martins (Águas do Porto), Joaquim Ponte (CM Vila do Conde), Karina Barreto, Luís Baltazar (IGP), Mafalda Sousa, Mário Caetano (IGP), Mendes Joaquim (EDP), Mercês Ferreira (CM Vila Nova de Gaia), Miguel Baio Dias (EST-Barreiro), Miguel Pimentel, Miguel Torres, Mónica Ferreira (CM Maia), Nelson Barros (UFP), Paulo Alves (FCUP), Paulo Santos (FCUP), Rui Pimpão (CM Póvoa de Varzim), Rui Ramos (U. Minho), Sandra Roque (Veoliaagua), Tânia Fontes (UFP), Teresa Andresen (FCUP), Teresa Menezes (Segurança Social) and Vilma Silva (FCUP). I want to thank all of these persons for their help.

Finally, I would like to credit Fundação para a Ciência e Tecnologia (the Portuguese research foundation) for their financial support (scholarship SFRH / BD / 18588 / 2004), which was essential for the preparation of this thesis.

I dedicate this thesis to my sisters, who are great researchers.

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Abstract

A conceptual framework about sustainable urban development was developed from several scientific and political approaches to sustainability. Several territorial structure dimensions were then researched with the objective of understanding how they influence mobility patterns, residential energy consumption, residential water consumption, and urban growth. The scale of analysis is the borough. The overarching goal was to contribute to a better understanding of urban dynamics, namely how selected urban sustainability goals conflict with each other. Indicators comprising several urban sustainability domains were gathered, thematically aggregated, and processed for the 130 boroughs of the Metropolitan Area of Porto. Statistical methods including structural equations, multiple regression, generalized estimating equations and support vector machines were applied to model mobility patterns, residential energy and water consumption, criminality, and urban growth. Results show that socioeconomic factors – particularly income, education, and family size – are the most relevant in shaping mobility and consumption patterns at the borough level. Urban form also plays a significant role in determining mobility patterns and, to a lesser extent, residential energy consumption. Urban growth is largely determined by the level of accessibility to highway infrastructure. During the last decades, incomes have been increasing, family sizes diminishing, and population densities decreasing, but all these trends push urban areas away from sustainability. Since human capabilities are not supposed to decrease, planning for a compact urban form could at least attempt to counteract the negative environmental effects caused by socioeconomic trends.

Keywords: sustainable development; urban sustainability; urban form; sustainability indicators; energy, water and mobility patterns; urban growth; Metropolitan Area of Porto

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Resumo

Desenvolveu-se uma estrutura conceptual relativa à sustentabilidade urbana resultante de diversos modelos científicos e políticos de desenvolvimento sustentável. Investigaram-se, de seguida, diversas dimensões da estrutura urbana com o intuito de compreender a sua influência nos padrões de mobilidade, no consumo residencial de energia, no consumo residencial de água, e na expansão urbana. A escala de análise é a da freguesia. O objectivo último deste trabalho é contribuir para um conhecimento mais aprofundado das dinâmicas urbanas, nomeadamente de que forma alguns dos objectivos de sustentabilidade urbana podem entrar em conflito uns com os outros. Recolheram-se, agregaram-se tematicamente e processaram-se indicadores relativamente aos diversos domínios da sustentabilidade para as 130 freguesias da Área Metropolitana do Porto. Modelaram-se os padrões de mobilidade, o consumo residencial de água e energia, a criminalidade e o crescimento urbano através de métodos estatísticos como equações estruturais, regressão múltipla, equações de estimação generalizadas e máquinas de suporte vectorial. Os resultados mostram que as variáveis socioeconómicas – especialmente o rendimento, a educação e o tamanho da família – são os que mais fortemente influenciam os padrões de mobilidade e de consumo à escala da freguesia. A forma urbana também desempenha um papel significativo na determinação dos padrões de mobilidade e, em menor escala, no consumo residencial de energia. O crescimento urbano é em grande parte explicado pelos níveis de acessibilidade a infra-estruturas rodoviárias. Nas últimas décadas os rendimentos têm aumentado, o tamanho das famílias diminuído e as densidades populacionais decrescido, mas estas tendências afastam as cidades da sustentabilidade. Visto que as capacidades humanas não devem diminuir, planear formas urbanas compactas poderia pelo menos contrariar os impactes ambientais negativos causados pelas tendências socioeconómicas.

Palavras-chave: desenvolvimento sustentável; sustentabilidade urbana; forma urbana; indicadores de sustentabilidade; padrões de consumo de energia, água e de mobilidade; crescimento urbano; Área Metropolitana do Porto

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Acronyms and glossary

Acronym	Designation
A & F	Agriculture and fisheries
CDI	City development index
DPSIR	Driving force-pressure-state-impact-response
EEA	European Environment Agency
ENDS	National Strategy for Sustainable Development
EPI	Environmental performance index
EROI	Energy return on (energy) input
ESDP	European Spatial Development Perspective
H & R	Hotels and restaurants
HDI	Human development index
IISD	International Institute for Sustainable Development
INE	Statistics Portugal
ISEW	Index of Sustainable Economic Welfare
ISI	Institute for Scientific Information
IUCN	International Union for Conservation of Nature
LA2I	Local Agenda 2I
LPI	Living planet index
MEA	Millennium Ecosystem Assessment
MIPS	Material input per service unit
NRC	United States National Research Council
OECD	Organization for Economic Co-operation and Development
PNPOT	National Program for the Territory and Land use Policies
PT	Public transports
SEEA	Integrated Environmental and Economic Accounting
SEM	Structural equation modeling
SOM	Self-organizing map
SVM	Support vector machines
T & S	Trade and services
TOD	Transit oriented development
UAA	Utilized agricultural area
UNCED	United Nations Conference on Environment and Development
UNCHE	United Nations Conference on the Human Environment
UNDP	United Nations Development Program
UNSD	United Nations – Division of Sustainable Development
UNEP	United Nations Environment Program
UNFPA	United Nations Population Fund
WCED	World Commission on Environment and Development
WRI	World Resources Institute
WSSD	World Summit on Sustainable Development

Note: acronyms for data sources are provided in the annex A.4.

(The following tables clarify the meaning of some terms used throughout this thesis.)

Basic terminology related to data analysis.

Term	Meaning
Variable	General term designating any property of a system that can change its value.
Raw data	Data collected on source that has not been subjected to processing or any other manipulation.
Indicator	A symbolic representation designed to communicate a property or trend in a complex system or entity (Moldan & Dahl, 2007). Indicators are partial reflections of reality, based on uncertain and imperfect models (Meadows, 1998).
Factor	An unobserved variable describing the common variability among observed variables as obtained from statistical factor analysis. One factor may be able to summarize several one-dimensional indicators with increased reliability.
Dataset	In this thesis, two datasets were used as the basis for modeling: a longitudinal (1991–2001) and a cross-sectional (2006). Each is composed by factors and by other relevant indicators.
Model	A formalized expression of a theory or the causal situation which is regarded as having generated observed data. In statistical analysis the model is generally expressed in symbols (in a mathematical form), but diagrammatic models are also found (OECD, 2009). Sets of assumptions about how the world works, what is important, what should be measured (Meadows, 1998). See also the definition of <i>framework</i> .
Framework	The broad and schematic representation of model components and their interrelations. In this thesis, <i>framework</i> refers to the most general diagram portrayed in Figure 4.2-I, while <i>model</i> refers to more specific and goal based submodels.

Basic terminology related to the components of human ecosystem.

Term	Meaning
Human ecosystem	A coherent system of biophysical and social factors capable of adaptation and sustainability over time. Human ecosystems can be described at several spatial scales, and these scales are hierarchically linked (Machlis & Force, 1997).
Territorial structure or urban structure	The spatial configuration of resources, including human capabilities, to the spatial configuration of physical capital and transportation system, and to the spatial configuration of the processes that enable the proper functioning of the human ecosystem, which include the economy and the life supporting systems.
Urban form or built environment	The spatial configuration of fixed elements within a metropolitan region, including the spatial pattern of land uses and their densities as well as the spatial design of transport and communication infrastructure (Anderson, Kanaroglou, & Miller, 1996; Handy, 2006). Urban form is a component of the territorial structure.
Interactions	The flows of goods, people and information among different locations in the city (Anderson, et al., 1996), the metabolism of society, and the impacts caused by them.
Metabolism	The exchange of energy and matter between social and natural systems (Fischer-Kowalski & Haberl, 2007).
Urban design	The physical form of the public realm over a limited physical area of the city. Lies between the design scales of architecture, which is concerned with the physical form of the private realm of the individual building, and town and regional planning, which is concerned with the organization of the public realm in its wider context (Gosling and Maitland, 1984, as cited in Frey, 1999). Urban design must also set some rules for the design of those elements of the private realm that are involved in the formation of the public realm (Frey, 1999).
Conflicts	Detrimental impacts on the quality of life of people such as criminality, accidents, certain diseases, etc.

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I. Introduction

I.1 The importance of sustainability research

Sustainability as an imperative

The power of human beings in the colonization of nature has never been so significant as in present times. Hibbard, et al. (2007) has named this increasing scale of human economy as the *great acceleration*: world human population increased four-fold between 1890 and 1990; in the same period, industrial output increased 40-fold, energy consumption 16-fold, water consumption 9-fold, and fish consumption 35-fold; total economic volume was multiplied by 14 (John Mc Neil, as cited in Lambin, 2004). Other data indicate the degree of colonization of natural processes: carbon dioxide levels in the atmosphere have surpassed pre-industrial levels by 30%; humans appropriate about 40% of the terrestrial photosynthetic products; between one third and half of the Earth's surface has been altered by human intervention; and more than half of the freshwater available is used by societal metabolism (Vitousek, Mooney, Lubchenco, & Melillo, 1997). The resulting environmental impacts are also a great concern for humankind: e.g., the rate of species extinction is the highest over the last 65 million years; one in seven bird species is threatened with extinction or is already extinct; and humanity's ecological footprint in 2005 amounted to 2,7 ha *per capita* and exceeded available biocapacity by 30%. Most of these trends and impacts need a considerable time until they stabilize or revert, so the imperative for changing course is even greater.

The introduction of sustainable development as a concept can be understood as an intellectual answer to address the impacts caused by human activity and an attempt to reconcile the goals of environmental protection and economic growth. The concept gained wide acceptance after the publication of the Brundtland Commission's report "Our Common Future," which coined its most commonly cited definition: "Sustainable development is the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development [WCED], 1987). Probably as a result of this politically correct definition – which cleverly avoids mentioning trade-offs between conflicting goals – sustainable development has entered the lexicon of worldwide decision-makers, scientists, and citizens.

Calamities such as famine, poverty and AIDS, and the environmental burdens described before, should be accepted as an urgent call for society to find a more respectful way of interacting with nature, and a call for human beings to dignify each other. There is no doubt that sustainability is an imperative. But it is a challenge as well.

Sustainability as a challenge

The implementation of sustainability remains a challenge to society. While an abundance of literature concerning sustainable development has been published, only recently – since the emergence of the so-called *sustainability science* – has a solid scientific background started to permeate research efforts. Sustainability science is an important step towards an overarching sustainability theory that brings together several fields of knowledge into a research program of its own and attempts to assemble the large range of scientific production into a meaningful result. Sustainability science can also bridge the gap between policy and science because it is problem driven.

A theory of sustainable development must acknowledge the primary role of ethics and of societal choices in determining which goals are pursued, while leaving enough room for scientific knowledge to be taken into account. Likewise, sustainability should be understood more as a path to be followed than as an end state (United States National Research Council [NRC], 1999). In fact, there is no end state upon which society could agree; goals are progressive, and as long as they are reached, more ambitious ones take their place. The notion of progress is also compatible with learning. Most scholars agree that sustainability requires a fundamental shift in people's values and behaviors, and these can only be changed through learning, which is usually a lengthy process. However, as society learns how to be sustainable, eventually a new socioeconomic paradigm will replace neoliberalism as the dominant worldview.

Sustainability therefore comprises multiple challenges, but as nowadays most people live in cities, a sustainability transition is necessarily an urban sustainability challenge.

The quest for urban sustainability

Earth is an increasingly urban planet. People have been moving to the cities looking for opportunities and a better way of life, but this movement is not without impacts. As people adopt urban lifestyles, their consumption patterns become more intensive in materials, energy and information, and, as a consequence, their *per capita* ecological footprint rises (Rees & Wackernagel, 1996). These impacts need not to be locally visible, as far away regions and ecosystems export their products and services to cities. Along with urbanization and improved transport infrastructure, socioeconomic changes explain why cities have been spreading over vast territories – usually much faster than they are growing in population. This sprawling process often destroys high quality agricultural soils and leads to higher commuting distances and greenhouse gas emissions. The automobile triggered this structural morphological change of cities at the first place. As people have to travel longer distances, often from or to places with poor links to public transportation networks, the car became as much of a choice as of a basic daily need.

Nonetheless, urbanization is also strongly connected with sustainability. The most urbanized countries are also the wealthiest and those whose population is most educated and free from a political standpoint. According to Sen (1999), people in these countries enjoy greater opportunities to develop their capabilities. Therefore, it is reasonable to think that the creativity and learning skills essential for a sustainability transition will most likely to be present in cities. In addition, most European and Asiatic urban areas have a dense core, which, when compared with sprawling patterns of development, is associated with a lower *per capita* ecological footprint. Economies of scale support cheaper and environmental friendly solution in such fields as transportation, water treatment, sewage collection and recycling, and energy usage and production; economically, cities provide firms with the labor and skills they need to settle and prosper; sociologically, cities provide the critical mass that some ideas need until they start to be widely known.

Human concentration in cities, although in different levels, has been a definite characteristic of societal evolution. Finding more sustainable patterns of urban development could diminish the undesirable side effects of urban growth while maintaining all of its positive consequences. The sustainability challenge encompasses, therefore, an urban sustainability challenge.

1.2 Relevant sustainability knowledge

This thesis builds on several studies with a holistic focus that cover the several dimensions of sustainability. Goodland (1995) analyzed the scientific dimension of environmental sustainability, namely the implications in terms of growth, limits, scale and capital substitutability. Kates & Parris (2003) examined the influence of long-term global trends on the transition to sustainability. Parris & Kates (2003a) characterized specific goals, targets and associated indicators as embodied in international agreements and plans of action, and described the current state and efforts to attain four such goals (reducing hunger, promoting literacy, stabilizing greenhouse-gas concentrations, and maintaining fresh-water availability). Parris & Kates (2003b) highlighted similarities and differences in the motivation, process, and technical methods used in a dozen prominent examples of sets of sustainability indicators. Røpke (2005) extensively reviewed the development and characteristics of ecological economics. Leiserowitz, Kates, & Parris (2006) surveyed five major efforts to identify values and behaviors essential for a sustainability transition; they also analyzed how contextual trends (freedom and democracy, capitalism, globalization and equality) could influence societal ability to adopt those values, attitudes and behaviors. Sneddon, Howarth, & Norgaard (2006) explained some of the rationales behind sustainable development although leaving important contributions such as the resilience approach behind. Costanza, Graumlich, & Steffen (2007b)

published numerous insights concerning the interactions between society and nature through time which may in the future be used as building blocks of a sustainability theory.

1.3 Research objectives and hypothesis

The main goal of this thesis is to assess the influence of *territorial structure*¹ on *mobility patterns*, on *residential energy consumption*, and on *residential water consumption*. The thesis also intends to assess how territorial structure drives *urban growth*. A more detailed analysis of the influence of urban form² on these variables shall be made.

The issues referred above are some of the dimensions identified in a general urban sustainability framework derived to anchor and support theoretically the proposed investigation. A multidimensional perspective of urban sustainability is therefore pursued and favored. However, as this thesis mainly concentrates on the territorial structure at borough scale, sustainability dimensions like governance, which assume a more pronounced relevance at higher levels (e.g., the regional, national and global), are absent from the statistical modeling. The general framework was used as a basis from which a more detailed and operational model was built.

This thesis contributes to a better understanding of some of the most relevant urban processes by providing knowledge about their dynamics and interaction. I am interested in making explicit how different urban sustainability dimensions conflict with each other, since a desirable progress in one dimension may imply an undesirable change in other dimension. Clarifying these trade-offs – almost a taboo for decision-makers – is particularly important, specially to guarantee that values and options behind decisions are transparent and can be scrutinized by the public.

As a general goal, and having performed the research and the literature review as background, I also intend to reflect about the evolution of the sustainability concept, its political and research developments, and the role of cities in fostering a sustainability transition. At the same time, it is not my intention to perform a sustainability assessment of urban systems, but rather contribute to the body of knowledge these assessments require in order be scientifically grounded.

¹ Territorial structure is a concept that refers to the spatial configuration of resources, including human capabilities, to the spatial configuration of physical capital and transportation system, and to the spatial configuration of the processes that enable the proper functioning of the human ecosystem, which include economy and life supporting systems.

² Urban form refers to the spatial configuration of fixed elements within a metropolitan region, including the spatial pattern of land uses and their densities as well as the spatial design of transport and communication infrastructure. Urban form is a component of the territorial structure.

From a motivational perspective, this thesis represents an effort to complement the work of Lourenço (2003), who identified the most relevant enabling and facilitating conditions influencing the capacity of territorial plans to be implemented. Adding to her analysis, I focus on the substantive character of planning having a sustainable territorial structure as reference, and less on the planning process. The two domains are equally important.

The research hypotheses of this thesis are:

1. territorial structure at the borough level has a distinct influence on mobility patterns, on residential energy consumption, and on residential water consumption;
2. particularly, urban forms characterized by high densities, mixed land uses, and served by high service levels of public transports are associated with lower shares of car dependency, and higher shares of walking and use of public transports;
3. the effect of rising densities, mixing land uses and providing better public transportation services on mobility patterns, on residential water consumption, and on residential energy consumption is hindered by when the socioeconomic status of people increases.

I.4 Methodology

A global structure of the thesis is presented in Figure I.4-1 and summarized in this section. A detailed description of the framework used to analyze data and a description of the specific statistical methods employed in that task is provided in chapter 4.

I.4.1 Literature review

This thesis started with a literature review covering topics such as sustainable development, ecological economics, sustainability science, urban sustainability, urban planning, and the relationship between territorial structure and other indicators (mobility patterns, water consumption and energy consumption). Connected topics were also screened, including the theories of complexity and self-organization, vulnerability and resilience, social-ecology, human needs, governance, ecosystem services and economic valuation. With time, the review became increasingly focused in order to better fit the thesis' objectives: general papers and books about sustainable development were analyzed first, and more specific literature directly related to the research questions later on. Bibliographic databases such as the Web of Knowledge (<http://newisiknowledge.com>), b-on (<http://www.b-on.pt>) and Google Scholar (<http://scholar.google.com>) were repeatedly queried to avoid missing relevant literature. In addition, the recommended practice of scanning cited references iteratively was useful to spot often-cited papers (see also the bibliometric analysis presented in section 2.6).

In terms of methodology, several sources were studied as well. On a first approach, literature concerning indicators, standard statistical analysis (e.g., factor analysis, cluster analysis, multiple regression and the general linear model) and data mining was read. With the aid of expert opinion, this allowed for a better understanding of the kinds of analysis that could be performed. Specific literature pertaining selected methods was then analyzed so that the scientific validity of data analysis could be guaranteed.

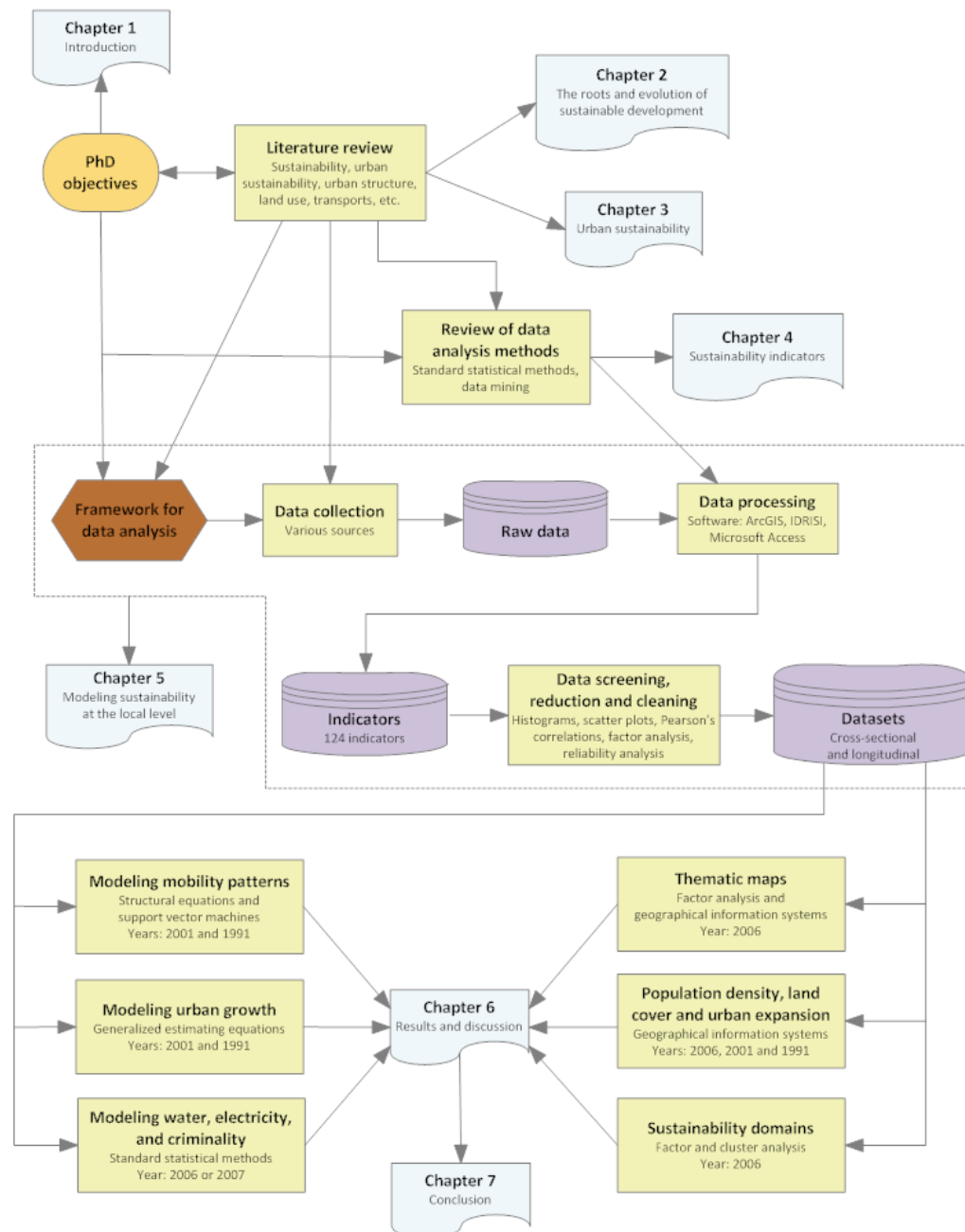


Figure I.4-I: Flowchart showing the structure of the thesis.

I.4.2 Building the sustainability framework for data analysis

The statistical modeling performed is anchored in a larger framework clarifying the dimensions of urban sustainability and the relationships between them. This framework is based on the several approaches described in the literature review about sustainable development and urban sustainability. The framework is used as the theoretical basis for data analysis in order to guarantee the consistency of methodology, results, and conclusions. As a conceptual contribution, the framework provides a structure that accounts (a) for human-nature interactions, (b) for the societal evolution towards biological and cultural ends, (c) for the metabolism of human ecosystem, and (d) for some cause-effect relationships between driving forces and impacts.

I.4.3 Data collection and processing

Because of the latitude of domains relevant when studying territorial structure, data concerning as many of those dimensions as possible was needed. Numerous data sources were obtained, including Census data from INE – Statistics Portugal, social security information, satellite images and land cover cartography, and environmental data about the residential consumption of energy and water. A complex process of variable processing followed, the overall goal being the selection of meaningful indicators for each of the 130 borough of the Metropolitan Area of Porto and for the widest time span available (1991, 2001, and 2006, whenever possible). Data in geographical formats required the longest processing time, including the computation of distances, accessibilities, and areas. The classification of satellite images to produce land cover maps and statistics was particularly laborious. Data in the form of statistics required only minor processing such as the computation of ratios or location quotients. This phase yielded 124 indicators covering different urban sustainability domains.

I.4.4 Data screening, reduction and cleaning

The great number of indicators, much of them portraying equivalent processes, recommended its reduction to a manageable and more realistic set. Some variables were discarded because of extreme skew, because odd values were found or because of incompatible collection methods in different periods. The remaining variables (the majority) were divided into domains according to the framework used and each group was factor analyzed. Factors and single indicators (not well represented by the factor structure) were assembled into a cross-sectional dataset (mostly for 2006) and a longitudinal dataset (for 1991 and 2001).

1.4.5 Data analysis

Data analysis was carried out using different statistical methods according to the specific modeling goals and to the strengths and limitations of each method:

- modal shares were modeled using structural equations and support vector machines;
- residential water consumption, residential electricity consumption, and criminality against people in 2006 were modeled using multiple regression or extensions of this method (the generalized linear model);
- urban growth was modeled for the periods 1990–2000 and 2000–2006 through generalized estimating equations;
- cluster analyses were performed for each sustainability domain to access the existence of characteristic urban patterns across boroughs.

For regression-like statistical methods and structural equation modeling, it is possible to derive conclusions through the analysis of the coefficients obtained. By comparing the relative size and significance of these coefficients, it is possible to access the relative effect of territorial structure variables (density, land-use mix, level of public transports, level of education, wealth, etc.) on each dependent variable (modal shares, residential energy consumption, residential water consumption, urban growth, and criminality against people). For other methods it is necessary to perform different procedures, as explained in chapter 4. Some of the results achieved were worked out in order to yield more intuitive results. Clusters of territorial structure, for instance, were grouped and classified according to their sustainability level. A number of graphs and maps were in addition produced to facilitate the visualization and perception of results.

1.5 Utility for theory and practice

Research carried out in this thesis adds to the body of research dealing with urban sustainability, particularly with sustainable territorial structure and urban form. Conclusions demonstrate the importance of urban form at the borough level in shaping mobility patterns. Density, mixed land uses and the service level of public transports were found the most important factors reducing car dependency. Results also testify the significance of urban form in reducing electricity consumption, although the effect is less pronounced. No significant influence on the residential consumption of water was found. The positive effect of urban form cannot, however, be seen in isolation. This thesis clearly shows that socioeconomic factors play an even larger role than urban form in shaping mobility and consumption patterns.

From a theoretical and methodological point of view, this thesis innovates by employing robust statistical methods that provide rich information about the dynamics of urban processes. A step was taken as to the establishment of causal relationships, which in urban setting prove particularly difficult to achieve. By controlling for several significant variables at the same time, the proposed models were able to provide accurate estimations of the unique effect of urban form and socioeconomic conditions on selected sustainability domains. As such, this thesis helps to clarify which trade-offs exist between conflicting goals. For instance, rising average wealth is certainly a sustainability goal, but results show that citizens will become more car dependent as they become richer.

Another contribution to theory is the borough scale of analysis and its relation with higher scales. The influence of urban form on travel behavior is strong. As such, planning for sustainable urban forms is an effective way of reducing the environmental burden of cities and improving their livability. As more and more people are living in cities, the role of urban form must not be underestimated.

Still from a methodological point of view, this thesis shows that indicators can be aggregated into higher order factors if scientific consistency is ensured by a conceptual framework of urban sustainability. As an alternative, a smaller set of indicators may also be chosen so that only the relevant processes for urban sustainability are selected, and the inclusion of “duplicate” indicators representing equivalent processes is avoided. This thesis contributes to the scientific validity of such choices, even if several other criteria, such as public legitimacy and political saliency, must also be met.

I.6 Research limitations

Research on urban settings is limited in the first place by the impossibility of carrying out controlled experiments. People and conditions usually vary freely and are affected by numerous conditions which are difficult, if not impossible, to account for. As a result, one of the main goals of scientific research – the ability to derive abstract conclusions – is also compromised. This thesis is necessarily limited by these constraints. Its conclusions are reliable for the specific context of the Metropolitan Area of Porto and for the borough scale of analysis.

Given the scope of the research, other limitations concerning the availability of data exist. There is a significant lack of data for Portuguese boroughs, with the exception of Census and economic statistics provided by INE – Statistics Portugal. Reporting obligations to INE do not usually go beyond the municipal level. When data could be obtained by directly querying their holders (for instance, institutions from the Public Administration and municipalities), comparability of data across municipalities was in some cases doubtful; moreover, missing data

were inevitable since some organizations do not deem to answer data requests. I heard after several phone calls, for instance, a secretary telling me that the Board of the public water company where she was working have decided “not to answer” [sic] my request. Data shortcomings were amplified by the broad realm of domains encompassed by the operational research model. Availability of environmental information is particularly deficient and fragmented between numerous institutions. The same is valid for the temporal scope of the information obtained, which was often restricted to a particular recent year. More ambitious reporting standards are crucially needed in order to stimulate research and transparency at the Administration level nearest to citizens: the boroughs.

1.7 Structure of the thesis

The thesis begins with a literature review presenting the most important approaches to sustainable development in both the scientific and political arenas. An assessment of their evolution was performed also with the aid of bibliometric data and indicators of environmental political activity. The end of chapter 2 concentrates on sustainability indicators because of their pivotal role in this thesis. Chapter 3 represents a step towards the borough level of analysis of this thesis. Sustainability is reviewed specifically at the urban context. This chapter describes in detail the goals pursued by sustainable cities and the role of planning in achieving them, as well as important processes such as sprawl and the relationships between territorial structure and selected environmental impacts.

From chapter 4 onwards the original contribution of this thesis is presented. Chapter 4 starts with the conceptual framework in which the thesis is anchored and describes, then, all the methodological steps followed during data analysis. Results are shown in chapter 5. They include descriptive statistics and maps, and diverse statistical output obtained from modeling mobility patterns, water consumption, electricity consumption, urban growth, and criminality. A cluster analysis and a straightforward classification of urban sustainability are also presented. Chapter 6 ends the thesis with conclusions drawn from the empirical models. These serve as an inspiration to a reflection about sustainable development and urban sustainability, namely the importance of urban systems in fostering a sustainability transition. Indications for further research are provided as well.

A note about writing style

This thesis is written in American English. References, in-text citations and other style issues comply to the possible extent with the Manual of the American Psychological Association (6th

edition). I avoided the use of footnotes as much as possible because they usually distract the reader from the central ideas of the text.

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2. Policy, science and measurement of sustainability

2.1 Introduction

This chapter concentrates on both the political and scientific dimensions of sustainable development. Although not directly linked to the sustainability of urban systems, the review and empirical work hereby presented are essential to the development of a solid theoretical framework to guide data analysis and allow the building of the thesis.

Sections 2.2 and 2.3 attempt to describe the political milestones at the global level of greater importance to the emergence and evolution of sustainable development as an ideal, and to depict the cyclical patterns of that political activity. In addition, this section aims at identifying the main sustainability goals and targets endorsed by such political initiatives. These tasks are accomplished by referring and discussing relevant meetings, agreements, and declarations by way of a literature review, and by an assessment of indicators dealing with political will such as the signature and ratification of environmental agreements, the creation of protected areas, the establishment of environmental ministries and the expenditure on environmental protection. The combined use of both the literature review – where judgments concerning the relative importance of different political events had to be made – and the objective standpoint conveyed by the indicator analysis allowed a more robust assessment and a graphical representation of the evolution of political activity, as intended. Parts of sections 2.2 and 2.3 were accepted for publication in a scientific journal (Quental, Lourenço, & Nunes da Silva, 2009).

The remainder of this chapter (sections 2.4 to 2.6) is an effort to identify the main scientific developments that eventually led to the emergence of sustainability science as a distinct scientific discipline, and to shed light on how they contributed and shaped the core of sustainability thinking. This task is accomplished by referring and discussing important topics under debate within each of those approaches to sustainable development, and by determining the most influential publications, authors, and journals in the field.

2.2 International politics and policy

A literature review was carried out in order to identify and describe the milestones of sustainable development policy since the sixties, and the goals and targets they endorse. This is a difficult and subjective task since no easily accessible indicators to measure regime effectiveness have emerged. Scholars have been under a lively debate to discuss the issue (see, for instance, Helm & Sprinz, 2000; Miles, et al., 2001; Mitchell, 2003, 2006; Underdal & Young, 2004; and Young, 1999). Most of the frameworks for analysis opt for several factors that

should be interpreted through contextual approaches. According to Mitchell (2003, p. 449), countries that are ecologically vulnerable and have low adjustment costs tend to be more responsive to agreements while those that are not affected ecologically or have high adjustment costs tend to be more recalcitrant. Selin & Linnér (2005) structured global cooperation and policy making on the integration of environment and development around four perspectives: the emergence and influence of an international environment and development discourse, the growing multilateralism and the building of new international institutions, the power politics and the North-South conflicts. In order to circumvent the difficulty of determining which political milestones were decisive for sustainable development, the most commonly ones referred in literature were adopted.

A tentative list of those milestones designated as multilateral agreements, institutional arrangements, conferences, and documents was compiled in Table 2.2-I drawing from the following sources: D'Amato & Engel, 1997; Ginn, 2008; IISD, 2007; Rodrigues, 2008; Runyan & Norderhaug, 2002; Selin & Linnér, 2005; UNEP, 2001, 2002, 2007, 2008; WRI, 2003, 2008. The identification of sustainability goals and targets resulted from the content analysis of relevant declarations ("soft law"), conferences' agendas and scientific literature (Leiserowitz, et al., 2006; Parris & Kates, 2003a, 2003b were particularly useful).

Table 2.2-1: Sustainable development political milestones since the sixties.

Year*	Name	Type*	Theme
1964	World Population Conference	C	(Various)
1966	International Covenant on Economic, Social and Cultural Rights	M	Human rights
1966	International Covenant on Civil and Political Rights	M	Human rights
1968	Biosphere Conference	C	Biodiversity
1971	Ramsar Convention on Wetlands of International Importance	M	Ecosystems
1972	United Nations Conference on the Human Environment	C	(Various)
1972	UNEP	I	Governance
1972	Convention Concerning the Protection of the World Cultural and Natural Heritage	M	Cultural protection
1973	Convention on International Trade in Endangered Species	M	Biodiversity
1973	Convention for the Prevention of Pollution from Ships	M	Waste, chemicals and pollution
1974	Symposium on Patterns of Resource Use, Environment and Development Strategies (Cocoyoc, Mexico)	C	(Various)
1976	United Nations Conference on Human Settlements	C	(Various)
1979	Bonn Convention on Migratory Species	M	Biodiversity
1979	Convention on the Conservation of Migratory Species of Wild Animals	M	Biodiversity
1979	Convention on Long-Range Transboundary Air Pollution	M	Waste, chemicals and pollution
1980	World Conservation Strategy	D	Ecosystems
1982	United Nations Convention on the Law of the Seas	M	Ecosystems
1982	World Charter for Nature	D	Ecosystems

Table 2.2-1 (continued)

Year*	Name	Type*	Theme
1985	Vienna Convention for the Protection of the Ozone Layer	M	Waste, chemicals and pollution
1987	Montreal Protocol on Substances that Deplete the Ozone Layer	M	Waste, chemicals and pollution
1987	Basel Convention on the Transboundary Movement of Hazardous Wastes	M	Waste, chemicals and pollution
1987	Our Common Future	D	(Various)
1988	Intergovernmental Panel on Climate Change	I	Waste, chemicals and pollution
1992	United Nations Conference on Environment and Development	C	(Various)
1992	United Nations Commission on Sustainable Development	I	Governance
1992	Convention on Biological Diversity	M	Biodiversity
1992	United Nations Framework Convention on Climate Change	M	Waste, chemicals and pollution
1992	Agenda 21	D	(Various)
1993	World Conference on Human Rights	C	Human rights
1994	Conference on Population and Development	C	(Various)
1994	Global Environment Facility	I	Governance
1994	United Nations Convention to Combat Desertification	M	Ecosystems
1995	World Summit for Social Development	C	(Various)
1995	Conference on Women	C	Human rights
1997	Kyoto Protocol	M	Waste, chemicals and pollution
1998	Aarhus Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Areas	M	Governance

Table 2.2-1 (continued)

Year*	Name	Type*	Theme
1998	Rotterdam Convention on Prior Informed Consent	M	Waste, chemicals and pollution
2000	Second World Water Forum	C	Ecosystems
2000	Cartagena Protocol on Biosafety	M	Biodiversity
2000	Millennium Summit and Millennium Declaration	C, D	(Various)
2001	Stockholm Convention on Persistent Organic Pollutants	M	Waste, chemicals and pollution
2002	World Summit on Sustainable Development	C	(Various)
2005	World Summit	C	(Various)

* Dates refer to the year that multilateral agreements (M) were signed, conferences (C) were organized, institutions (I) were established or documents or declarations (D) were issued.

The following paragraphs review the main developments of sustainable development policy according to a framework consisting of four main stages.

2.2.1 Until the end of seventies: the first steps

Environmental discourse grew slowly from the fifties triggered by worsening socioeconomic and ecological conditions. Kirkby, O'Keefe, & Timberlake (1999) refer to a development crisis characterized by escalating poverty and social inequalities, a security crisis driven by the nuclear race and by several post colonial wars, and an environmental crisis fed by concerns such as toxic pollution, health effects of thalidomide, the death of Nordic lakes and the rising world population. Pioneering efforts led in 1948 to the creation of the nowadays-called *International Union for Conservation of Nature* (IUCN), the United Nations Scientific Conference on the Conservation and Utilization of Resources in 1949, the World Population Conferences in 1954 and 1964, and the Biosphere Conference in 1968.

The United Nations Conference on the Human Environment was held in Stockholm in June 1972 and is usually credited as a fundamental catalyst for international awareness to the Earth's environment and development problems (Kates, Parris, & Leiserowitz, 2005; UNEP, 2002). Built around the René Dubos and Barbara Ward's book "Only One Earth," and attended by 132 member states of the United Nations – but missed by the former USSR and most of its allies due to the Cold War divide – the conference had important outcomes which extended throughout the seventies and beyond. Three agreements were reached: the Stockholm Declaration with 26 principles, which constituted the first body of soft law in international environmental affairs; an Action Plan of 109 recommendations; and five issue-specific resolutions.

While the Declaration coherently merged the North's aspirations of environmental sustainability with the South's goal of achieving development, which were very much at the centre of the debate, ("poverty is the worst form of pollution" as the Indian Prime-Minister Indira Ghandi put it during the works), the Action Plan enriched and complemented it. Decisions regarding the creation of the UNEP and of an environmental fund, among others, were taken through the resolutions (Selin & Linnér, 2005). Principles and rights taken for granted in nowadays legal and cultural frameworks, such as the right to live in an environment of quality and the principle of compensating other nations when transboundary impacts occur, were devised in Stockholm, albeit more controversial issues such as the principle of national sovereignty remained unchanged.

During the seventies, a number of key multilateral environmental agreements were achieved. They include the Ramsar Convention on Wetlands of International Importance (1971), the World Heritage Convention (1972), the Convention on the Prevention of Marine Pollution by

Dumping of Wastes and Other Matter (1972), the Conference on International Trade in Endangered Species of Wild Fauna and Flora (1973), the Convention on the Conservation of Migratory Species of Wild Animals (1979) and the Convention on Long-Range Transboundary Air Pollution (1979). Indirect outcomes at the national level involved the growing designation of national parks, the approval of several environmental protection laws and the creation of environmental ministries (D'Amato & Engel, 1997; Selin & Linnér, 2005; Soromenho-Marques, 2005; see also section 2.3). Scientific advancements such as the understanding of climate change, the mechanisms behind the ozone hole (although only confirmed in 1985) and the problem of desertification, as well as the Stockholm Conference helped to increase environmental awareness.

2.2.2 1980–1986: a stagnation period

In 1974, the symposium on Patterns of Resource Use, Environment and Development Strategies took place in Cocoyoc, Mexico, to debate the social and economical causes of environmental degradation. Its declaration contains several statements that are still actual: “The first point to be underlined is that the failure of world society to provide ‘a safe and happy life’ for all is not caused by any present lack of physical resources. The problem today is not primarily one of absolute physical shortage but of economic and social maldistribution and misuse.” The declaration called UNEP to pursue efforts of “eco-development.” Although conceptually equivalent to the now ubiquitous concept of “sustainable development,” the former never received much attention (Selin & Linnér, 2005).

During the eighties, social inequalities were exacerbated in several developing countries through the implementation of the Washington Consensus policies (Kirkby, et al., 1999). Trade liberalization, tax reforms and privatization of public services that followed often broke local institutions leading to massive natural resources exploitation (Dasgupta, 2001). The number of war refugees doubled from about 9 million in 1980 to more than 18 million by the early nineties (UNEP, 2002). Famine spread through large parts of Africa, killing in Ethiopia more than one million people between 1984 and 1985. The attention of international community shifted to economic growth – which was thought to be compatible with environmental improvements – as a solution for poverty and social inequalities (Røpke, 2005). Security issues also played a pivot role because of the Cold War (Selin & Linnér, 2005). The world experienced serious environmental accidents: in 1984, a toxic cloud leaked from a Union Carbide plant, in Bhopal, India; in 1986, a nuclear reactor at the Chernobyl power plant exploded releasing a radioactive cloud which floated over Russia and part of Europe; three years later, in 1989, the tanker Exxon Valdez spilled 50 million liters of oil in Alaska’s Prince William Sound.

Besides the stagnation of global environmental policy, sustainable development, or more specifically environmental sustainability, was emphasized by the World Conservation Strategy (Kirkby, et al., 1999). Jointly devised by IUCN, UNEP and WWF, and launched simultaneously in 35 countries in 1980, the strategy sought to maintain essential ecological processes, to preserve genetic diversity and to ensure the rational use of species and ecosystems (Adams, 2006). Curiously, although pushing for sustainability, the strategy found it to be compatible with economic growth (Goodland, 1995). An update of the document entitled “Caring for the Earth: a strategy for sustainable living” was issued in 1991. Moreover, the United Nations General Assembly approved in 1982 the World Charter for Nature, celebrated the Stockholm Conference’s anniversary (the so called “Stockholm +10,” even if it occurred in Nairobi), and approved the United Nations Convention on the Law of the Sea.

2.2.3 1987–1995: major achievements

The beginning of a new growth period in global sustainable development policy was marked by the accomplishments of the WCED. The commission was set up by the General Assembly of the United Nations in 1982 as an “independent” group of high-level experts and government officials chaired by the then-Prime Minister of Norway Gro Harlem Brundtland. The commission was asked to formulate a “global agenda for change” and, more specifically, to “propose long-term environmental strategies for achieving sustainable development by the year 2000 and beyond” (WCED, 1987). The report “Our Common Future,” released in 1987 after three years of public hearings, is the most cited document in the sustainable development literature (see section 2.6). Being able to reconcile the environmental interests of the North with the development needs of the South, the commission effectively joined the world through the catchphrase “sustainable development.” The concept, defined as “meeting the needs of the present generation without compromising the ability of future generations to meet their own needs,” although stated with a similar meaning as far back as 1979 (as can be checked through a search in Mitchell, 2008), became popular only after Brundtland’s work (Selin & Linnér, 2005).

The report explores the factors behind the growing equity gap between the rich and the poor, and issued guidance so that countries could integrate sustainable development into their policies. These ranged from asking for more growth, conserve and enhance the resource base, ensure a sustainable level of population, reorient technology, integrate environmental concerns into decision-making and strengthen international cooperation (WCED, 1987). The publication of the report prompted a strong international awareness of the sustainability issues, which, *inter alia*, contributed to the perceived success of both the Rio Summit in 1992 and its affiliated documents (Kirkby, et al., 1999).

Some of the commission's statements were rather controversial. For instance, the appeal for a sustainable economic growth is at odds, according to Daly (1996), with sustainable development. However, it is important to bear in mind the procedural and political contexts under which the report was prepared, which probably prevented the commission from refining all discrepancies and lead to what Kirkby, et al. (1999, p. 9) called "irreconcilable positions." Or it may be that the commission truly believed that the growth limits were only technical, cultural and social (Kirkby, et al., 1999), dismissing the biophysical limits that nowadays seem very present. Brundtland's original call for a "5 to 10-fold more growth" was rectified and reversed in 1992 by placing population higher on the agenda of sustainability (Goodland, 1995). The progress of international governance was patent through the signature of the Montreal Protocol on Substances that Deplete the Ozone Layer (1987) and of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (1989), as well as through the creation of the International Panel on Climate Change (1988) and of the Global Environment Facility (1991). At the same time, the nineties, which started with the social and environmental catastrophe of the Gulf War, witnessed the loosening of trade rules, especially since the establishment in 1995 of the World Trade Organization.

The positive context referred by Conca (2007), partially as a result of the end of the cold war, helps explaining why the expectations were so high at the United Nations Conference on Environment and Development (UNCED), in 1992. More than 100 chiefs of state, 1400 nongovernmental organizations, 9000 journalists and a total of 30 thousand people participated in the conference (UNEP, 2002). Although divergences between North and South were present – leading to a "greener agenda" and a mismatch when compared with the more balanced outcomes of the Brundtland report (Kirkby, et al., 1999) – the results can be considered a success: two international agreements (the United Nations Framework Convention on Climate Change, the Convention on Biological Diversity and, in 1994, the United Nations Convention to Combat Desertification), a 40 chapter long blueprint for sustainable development called Agenda 21, the 27 principles of the Rio Declaration on Environment and Development, the creation of the United Nations Commission on Sustainable Development, and the nonbinding Principles for the Sustainable Management of Forests. Besides all these accomplishments, no agreement was reached regarding a universal Earth Charter that could guide the transition to sustainable development.

The Rio Declaration reaffirmed the main issues addressed by the Stockholm declaration. Its first principle expresses an inspired view about human life: "Human beings are at the centre of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature."

2.2.4 Retrogressing in the new millennium

During September 2000 the heads of state gathered at the United Nations hosted Millennium Summit to discuss a broad agenda that covered both development and environmental concerns. The meeting resulted in the Millennium Declaration, which stressed freedom, equality, solidarity, tolerance, respect, and shared responsibility as the essential values governing international relations in the XXI century, and resulted in several global targets called Millennium Development Goals. These comprise, among others, halving poverty, halving the proportion of people without access to safe drinking water, halting the spread of AIDS and insuring universal primary school education, all of them by 2015.

The follow-up of the Rio's Earth Summit took place in Johannesburg in 2002. The World Summit on Sustainable Development (WSSD), attended by over 100 heads of state and close to 25 000 different organizations, is still considered the largest event organized by the United Nations (Wapner, 2003). Along with the main sessions, a number of parallel events arranged by the civil society took place. As usual, the summit resulted in a declaration and a more detailed plan of implementation.

The main goal of the Summit was to put in place the necessary mechanisms to implement Rio's decisions, since progress during the 10 years interval had been disappointing (see, e.g., Millennium Ecosystem Assessment [MEA], 2005; Kates, et al., 2005; Parris & Kates, 2003b). The conference is considered a flop in that it generally recalled the targets already established during the Millennium Summit. The world was not able to pursue more stringent commitments Wapner (2003) blames September 11 and the world's concern with the terrorism threat, adding that the old principle of requiring environmental protection in the North and asking for development aid in the South was overruled by the belief that economic globalization was a cure for all problems. In fact, care was taken to avoid embarrassing contradictions between trade and environmental agreements. At the same time, some Southern countries started to realize that their natural resources could be a major source of welfare if carefully managed and that ruthless free trade might jeopardize them. Conca (2007) and Redclift (2006) argue that the neoliberal ideology pursued by most countries is characterized by a smaller degree of institutionalization, which motivated the expansion of the human rights and the environmental protection movements. Conclusions regarding the weaker outcomes of WSSD, although may prove correct, can be due to an increasing responsibility and role played by the civil society. This is visible, for example, in the 344 partnerships between governments, industry and nongovernmental organizations established since the Johannesburg conference to carry out sustainability actions (United Nations – Division of Sustainable Development [UNDSD], 2008b). Haas (2004) added that a new complex decentralized international governance system is emerging. It is characterized by a multitude of actors working at various levels. Hence,

relying the analysis of societal efforts for a sustainability transition solely on governmental actions is a reductionist and misleading approach.

Still, global environmental policy experienced significant accomplishments in regulating specific threats arising from technological developments. That is the case of the 2000 Protocol on Biosafety and the 2001 Stockholm Convention on Persistent Organic Pollutants. Before, in 1997, world leaders signed the Kyoto Protocol, but it was not until 2005 that it came into force.

2.3 Metrics of political activity

Data that could serve as a proxy of sustainable development policy and capable of depicting the patterns of political activity was gathered³. Five indicators were used for this purpose: the number of new parties to multilateral environmental agreements as registered by WRI (2008); the number of environmental agreements, amendments and protocols signed according to Mitchell (2008); the number of protected areas created (UNEP & IUCN, 2008); the number of environmental ministries established (Selin & Linnér, 2005); and the government expenditure on environmental protection (Organization for Economic Co-operation and Development [OECD], 2008). Mitchell (2003, p. 432) defines an international environmental agreement as an “intergovernmental document intended as legally binding with a primary stated purpose of preventing or managing human impacts on natural resources.” Those are reliable indicators cited in respectable publications (e.g., Selin & Linnér, 2005; UNEP, 2002; WRI, 2003), but they were also the only ones available at a global or regional level with a convenient time coverage. Data concerning environmental expenditures were available from OECD (2008) on a country basis and as national currencies at current prices. Data gaps were large before 1996, potentially leading to inconsistent results. To avoid this misleading effect, values prior to 1996 were discarded and the remaining values were converted to Euros at the exchange rate as of 18 December 2008. For each year, a weighed *per capita* average for the whole set of countries (Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Netherlands, Norway, Spain, Sweden and United Kingdom) was calculated.

To facilitate comparisons between variables – as units and scales were highly diverse – an index was computed in such a way that, for each indicator, zero was made to correspond to its minimum value and 100 to its maximum. Then, in order to smooth the lines and avoid their excessive yearly fluctuation, data were averaged on a three-year basis, *i.e.*, each point represents the average between the values of the previous, current, and following years.

³ The methodology hereby described refers to the specific study presented in this chapter and should not be confused with the overall methodology of this thesis (chapter 4).

The Fletcher database (Ginn, 2008) was used to characterize the primary topics covered by multilaterals agreements. This source was favored instead of Mitchell (2008) because of its higher selectivity (only the most relevant agreements are listed) but broader thematic scope (human rights and cultural protection agreements are included, contrary to what happens with Mitchell's database, which deals only with environmental agreements).

2.3.1 Policy cycles

Global political activity concerning sustainable development followed an intermittent path characterized by periods of significant accomplishments and by others less successful. Figure 2.3-1 depicts this cycling pattern through the use of data indicating political will (cf. Table 2.3-1 for some descriptive statistics about these indicators).

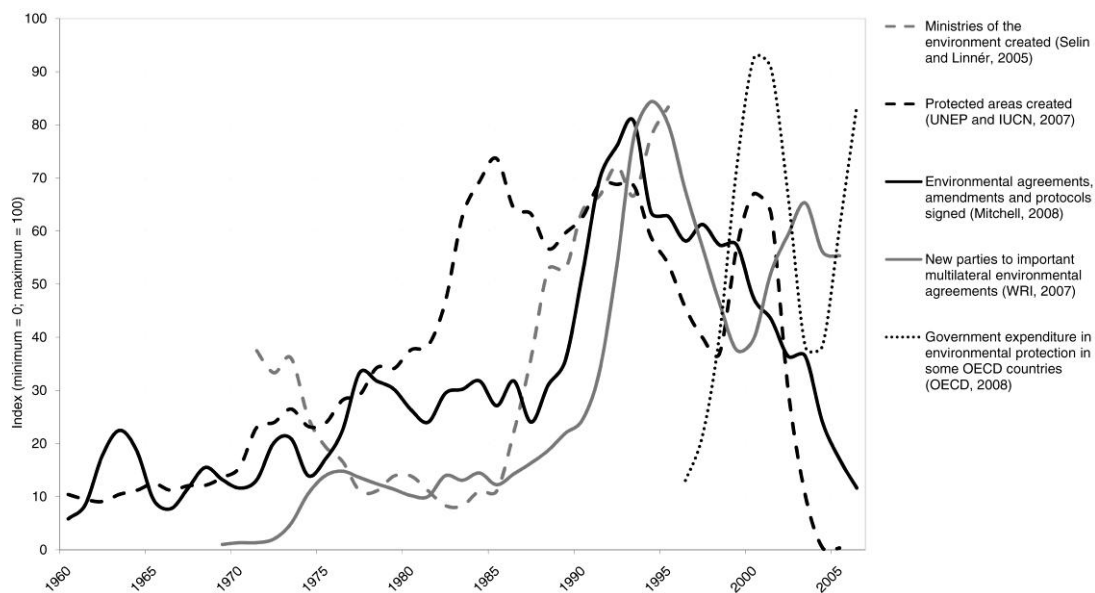


Figure 2.3-1: Indicators reflecting the evolution of sustainable development political activity. Source: own work based on the references cited.

Table 2.3-1: Descriptive statistics for the indicators of political activity used.

Name	Source	Index = 0	Index = 100	Average	Units
Ministries of the environment created	Selin & Linnér, 2005	0	12	4,1	Number
Protected areas created	UNEP & IUCN, 2008	238	3562	1450	Number
Environmental agreements, amendments and protocols signed	Mitchell, 2008	4	47	17,4	Number
New parties to important multilateral environmental agreements	WRI, 2008	1	197	57,3	Number
Governmental expenditure in environmental protection in some OECD countries*	OECD, 2008	235	250	244	Euros per capita

* Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Netherlands, Norway, Spain, Sweden, and United Kingdom.

Although it is beyond the scope of this chapter a careful analysis of each of the indicators represented in Figure 2.3-1, since the intention is to depict cycles of political activity from their joint interpretation, some interesting results are worth mentioning. Between the United Nations Conference on the Human Environment (UNCHE) and UNCED, the rate of agreements, amendments, and protocols was around 17 per year. That rate increased significantly to around 30 until WSSD. A similar transition is recognizable in the creation of protected areas: the rate increased from 1275 parks per year between UNCHE and the Stockholm +10 summit (in 1982), to 2213 until WSSD. Curves may also show different stages of environmental policy. For instance, the first efforts of establishing environmental ministries were followed by the creation of protected areas, which cannot also continue indefinitely, and the signature of environmental agreements requires the existence of issues not properly covered by existing treaties. Conca (2007) and D'Amato & Engel (D'Amato & Engel, 1997) suggest that governments nowadays privilege “soft-law” instead of “hard law” as a way to “maximize flexibility and minimize binding,” which may also explain the declining numbers of environmental treaties signed per year since 1994. In addition, there is an excessive proliferation of treaties and a fragmentation of international bodies which are in part to blame for implementation difficulties of the environmental agenda (UNEP, 2007; WRI, 2003).

Despite these possible confounding factors and the fact that the curves do not always follow each other's trends, they do form a pattern of four main periods of growth and decline: a first period of “starting up” growth until around 1979 (3 out of 4 indicators); a second period of stagnation or even recession between 1980 and 1986 (3 out of 4 indicators); a third period of

steep growth between 1987 and 1995 (4 out of 4 indicators); and a final period of decline since 1995, although interrupted by a short peak around 2000 (5 out of 5 indicators). Data is valid until 2006, from when no conclusions can be drawn.

These conclusions are supported by qualitative assessments of environmental policy and awareness made by Conca (2007), by the brief environmental sociology presented in Røpke (2005), and by the deep perspective of the Portuguese philosopher Soromenho-Marques (2005, pp. 46-47). All of them propose periods of growth and decline in political activity that differ only slightly from the time intervals above.

Interestingly, peaks in the curves of Figure 2.3-1 occur in stages of higher concentration of the political milestones identified in Table 2.2-1, particularly with the decennial Earth Summits. The first of them, around 1973, coincides with the UNCHE, with three agreements (World Heritage Convention, Conference on International Trade in Endangered Species of Wild Fauna and Flora, and the Convention for the Prevention of Pollution from Ships) and with the creation of UNEP; the second peak, around 1992, coincides with UNCED, with two agreements (Convention on Biological Diversity and United Nations Framework Convention on Climate Change), with the creation of United Nations Commission on Sustainable Development and with the approval of Agenda 21; lastly, the peak around 2000–2001 coincides with two conferences (the Millennium Summit and WSSD) and with two agreements (the Cartagena Protocol on Biosafety and the Stockholm Convention on Persistent Organic Pollutants). As suggested by Hibbard, et al. (2007) and supported by these results, major events such as the Earth Summits appear to function as catalysts of political action and multilateralism.

2.3.2 Themes addressed

The interpretation of Figure 2.3-2, which pinpoints in time the signature of the multilateral agreements registered in the Fletcher Multilaterals Database (Ginn, 2008), suggests that significant global legislative efforts started around 1950 to protect biodiversity (there are only 3 records before this date, the first of them in 1911); developed in mid sixties for protecting human rights; progressed in late sixties for waste, chemicals and pollution issues (only two sparse records before), as well as for cultural protection; begun in late seventies for sustaining ecosystems (just two distant records before); and finally started in the beginning of nineties for governance issues, including transboundary cooperation and public participation.

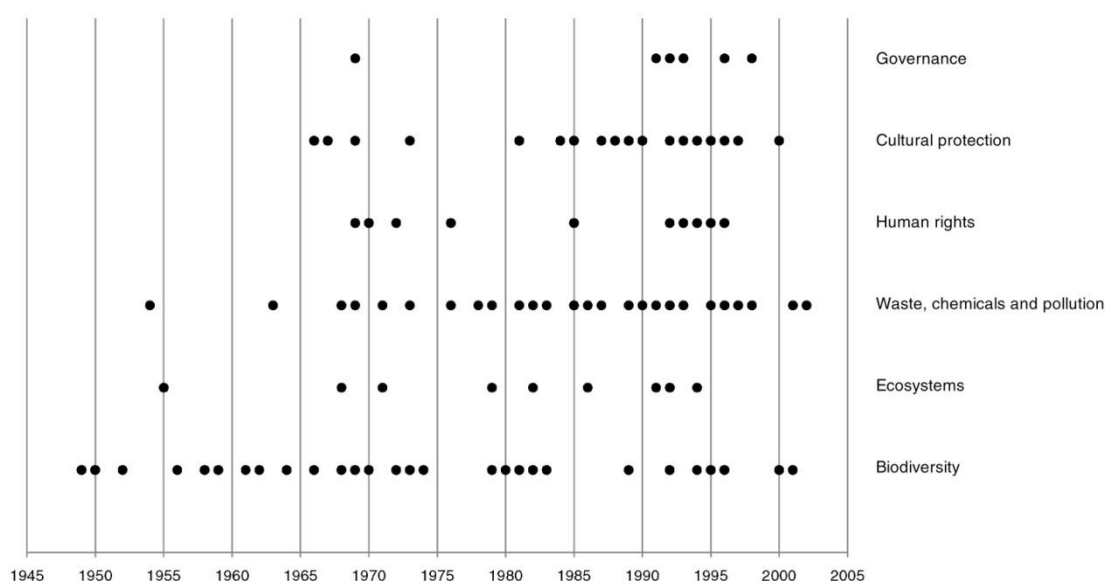


Figure 2.3-2: Thematic representation of international multilateral agreements. Source: own work based on the Fletcher database (Ginn, 2008).

Almost half ($n = 348$) of all multilateral environmental agreements registered by Mitchell (2008) attempt to protect species or manage human impacts on those species. From these, more than one third relate to the management of fisheries, and another third deal with marine animals including whales, turtles and seals. More than half of all pollution agreements ($n = 126$) address marine pollution, but many concentrate on lake and river pollution (Mitchell, 2003). Over time, new agreements have progressed from focusing on “basic” and single issues such as pollution prevention and conservation of certain species, to more complex and integrated approaches such as the conservation of entire ecosystems, the management of watersheds and the attainment of air quality standards (WRI, 2003; D'Amato & Engel, 1997).

In a similar vein, the agendas, goals and targets of political milestones have been evolving. In order to facilitate meaningful comparisons, Table 2.3-2 summarizes the achievements of selected initiatives and classifies them into main topics. These resemble the traditional three pillars that are commonly referred as the dimensions of sustainable development (the Johannesburg Declaration on Sustainable Development, for instance, adopts the pillars of economic development, social development and environmental protection).

Table 2.3-2: Comparison of sustainable development agendas, goals and targets as expressed in selected conferences, declarations and publications.

The table draws from Leiserowitz, et al. (2006), Selin & Linnér (2005), Soromenho-Marques (2005) and Kirkby, et al. (1999).

Sustainability milestone*	Sustaining natural capital and life support systems	Minimizing human impacts	Developing human and social capital	Developing economy and institutions	Other general outputs
UNCHE (1972)	(A) Biodiversity (A) Soil erosion (A) Deforestation	(A) Ozone depletion (A) Air and water pollution (A) Household, hazardous and radioactive waste (A) Global warming Population growth		(A) Rapid industrialization (A) Cooperation on environment and development (I) UNEP	(D) Stockholm Declaration (26 principles) (D) Stockholm Action Plan (109 recommendations) (D) Five resolutions
World Conservation Strategy (1980)	(A) Genetic diversity (A) Ecological processes (A) Life support systems (G) Sustainable use of species and ecosystems				

Table 2.3-2 (continued)

Sustainability milestone*	Sustaining natural capital and life support systems	Minimizing human impacts	Developing human and social capital	Developing economy and institutions	Other general outputs
WCED (1987)	(A) Resources	(A) Population growth	(G) Meet basic needs	(A) Growth (A) Quality of growth (A) Technology (A) Risk (A) International cooperation (G) Green economy (T) 5 to 10-fold more growth	(D) "Our common future" (T) Achieve sustainable development by 2000
UNCED (1992)	(A) Biodiversity (A) Biotechnology (A) Forests (A) Soils (A) Resources (A) Water (D) Statement of Forest Principles (M) Convention on Biological Diversity (M) United Nations Convention to Combat Desertification	(A) Hazardous waste (A) Climate change (M) United Nations Framework Convention on Climate Change	(A) Environmental education (A) Poverty	(A) Financing (T) 0,7 per cent of gross national product for official development assistance (I) United Nations Commission on Sustainable Development (I) Global Environment Facility	(D) Rio Declaration (27 principles) (D) Agenda 21 (40 chapters)

Table 2.3-2 (continued)

Sustainability milestone*	Sustaining natural capital and life support systems	Minimizing human impacts	Developing human and social capital	Developing economy and institutions	Other general outputs
United Nations Millennium Declaration (2000)	(G) Respect for nature (G) Protect common environment		(G) Tolerance (G) Peace (G) Freedom (G) Security (G) Disarmament (G) Human rights (G) Equality (G) Poverty eradication (G) Solidarity (G) Protect the vulnerable	(G) Democracy (G) Good governance (G) Shared responsibility (G) Strengthen the United Nations	

Table 2.3-2 (continued)

Sustainability milestone*	Sustaining natural capital and life support systems	Minimizing human impacts	Developing human and social capital	Developing economy and institutions	Other general outputs
WSSD (2002)	(A) Biodiversity (A) Water (T) Significantly reducing the rate of biodiversity loss by 2010 (T) Returning fisheries to maximum sustainable yield levels by 2015		(A) Health (A) Sanitation (T) Halve, between 1990 and 2015, the proportion of people whose income is < \$1 a day (T) Between 1990 and 2015 reduce by 2/3 the < 5 mortality rate (T) By 2015 halt and begin to reverse the spread of AIDS (T) Halve, by 2015, the proportion of people without access to safe drinking water (T) Achieve, by 2020, a significant improvement to the lives of at least 100 million slum dwellers	(A) Energy (A) Agriculture (A) Institutions for sustainability	(D) Johannesburg Declaration (37 principles) (D) Johannesburg Plan of Implementation (170 paragraphs)

* A: topic of the agenda; D: declaration; G: goal; M: multilateral agreement; I: institution; T: target.

2.4 Scientific approaches to sustainability

A presentation of the different achievements of sustainable development research poses the problem of how to do it. Each approach constitutes a distinct body of knowledge with its own structure, reputation and publications, but boundaries are often blurred and interconnections abundant. Inspiration was then sought in Sneddon, et al. (2006) and Røpke (2005). Sneddon, et al. divide sustainable development approaches into ecological economics, political ecology and development as freedom. Røpke (2005), in analyzing the development of ecological economics, sticks to a framework consisting of five categories: its knowledge structure, reputational autonomy, internal organization, institutionalization, and relations to the outside world. This section of the thesis uses a more empirical classification based on the similitude between the different sustainability approaches.

A literature review was carried out describing the main scientific approaches that helped to shape the development of sustainable development since the sixties. Ethical, philosophical or environmentalist contributions are beyond the scope of this chapter. While care was taken to include commonly cited research and to grasp the complexity and wide array of topics comprised within sustainable development, there was no intention to be exhaustive. The selection hereby presented should be interpreted as illustrative of important scientific paradigms. For organizational and summary purposes, sustainability approaches were grouped into categories. The principle behind this division was the similitude of ideological positioning as concluded from normative attitudes and rationale of human-environment relationships. The sequence is both chronologically and conceptually sound, even if some of the approaches could reasonably fit more than one category. Some of the developments presented are dated (“The population bomb,” for instance), but others represents schools of thought characteristic of specific scientific disciplines that coexist nowadays (e.g., thermodynamics, ecological economics, etc.).

2.4.1 The limits approach

Paul Ehrlich’s “Population bomb”

The idea of limited planetary resources appeared at least in 1966, when the British economist Kenneth Boulding published “The economics of the coming spaceship Earth.” Only two years later, in 1968, American biologist Paul Ehrlich published his most famous and polemic work. In “The population bomb,” Ehrlich presented a neo-Malthusian theory claiming that during “the seventies and eighties, hundreds of millions of people will starve to death in spite of any crash programs embarked upon now” and assuring that “the battle to feed all of humanity is over”

(Ehrlich, 1968). These predictions proved to be wrong and have been severely criticized since the book's publication (Selin & Linnér, 2005), but they raised awareness to the issue of population growth and to the scarcity of resources available to feed it. Ehrlich failed to take into account the significant increase in agriculture productivity brought about by the green revolution, even if famine and undernourishment are still commonplace nowadays in the developing world.

Garret Hardin's "Tragedy of the commons"

In the same year of 1968, Garret Hardin published what is identified in section 2.6 as one of the most cited articles in the sustainable development literature. The "tragedy of the commons" is a metaphor that symbolizes the institutional failure of managing open access resources such as the atmosphere. The lack of well-defined property rights results in the absence of successful management systems and of enforcement mechanisms, encouraging each agent (farmer, fisher, polluter, etc.) to free ride the resource, eventually leading to its overexploitation.

Thermodynamics

Sustainability thinking has been strongly influenced by thermodynamic concepts, in particular the entropy law. The work of the Romanian economist Nicholas Georgescu-Roegen, namely "The Entropy Law and the Economic Process" (1971), is frequently credited as a source of inspiration and deep thought about the physical conditions that effectively limit the scale of human enterprise (Hammond, 2004). Literature about the energetic and thermodynamic implications on a system's viability is vast and complex, but its main implications may be summarized as follows: on one side, the quality and amount of available energy ("exergy," which can be understood as the opposite of "entropy") constrains the level of complexity attainable by a system according to the maximum empower principle (Falkowski & Tchernov, 2004; Odum & Odum, 2006) and, hence, its capacity to maintain nonequilibrium dynamics with its environment. That is the case of urban systems, which are considered self-organizing dissipative structures dependent on large amounts of high quality energy coming from the exterior (Portugali, 2000). On the other side, some authors have argued that exergy degradation is inversely correlated with economic efficiency, and thus could serve as an indicator of environmental sustainability (Hammond, 2004). Odum & Odum (2006) even analyzed the implications to society of several thermodynamic principles, concluding that a "prosperous way down" is necessary if civilization aspires to progress. Relying on thermodynamics for sustainability assessment was argued by Hammond as being an approach grounded in the domain of the metaphor rather than in science.

Thermodynamic constraints had a significant influence on ecological economics (Pearce, 2002) and, particularly, on the development of the Natural Step conditions in 1989, which constitute a possible way, even if ambiguous, to operationalize sustainability. Funtowicz (1999) concluded that, for an economy to be sustainable, the energy productivity of human labor must be higher than the efficiency of the transformation of energy intake into human work. Daly (1990) devised four system conditions—later improved by Robèrt, Daly, Hawken, & Holmberg (1997)—which should also be considered as minimum sustainability requirements: substances from the lithosphere must not systematically increase in the ecosphere; substances produced by society must not systematically increase in the ecosphere; the physical basis for the productivity and diversity of Nature must not be systematically deteriorated; and fair and efficient use of resources with respect to meeting human needs.

Club of Rome's "Limits to growth"

"Limits to growth," the report prepared in 1972 by Meadows, Meadows, Randers, & Behrens (1972) for the Club of Rome (a global think tank dealing with international political issues) called the attention of the world to the biophysical limits imposed on economic growth. Its major importance for the sustainable development literature is numerically demonstrated in section 2.6. In examining future scenarios for five variables—technology, population, nutrition, natural resources, and environment—Meadows, et al. (1972) claimed that "if the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next 100 years." Based on the prediction model World3, the authors added that sustainability was still possible to achieve if the population and economical growth ceased (UNEP, 2002).

The implications of this discourse were far reaching since it challenged basic human assumptions about unrestrained growth (Goodland, 1995). As such, the criticisms from opponents were severe and often misinformed. Meadows (2007), in a recent review of his team's work, reaffirmed the main conclusions of "Limits to Growth" and its subsequent updates ("Beyond the Limits" and "Limits to Growth: the 30-year update"). The important conclusion is not about the prediction accuracy, but that humanity faces a problem of growth where resources are limited and thus actions are needed in order to avoid collapse.

2.4.2 The means and ends approach

Steady state economics

Contrasting with the conventional economic theories that emphasize throughput growth and consider as limiting production factors only labor and man-made capital, former World Bank

economist Herman Daly presented the idea of a steady state economy (Daly, 1973). Building on John Stuart Mill's proposals formulated back in the XIX century and influenced by the thermodynamic constraints described by Georgescu-Roegen (Pearce, 2002), Daly struggles for an economic development within Earth's carrying capacity, or, as he puts it later on, "development without growth" (Daly, 1996, p. 69). Growth should be understood as an increase in throughput holding production efficiency constant, and development as an increase in services obtained from both higher production efficiency (stock per unit of throughput ratio) and effectiveness (service per unit of stock ratio) holding throughput constant. The very notion of "externalities" is criticized by Daly, who argues that fundamental issues such as the maintenance of life supporting systems cannot be conveniently addressed as a lateral issue in economics.

Since the sources of social welfare are the capital assets of an economy, they must not be depreciated through time. But that's exactly what is happening with the natural capital, rendering it the limiting production factor in the economy. Thus, Daly concludes, sustainable development is only possible in a steady-state economy whose scale is sufficiently small so as to allow the proper function of Earth's ecosystems (Daly, 1996).

Meadows' sustainability pyramid

In his already mentioned work, Daly (1973) proposed a simple conceptual framework for sustainability indicators. The pyramid, later improved by Meadows (1998), draws attention to the main socioeconomic resources and processes essential to ensure a system's viability (cf. Figure 2.4-1). The hierarchical structure portrays a grading from (a) *ultimate means* at the base (natural capital, or the resources out of which all life and all economic transactions are built and sustained), followed by (b) *intermediate means* (human and built capital, which define the productive capacity of the economy), then by (c) *intermediate ends* (human and social capital, or the goals that economies are expected to deliver, such as consumer goods, health, knowledge, leisure, communication and transportation), eventually leading to society's (d) *ultimate ends* (the *summum bonum* of society: happiness, identity, freedom, fulfillment, etc.). Meadows' structure is deeply rooted in the capital approach of indicator frameworks (cf. section 2.7).

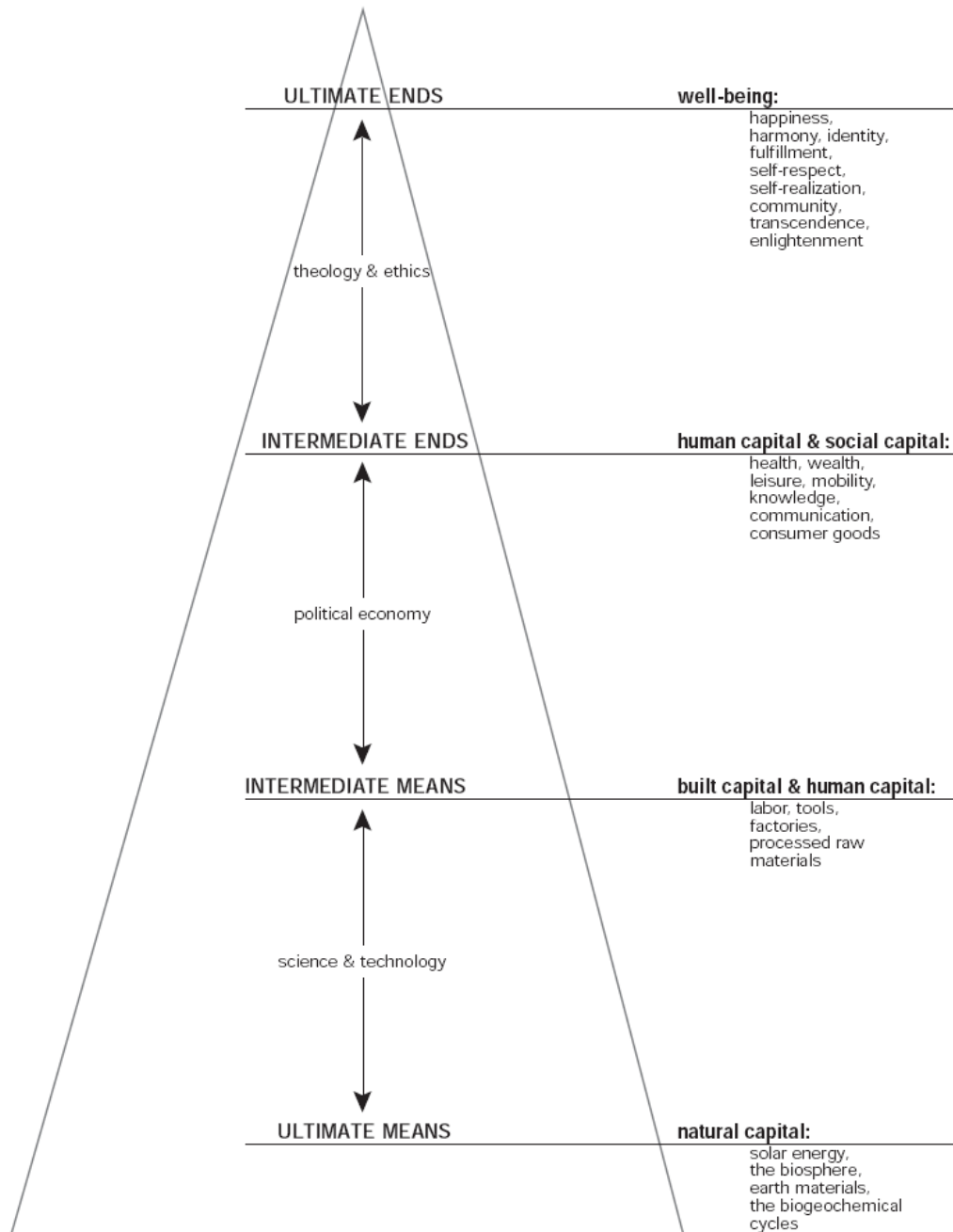


Figure 2.4-1: Meadows' sustainability pyramid.

2.4.3 The needs and capabilities approach

Brundtland's report "Our common future"

The WCED was set up by the General Assembly of the United Nations in 1982 as an "independent" group of high-level experts and government officials chaired by the then-Prime Minister of Norway Gro Harlem Brundtland. The commission was asked to formulate a "global agenda for change" and, more specifically, to "propose long-term environmental strategies for achieving sustainable development by the year 2000 and beyond" (WCED, 1987). The report

“Our Common Future,” released in 1987 after three years of public hearings, is the most cited document in the sustainable development literature (see section 2.6). Being able to reconcile the environmental interests of the North with the development needs of the South, the commission effectively joined the world through the catchphrase “sustainable development.” The concept, defined as “meeting the needs of the present generation without compromising the ability of future generations to meet their own needs,” although stated with a similar meaning as far back as 1979 (as can be checked through a search in Mitchell, 2008), became popular only after Brundtland’s work (Selin & Linnér, 2005).

The report explores the factors behind the growing equity gap between the rich and the poor and issued guidance so that sustainable development could be integrated into countries’ policies. These ranged from asking for more growth, conserve and enhance the resource base, ensure a sustainable level of population, reorient technology, integrate environmental concerns into decision-making and strengthen international cooperation (WCED, 1987).

Some of the commission’s statements were rather controversial. For instance, the appeal for a sustainable economic growth is at odds, according to Daly (1996), with sustainable development. However, it is important to bear in mind the procedural and political contexts under which the report was prepared, which probably prevented the commission from refining all discrepancies and lead to what Kirkby, et al. (1999, p. 9) called “irreconcilable positions.” Or it may be that the commission truly believed that the growth limits were only technical, cultural and social, dismissing the biophysical limits that nowadays seem very present. Brundtland’s original call for a “5 to 10-fold more growth” was rectified and reversed in 1992 by placing population higher on the agenda of sustainability (Goodland, 1995, p. 9).

A broad range of needs and goals

A long debate has been going on regarding how to improve quality of decision-making processes. Several authors argue for a broader set of criteria instead of aggregating different categories into an often misleading single unit (e.g., Costanza, 2003a; Finco & Nijkamp, 2001; Funtowicz, 1999; Munda, 2008). There are two main issues at stake: first, the substantial question of whether different criteria (namely, nature conservation and economic prosperity) should, in principle, be aggregated; second, when such aggregation is accepted on ethical or practical grounds, the question of how to carry out a scientifically sound process follows. The latter has been called the “commensurability problem” (Böhringer & Jochem, 2007).

The influence of social scientists such as Abraham Maslow and, more recently, Manfred Max-Neef, has swept through the ecological economics and planning fields. They stress the irreducible character of human needs (Funtowicz, 1999; Lambin, 2004). Alkire (2002) surveyed several other theoretical proposals and lists of human development dimensions. Bossel (1999) attempted to further extend the concept of needs to all systems, and formulated what he calls

the “basic orientators” (Figure 2.4-2). Tantamount to human needs, these orientators (existence, effectiveness, freedom of action, security, adaptability, coexistence) must be satisfied in some extent for a system to be viable, but no clues are given as to draw the borderline between sustainability and unsustainability. Because orientators guide system’s response to environmental properties, Bossel reasons, they also act as evolutionary forces.

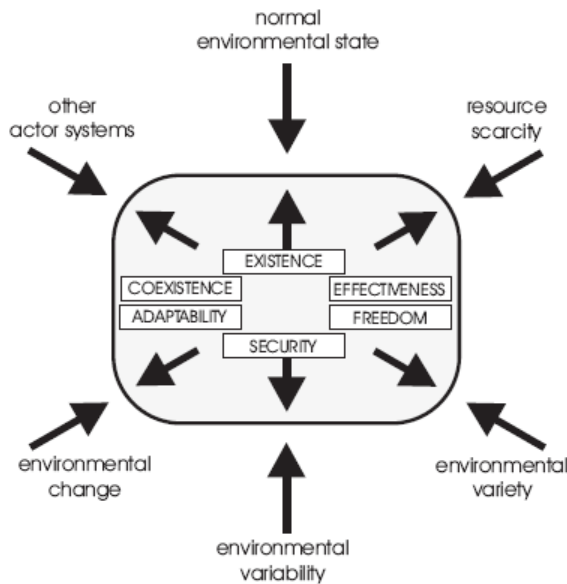


Figure 2.4-2: Fundamental properties of system environment and their basic orientator counterparts in systems. Source: Bossel, 1999.

The second question – of how to correctly aggregate different criteria into a single unit – is a promising methodological research field. Aggregated environmental indices are being devised and improved by scientists in spite of the inherent difficulties of such a process and the serious doubts about what is exactly being measured (Parris & Kates, 2003b). Valuation tools used in multicriteria and cost-benefit analyses are making progresses in calculating a good’s total economic value, which comprises both use and nonuse values seldom valued by existing markets. Indices such as the ecological footprint or the human development index use different aggregation methods.

This aggregation controversy should not be separated from the conflict between model complexity and measuring capacity. One may have to be compromised in favor of the other. Ultimately, the decision about whether or not to aggregate depends on the desired goal. Decisions concerning projects with significant impacts should in principle be based on more complex multicriteria analyses with limited and precisely explained aggregations, so as to capture a more faithful picture of the reality (Costanza, 2003a; Funtowicz, 1999), instead of relying on narrowly defined and utilitarian views of social welfare such as the aggregate economic growth (Daly, 1996; Dasgupta, 2001; Pearce, 2002; Sneddon, et al., 2006).

The concept of human needs was somehow replaced by the modern ideology emphasizing human rights (Redclift, 2006) and corresponding human values. Freedom, equality, solidarity, tolerance, respect, and shared responsibility were identified by the United Nations Millennium Declaration as the essential values governing international relations in the XXI century, but the gap between those values, attitudes, and behaviors needs to be bridged for a sustainability transition to occur (Leiserowitz, et al., 2006).

Sen's "Development as freedom"

Indian economist and Nobel prize Amartya Sen built a robust approach to development economics, reclaiming its original significance of improving people's welfare and stressing its role as a process of expanding people's substantive freedoms. "Development as freedom" (Sen, 1999/2003) builds on hundreds of studies covering a multitude of sectors – many of them portraying Indian and Asiatic realities – to provide a deep argument about the foundations of society's progress and development. Adam Smith and other "fathers" of modern economics are repeatedly cited, often to correct commonplace but misleading ideas about them. Several phenomena, such as the Bengal famine of 1943 and the decline in fertility rates, are explained through a combination of social and economic data – a method that is increasingly used to explain complex system behavior, instead of simple cause and effect mechanisms (Costanza, Graumlich, & Steffen, 2007a).

Sen's *capability approach* shed new light on the process of development, which was conceptualized as an expansion of individual capabilities and social opportunities, and not as an increase in consumption, health, and education alone. In addition, Sen argued against the existence of a universal list of capabilities that should be promoted. Instead, priorities are value judgments that should be made explicitly, and in many cases by a process of public debate (Alkire, 2002). Well-being is conceptualized by Sen into constituents and determinants. Constituents have an intrinsic value, whereas determinants are only of instrumental importance insofar they contribute to a higher level of the former.

An important lesson for the sustainability debate should be derived from Sen's argument: that development issues, too often left on a secondary place, are at the centre of sustainable development.

2.4.4 The complexity approach

Complex socioecological systems

Human ecology approaches were introduced in the 1920s and 30s in order to study the interactions between society and the environment (Machlis & Force, 1997). With the advent of the *great acceleration* (Hibbard, et al., 2007) or the *anthropocene* (Crutzen, 2002), most

environmental problems can only be understood as a result of the interplay between human driving forces and ecosystem dynamics (Gallopín, 2002; Scheffer, Westley, Brock, & Holmgren, 2002). Socioecological models combine information from several disciplines and therefore are, in principle, better suited to account for system changes. A number of such frameworks revealing the interactions between human beings and nature have been proposed (e.g., Alberti, et al., 2003; Haberl, Fischer-Kowalski, Krausmann, Weisz, & Winiwarter, 2004; Hjorth & Bagheri, 2006; Machlis & Force, 1997; Ostrom, 2007; Pickett, et al., 1997; Piracha & Marcotullio, 2003; Young, et al., 2007; see also Figure 2.4-3).

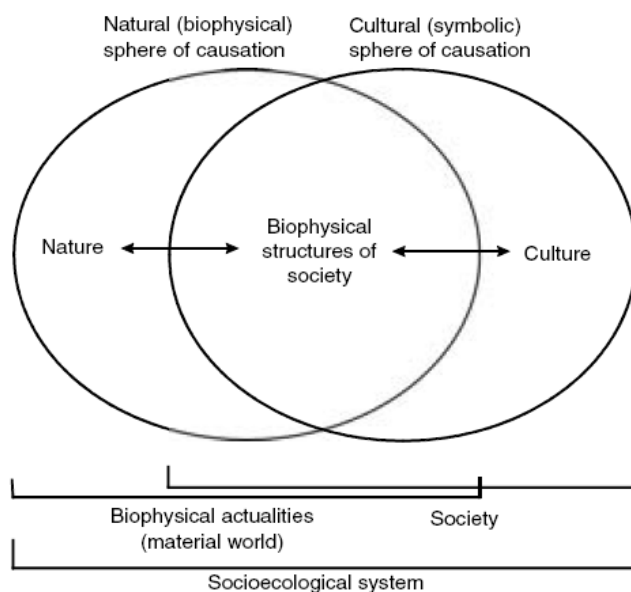


Figure 2.4-3: Socioecological systems as the overlap of a natural and a cultural sphere of causation. Source: Haberl, et al., 2004.

Elinor Ostrom is a notable example: her long-lasting studies about the governance of public goods integrate social and natural sciences and provide powerful insights and conclusions about the factors that account for systematic changes in the systems being studied (Figure 2.4-4). Ostrom & Nagendra (2006), for instance, combined multiscale information obtained from land cover cartography, on the ground assessments and laboratory experiments to examine the relationships between forest conditions under a variety of tenure arrangements.

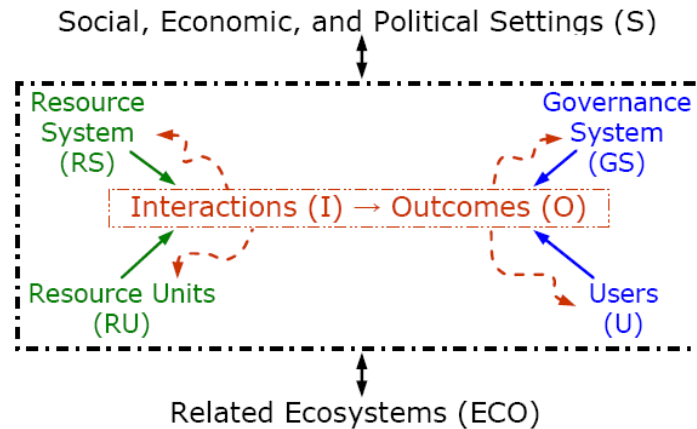


Figure 2.4-4: A multitier framework for analyzing a socioecological system. Straight arrows represent direct causal links; red, curved arrows represent feedbacks. Source: Ostrom, 2007.

Another promising use of a combined social and ecological analysis is that of the syndrome approach: narratives of “archetypical nonsustainable patterns of civilization-nature interactions” (de Vries, 2007). The syndrome approach is a response to the difficulties posed by the complex nature of the systems being studied. Instead of relying on simple cause-effect mechanisms, patterns of interactions between important variables are preferred which account for system’s multiple states, self-organization, nonlinearities and eventually collapses (Costanza, et al., 2007a; International Council for Science, 2002; MEA, 2005).

Panarchy, adaptive cycles and resilience

A dynamic view of sustainable development is provided by Gunderson & Holling’s (2002) theory of panarchy. Refurbishing and elegantly merging existing theories in the fields of ecology and sociology, the theory of panarchy rests on the concepts of resilience, connectedness and potential to explain the cyclical patterns of a complex system’s evolution (Figure 2.4-5). A panarchy thus consists of a nested set of adaptive cycles, each undergoing its own evolution through four different phases: long periods of slow accumulation and transformation of resources (from exploitation to conservation), and faster periods that create opportunities for innovation (from release to reorganization) (Holling, 2001).

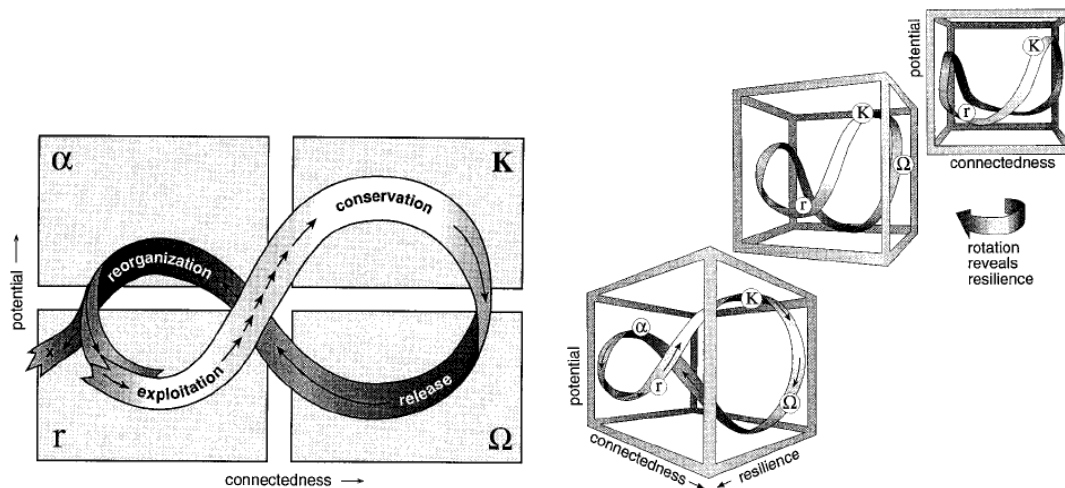


Figure 2.4-5: The four phases of a panarchy. Source: Holling, 2001.

One of the interesting traits of this theory is its ability to address the relationships between geographical and temporal scales, or how “slower and larger levels set the conditions within which faster and smaller ones function” (Holling, 2001, p. 397). The whole panarchy promotes a system’s sustainability and development: sustainability because it enhances, tests, and maintains its adaptive capability; and development because it fosters the emergence of new opportunities that may prove essential for its survival. Holling argues that the term sustainable development therefore is not an oxymoron, since the combination of the two properties shape a “logical partnership.”

Learning and adaptive capacity play a central role in the theory of panarchy and are stressed by several scholars as fundamental conditions needed for a sustainability transition (Bossel, 2000; Clark, Crutzen, & Schellnhuber, 2004; Hjorth & Bagheri, 2006; Holling, Gunderson, & Ludwig, 2002; International Council for Science, 2002; Kates & Parris, 2003; Lambin, 2004; MEA, 2005).

2.4.5 The consilience approach

Ecological economics

In reviewing the history of ecological economics, Pearce (2002) traces its origins back to the fifties, when the NGO “Resources for the Future” was established in the United States. Funtowicz (1999) refers to the later eighties, when discontentment with the dominant trends in economics, namely its negligence to ecological constraints, led to the appearance of contesting views. Røpke (2005), in turn, situates the birth of the discipline in 1988, when the International Society for Ecological Economics was established, or in 1989, when the first issue of its journal was published.

Ecological economics has been broadly defined as the science and management of sustainability (Costanza, 1991) – even if it is probably too much of an ambition. Ecological economics' distinctiveness may well be asserted to its scope, which embraces not only the allocation of resources addressed by conventional economics, but also distribution of resources and the scale of markets. Together, these issues tackle three fundamental concerns of sustainability: efficiency, justice and environmental impact (Daly, 1996). Ultimately, conventional and ecological economics differ strongly in what Joseph Schumpeter calls the “pre-analytic vision” of the world. Whereas the former considers resources and sinks almost limitless (an “empty world”), ecological economics stresses the limiting quality of natural capital and the impacts resulting from human economy (the “full world”) (Costanza, 2003b; Daly, 1996; Røpke, 2005). Economic scale should consequently be limited by the system's carrying capacity (Daly, 1996). The treatment given to externalities – impacts on any party not involved in a given economic transaction – is another matter of differentiation. They used to be regarded as “fairly minor and manageable deviations from the optimum” (Pearce, 2002), but ecological economists consider externalities a problem of institutional dysfunction at the first place. The problem of the external effects often derives from the insufficiently defined property rights, as Coase explained in his theorem in 1960. Typical neoclassical mechanisms devised to address this issue – such as the so-called Pigouvian taxes or the tradable pollution permits – are seen as “uncertain” (Pearce, 2002). Social welfare, in turn, is understood as a function of several needs or values that must be satisfied independently of each other (Funtowicz, 1999). Ecological economists thus regard utilitarian welfare and the choice of discount rates with suspicion. This brings me to another central issue in ecological economics: the debate about strong or weak sustainability. Conventional economics tend to consider human and built capital largely as substitutes for natural capital, whereas ecological economics emphasize their complementarity (Ayres, et al., 1996; Daly, 1996; Goodland, 1995; Røpke, 2005). Natural capital is seen as a critical resource base, or as an *ultimate mean*, on which the whole human ecosystem is dependent (Ekins, 2003; Meadows, 1998). The destruction of the capital base beyond certain thresholds could result in the collapse of ecosystems and eventually of larger systems. Further development of this idea led to the proposal of the critical natural capital concept, defined as “the natural capital which is responsible for important environmental functions and which cannot be substituted in the provision of these functions by manufactured capital” (Ekins, 2003). The level of admitted substitution between natural and man-made capital dictates the strength of sustainability: the stronger it is, the more complementary different forms of capital are considered.

An important application of the ecological economics principles is that of ecosystem services, i.e., “the conditions and processes through which natural ecosystems, and the species that

make them up, sustain and fulfill human life” (Daily, 1997). They were extensively studied between 2001 and 2005 by the 1360 experts involved in the MEA (2005).

As a synthesis, the excellent review of ecological economics’ development made by Røpke (2005) is instructive. She summarizes the core beliefs of the discipline as: the idea of the economy embedded in nature and limited in scale by the natural capital sustaining capacity; the need for transdisciplinary work and system thinking in order to correctly analyze socioecological systems; the acknowledgement of uncertainty and ignorance; the concern for how resources and wealth are distributed across society; and the broader set of criteria used in evaluating different development options, which include the intrinsic value of nature (Røpke, 2005, p. 267).

National Research Council’s “Our common journey”

NRC published in 1999 a landmark study about sustainable development that provided an in-depth review of several issues left answered by the Brundtland Commission. One of the achievements was the organization of a taxonomy of sustainable development arranged as “what is to be sustained” (nature, life support and community), “for how long” and “what is to be developed” (people, economy and society) (NRC, 1999, p. 24 – cf. Figure 2.4-6). Each of the subitems was further divided into more specific goals, thus strengthening the conceptual foundations of sustainable development and avoiding the usual criticism of an imprecise definition. While this is a significant advance, more challenging questions – about, for instance, how to achieve those goals and what is the precise scale of tolerable human interference on the Earth system – are left unanswered.

The Board on Sustainable Development of NRC emphasized the idea of a transition towards sustainability (hence the title “Our common journey”): “a transition over the early decades of the 21st century in which a stabilizing world population comes to meet its needs by moving away from action that degrade the planet’s life support systems and living resources, while moving toward those that sustain and restore these systems and resources” (NRC, 1999, p. 21). In accessing different future scenarios, the Board concluded that such a transition is possible over the next two generations, but “significant advances in basic knowledge, in the social capacity and technological capabilities to utilize it, and in the political will” are required to turn knowledge into action.

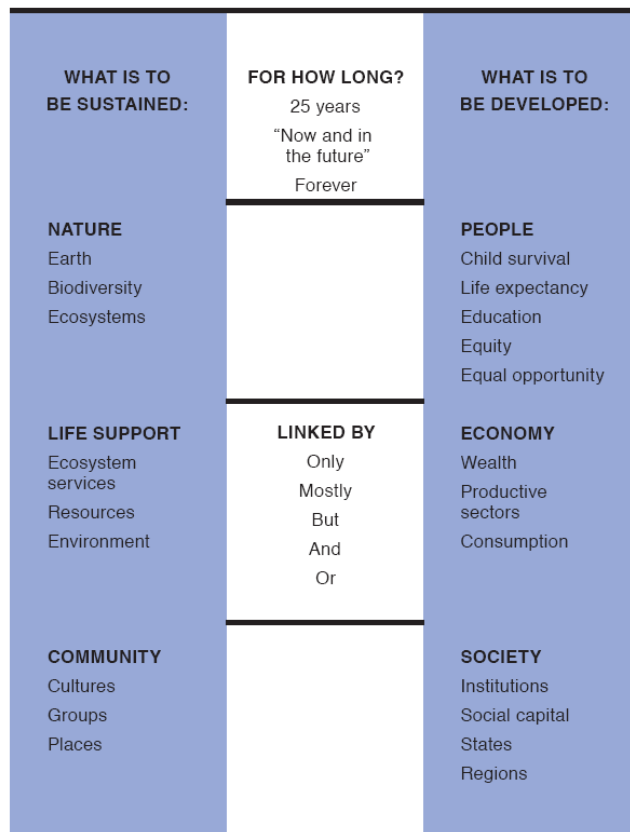


Figure 2.4-6: Taxonomy of sustainable development proposed by NRC. Source: NRC, 1999.

Sustainability science

The legacy of Bacon and Descartes translated into great scientific achievements and the beginning of modern science. Scientists split systems into their constituent parts so that interactions between them can be conveniently studied and replicated. This reductionist approach is the basis of the scientific method, but its limitations become apparent when dealing with complex phenomena. Eduard Wilson (1998) magnificently verbalized the challenge ahead of science in "Consilience: the unity of knowledge." "Predictive syntheses, the ultimate goal of science, are still in an early stage," he wrote (Wilson, 1998, p. 137). How to effectively incorporate information from different disciplines into meaningful theses is of primary importance for sustainable development. It is clear that traditional cause and effect mechanisms do not fit or cannot embrace the complexity of coupled human-environment systems from where the main environmental problems arise.

A new contract between science and society is emerging and its roots date back to the 2001 "Amsterdam Declaration," when delegates from more than 100 countries participating in four big international research programs on global environmental change met together (Clark, et al., 2004). The resulting research program was named sustainability science and focus on the "dynamic interactions between nature and society, with equal attention to how social change shapes the environment and how environmental change shapes society" (Clark & Dickson,

2003; Kates, et al., 2001). Other core questions being addressed include: how are long-term trends in environment and development reshaping nature-society interactions in ways relevant to sustainability; what determines the vulnerability or resilience of the nature-society system in particular kinds of places; which systems of incentive structures can most effectively improve social capacity toward more sustainable trajectories; and how can activities of research planning, monitoring, assessment and decision support be better integrated into systems for adaptive management and societal learning (Clark, et al., 2004; Kates, et al., 2001).

Sustainability science is considered post-normal, *inter alia*, because of its problem driven nature, high uncertainty, transdisciplinarity and openness (Gallopín, 2004; Omann, 2004). The selection of research priorities is accepted as a societal role and not as a sole responsibility of scientists, since “quality is crucial and refers more to the process than to the product” (Funtowicz, 1999, p. 9). Salience, legitimacy and credibility to the public and particularly to policy makers thus become primary criteria to judge the quality of the research process (e.g., Cash, et al., 2003; Funtowicz, 1999; Parris & Kates, 2003b).

International research programs such as the International Geosphere-Biosphere Program and the International Human Dimensions Program are already oriented towards a sustainability science approach, which is finding its own way as a distinct scientific field (Kajikawa, Ohno, Takeda, Matsushima, & Komiyama, 2007; Kates, et al., 2001). It is worth mentioning the research going on under the Integrated History of People on Earth project. A first report summarizing the main human-environment interactions from 10000 years ago until present time was already published (Costanza, et al., 2007a).

2.5 Comparison of sustainability approaches

A tentative synthesis of the sustainability approaches presented before is shown in Table 2.5-I. Relevant definitions and concepts are mentioned to facilitate comparisons.

Table 2.5-1: Comparison of mottos and values as expressed by major scientific approaches to sustainable development.

Reference	Motto	Sustaining natural capital and life support systems	Minimizing human impacts	Developing human and social capital	Developing economy and institutions	Integrative efforts
<u>The limits approach</u>						
“The population bomb” (1968)	Exponential population growth cannot continue because natural resources are in limited supply.	Natural resources	Population growth	Affluence	Technology	
“The tragedy of the commons” (1968)	Common pool resources must be effectively managed in order to avoid their free ride.	Common pool resources	Carrying capacity		Property rights Institutional regime	
Thermodynamics (1970s–)	The sustainability and level of complexity that a system can attain depends on the availability of exergy.	Exergy	Entropy			
“The limits to growth” (1972)	The limits to growth will be reached if the growth trends in population, industrialization, pollution, food production and resource consumption persist.	Natural resources Environment	Population growth	Nutrition	Technology Industrialization	
<u>The means and ends approach</u>						
Steady state economics (1970s–)	Development must be based on a higher economic efficiency and effectiveness so that economic scale can be kept constant and the level of natural assets is maintained.	Stocks (capital assets)	Throughput	Well-being	Services Efficiency Effectiveness	

Table 2.5-I (continued)

Reference	Motto	Sustaining natural capital and life support systems	Minimizing human impacts	Developing human and social capital	Developing economy and institutions	Integrative efforts
Sustainability pyramids (1973 and 1998)	A call to expand the economic calculus to include the top (development) and the bottom (sustainability) of the pyramid.	Ultimate means (natural capital)		Intermediate means (human and built) Ultimate ends (happiness, identity, freedom, fulfillment)	Intermediate ends (human and social capital)	
“Development as freedom” (2001)	Development is enhancing freedom through the expansion of political liberties, economic capabilities, social opportunities, transparency and security.			Social opportunities Security Political liberties	Economic capabilities Transparency	
<u>The needs and capabilities approach</u>						
“Our common future” (1987)	Sustainable development is the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs.	Resources	Population growth	Meet basic needs Equity	Growth and quality of growth Technology Decision-making International cooperation	Risk

Table 2.5-I (continued)

Reference	Motto	Sustaining natural capital and life support systems	Minimizing human impacts	Developing human and social capital	Developing economy and institutions	Integrative efforts
A broad range of needs and goals (1990s–)	A system, in order to be sustainable, must satisfy each of its irreducible needs beyond a certain threshold. Likewise, the development of society has multiple goals that cannot be aggregated into one dimension.			Irreducible needs	Multicriteria decision-making	Adaptability
<u>The complexity approach</u>						
Complex socioecological systems (1990s–)	Understanding the complex and nonlinear patterns of interactions between society and nature.	Resource system		Human system	Norms and institutions	Nonlinearities Self-organization Complexity Interactions
Panarchy, adaptive cycles and resilience (2001–)	Sustainable development is the goal of fostering adaptive capabilities while simultaneously creating opportunities.					Resilience Potential Connectedness
<u>The consilience approach</u>						
Ecological economics (1990s–)	The transdisciplinary research about the interactions between human economies and natural ecosystems.	Natural capital Ecosystem services	Scale	Human capital Social capital	Manufactured capital Institutional capital Equity Efficiency	

Table 2.5-I (continued)

Reference	Motto	Sustaining natural capital and life support systems	Minimizing human impacts	Developing human and social capital	Developing economy and institutions	Integrative efforts
“Our common journey” (1999)	A transition over the early decades of the 21 st century in which a stabilizing world population comes to meet its needs by moving away from action that degrade the planet’s life support systems and living resources, while moving toward those that sustain and restore these systems and resources.	To be sustained (nature, life support)	Population growth	To be sustained (community) To be developed (people, society)	To be developed (economy)	Transition
Sustainability science (2001–)	The dynamic interaction between nature and society, with equal attention to how social change shapes the environment and how environmental change shapes society.			Planning Decision making Social learning	Institutions	Vulnerability Resilience Monitoring Transition

Each of the approaches to sustainable development presented somehow contributed to shape the core beliefs of current sustainability research. It is no wonder, then, that most of the prominent features of ecological economics and sustainability science can be traced back to those more specific approaches. It was the continuous development of sustainability thinking that eventually led to the emergence of those scientific disciplines.

A first distinctive trait of modern sustainability research is the stressing of biophysical and thermodynamical limits. As a result, it considers that the scale of the human economy must not exceed environment's carrying capacity. This line of reasoning was introduced by Boulding, Georgescu-Roegen and Daly. Ecological economics is built around a pre-analytic vision which considers the human economy as embedded in the ecosphere. Natural capital is a limiting production factor and is only partially replaceable by increased human or built capital. The fraction of natural capital that is not substitutable by other kinds of capital is critical for the functioning of the Earth system and therefore must be preserved.

A second attribute of modern sustainability conceptualization is that it is oriented towards societal welfare and development. Sen, for instance, is very much in tune with the spirit of ecological economics, in the sense that he dismisses the neoliberal approach stressing growth as a goal in itself in favor of a more balanced model of development. Daly and Meadows suggested a hierarchy where resources have an instrumental value in attaining ultimate ends, similarly to Sen's distinction between determinants and constituents of well-being. While efficiently communicating the strong sustainability approach endorsed by ecological economics, the structure is lacking some of the dynamics, process orientation, and scale dependence referred by contemporary literature. The taxonomy highlights the substantive character of sustainable development. At a broad scale, according to NRC, sustainability aims at maintaining nature, life support systems, and the community, and at developing people, society and economy. At the individual scale, freedom, equality, solidarity, tolerance, respect, and shared responsibility were identified by the Millennium Declaration as the core values of sustainable development. Sen, in turn, recovered the classical notion of development which he further elaborated as the expansion of political liberties, social opportunities, security, economic capabilities and transparency as the goals.

The third characteristic of sustainability identified in this chapter is the understanding that each system, and particularly every human being, has its own minimum needs in order to be viable. No compensation between different needs is possible beyond this critical point (e.g., money serves of no compensation for a serious health problem). This broad multicriteria vision has several consequences. At the individual level, the irreducible human needs identified by Maslow and Max-Neef are worth mentioning. At an intermediate level, for instance at when a project is devised, sustainability argues that evaluation must be made against a broad set of criteria, and

that it is not intellectually correct to aggregated them into a single measure (contrary to cost-benefit analysis, which translates all criteria into a monetary unit). At a macro scale, the vision translates into the strong sustainability approach advocated by ecological economics: human or built capital cannot fully replace natural capital. At an even broader scale, the implications reach the research process itself: sustainability science is intrinsically multidisciplinary, process oriented, and guided by the rules of legitimacy, saliency and credibility.

Powerful insights and concepts imported from ecosystem dynamics by Holling and colleagues comprise the fourth sustainability feature identified: that systems exhibit complex behavior which is difficult to model or predict accurately. This complexity arises from the numerous system components and variables, whose interconnections can become a real challenge for scientists. Complexity can assume a variety of forms: e.g., systems can have multiple stable equilibria, modify according to nonlinear equations, or change abruptly near a threshold to adopt a new unpredictable state or even to collapse. The meta-theory of panarchy portrays this complex system dynamics through a nested set of adaptive cycles that span across several scales. Each adaptive cycle evolves through four different stages (exploitation, conservation, release, and reorganization), which correspond to different combinations of three main system variables: resilience, potential, and connectedness. In spite of the dynamic and comprehensive view transmitted by the theory of panarchy, one may question if only three variables are enough to conveniently illustrate a system's behavior, or if they are too much of a simplification, let alone the measurement difficulties they pose. It is also excessively process oriented, disregarding that sustainability is also about desired consequences. A number of implications stemming from complexity theory were actively endorsed by modern sustainability research: the acceptance of basic ignorance in understanding nature and its connections with human economy, and its incorporation in models; the need for transdisciplinary work in order to transcend the limitations of sectarian or piecemeal approaches; the focus on a transition to sustainability, or a move towards this goal instead of regarding it as a fixed end state; and the development of new concepts, such as that of resilience, capable of conveying a more dynamic and accurate idea of carrying capacity that links environment and human society.

2.6 Bibliometric analysis

A bibliometric assessment was added to complement and support the literature review, thus providing for more robust conclusions⁴. Other researchers have carried out similar citation

⁴ The methodology hereby described refers to the specific study presented in this chapter and should not be confused with the overall methodology of this thesis (chapter 4).

analyses but did not take advantage from combining them with de
 et al. (2007) investigated which thematic clusters were covered by the sustainability science literature. They found 15 main research clusters, with a predominance of agriculture, fisheries, ecological economics and forestry. However, the criterion used to select the primary scientific literature was too inclusive (they searched for the term “sustainab*,” therefore covering both “sustainability” and “sustainable”), which probably led to the incorporation of papers not related to sustainability science. Ma & Stern (2006) identified the most cited papers by the Journal of Environmental Economics and Management and by Ecological Economics between 1994 and 2003. Similarly, Costanza, Stern, Fisher, He, & Ma (2004) concentrated on the latter journal while adding complementary methods such as the nomination of the most influential publications by the Ecological Economics’ editorial board and included book citations. The present research is a useful complement to these previous studies because the analysis is confined to papers that are very likely related to sustainable development and spans through all the journals indexed by the Institute for Scientific Information’s (ISI) Web of Science – which is especially important as that literature can be found in a variety of journals with different scientific backgrounds. In addition, all citations types (books, papers, etc.) are included.

2.6.1 Methodology

Gathering of the primary literature

The assessment was carried out over the rather extensive bibliographic database *Web of Science* (ISI, 2008), which contains over 40 million records from more than 10000 journals. Scientific disciplines are distributed through three datasets: the Science Citation Index Expanded (1900–), the Social Sciences Citation Index (1956–) and the Arts and Humanities Citation Index (1975–). These three datasets were searched simultaneously through the web interface of the Web of Science in October 2008.

On a first step, all the records that contained the expressions “sustainable development” or “sustainability science” in their title, abstract or keywords were retrieved. These expressions were preferred rather than “sustainable” or “sustainability” to avoid including papers that had little to do with the subject, since the words are extremely common and can be used in a variety of contexts. The option was therefore to use narrow and precise criteria to maximize the probability that the retrieved papers really addressed sustainable development issues. This search yielded 7800 records, the first record dating from 1981. The list was further restricted to those papers with two or more citations because many of them are probably of limited interest for the purposes of this section. After applying this criterion the number of papers was reduced to 3300.

Figure 2.6-1 shows the number of papers published about sustainable development. It depicts a “starting” period until the end of the eighties and a “mature” period characterized by an escalating and large number of published papers since then.

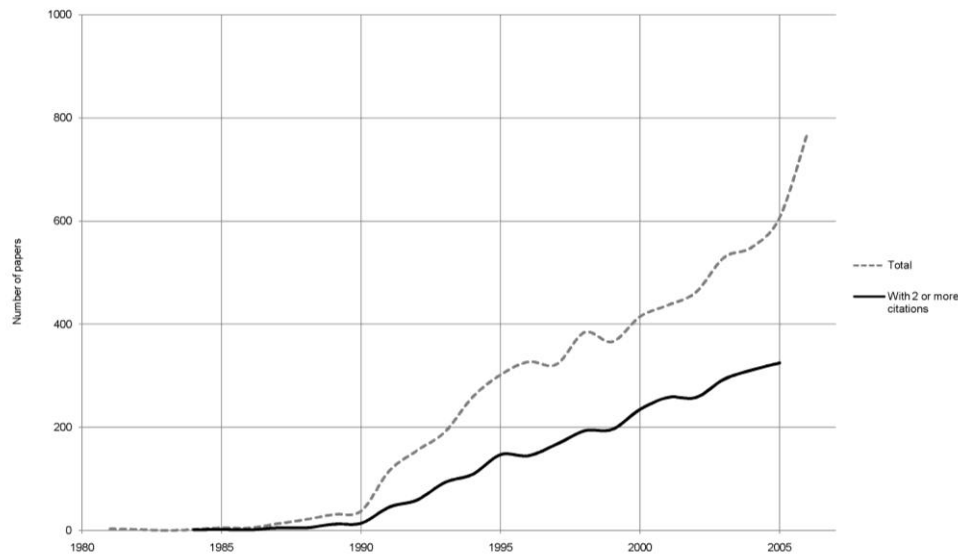


Figure 2.6-1: Number of articles published per year containing “sustainable development” or “sustainability science” in their title, abstract or keywords (1980–2005). Source: own work based on ISI (2008).

Analysis of scientific production and of its disciplinary evolution

The list of 3300 records was used directly as a source to analyze the evolution of scientific production and of the disciplines covered. Scientific production was computed simply by counting the number of papers published per year. Regarding scientific disciplines, the classification supplied by ISI for each paper was used as source. This classification was then grouped according to the division found in the Encarta Encyclopedia: life sciences, social sciences, physical sciences, mathematics, and technology. Papers were classified as multidisciplinary whenever they covered more than one of these large disciplines. As the number of mathematical papers was insignificant, they were discarded from this last analysis.

Initial compilation of the cited references database

The references contained in each of the 3300 papers were also studied in order to find out the most influential publications, primary authors, and journals. This analysis required a laborious procedure. First, all the cited references were joined into a single Excel file. This yielded as much as 127000 records (an average of 38 references per paper). A lengthy task of aggregating all variants of the same publication was needed because books and other publications (that are not indexed by the Web of Science) are registered in the database as they were typed by the authors of the citing paper (and usually in an abbreviated form). For instance, the author of the

Brundtland report could be typed as “WCED,” “BRUND COMM,” “BRUNDTLAND G,” “United Nations WORLD COMM ENV” or in many other even more imaginative ways. The aggregation required the combination of information from author, title and date in order to avoid mistakes. Papers indexed by ISI did not suffer from these problems, since their information was precisely registered. From this step on, database consolidation varied according to the purpose of the analysis.

Identification of the most influential publications

The aggregation procedure was not finished yet. A great help came from the shortening of titles and author names to their first word (titles retained two words if the first was less than 5 characters long). While maintaining the integrity of the database (ensured through the combination of author, title and date) this method allowed for a practical cleaning of name and title variants (for instance, “DALY HE” and “DALY H” recorded as “DALY”). Also, care was taken to group all editions of a same book, since they could be typed with different dates. The next step of the procedure was database consolidation to obtain unique records and count the number of occurrences of each. A total of 97600 different publications were obtained, of which the vast majority (87%) was cited only once. However, the use of citation counts *per si* could be misleading since it favors older publications. To avoid this pitfall, citation counts were divided by the number of papers published after the reference in question. To illustrate this point, Kates, et al. (2001) was cited 56 times; because only 1623 papers (from the set of 3300 records) have been published since 2002, the result obtained was 3,5% – ranking higher (6th place) than what would be expected solely from total citation counts (14th place). At the same time, though, this method could lead to inconsistent results on recent publications even with a small number of citations. Therefore, only references with 10 or more citations were considered in this analysis.

Identification of the most influential primary authors

The identification of the most influential primary authors required a slightly different procedure. Author names were shortened to their first word followed by the first letter of the second word. For instance, “DALY HE” and “DALY H” were both recorded as “DALY H.” This was especially important for common surnames, such as “SMITH,” which could misleadingly rank high if only the first word was retained.

Basic statistics

Table 2.6-1 summarizes some descriptive statistics about the bibliometric assessment. The overwhelming majority of references (87%) appears to be of limited importance since are cited only once.

Table 2.6-1: Descriptive statistics about the database of primary literature and cited references.

Statistic	Description
<u>Primary literature*</u>	
Number of papers	3334
Range of publication dates	1981–2008
Average publication date	2000
Range of ISI citations per paper	2–239
Average ISI citations per paper	9,6
<u>References cited by the primary literature</u>	
Number of citations	126958
Number of references	97618
Range of reference dates	1556–2008
Average reference date	1993
Range of citations per reference	1–744
Number of references with 1 citation	84666 (87%)
Number of references with 2 to 9 citations	12569 (13%)
Number of references with 10 or more citations	380 (0,4%)
Number of references with 15 or more citations	161 (0,2%)
Average references per paper (from the primary literature)	38
Number of authors with 10 or more citations	1822
Number of authors with 50 or more citations	144
Number of journals with 10 or more citations	973
Number of journals with 50 or more citations	173

* Inclusion criterion: title, abstract or keyword containing “sustainable development” or “sustainability science)

2.6.2 Influential publications

The most influential publications of the sustainable development literature, with 10 or more citations, amount to 380 and represent only 0,42% of all references (Figure 2.6-2). A smaller list of the first 60 is shown in annex A.1. About half of this list was also identified by Costanza, et al. (2004) or by Ma & Stern (2006) as influential in the field of ecological economics or environmental economics. Costanza, et al. (pp. 284-290) reached a list of 57 papers and 77 monographs (134 in total) cited at least 15 times in Ecological Economics, which is just below the 161 publications identified by the present research if the same criterion of 15 citations was applied (cf. Table 2.6-1).

Brundtland Commission's "Our common future" clearly stands out in Figure 2.6-2 and is cited by as much as 22,5% of the papers about sustainability published after 1987, suggesting that WCED's definition of sustainable development is indeed the most widely cited. Two other reports will be of pivotal importance if the pace of citations continues into the future: the 2001 Intergovernmental Panel on Climate Change's (IPCC) "Third assessment report" (with 9,7%), and the 2005 MEA (5,9%).

The group of the 60 most influential references includes a broad range of publications types and themes: classics (e.g., Hardin's "Tragedy of the commons," Hartwick's "Intergenerational equity" or Schumacher's "Small is beautiful"); reports and reviewing papers about sustainable development (e.g., Meadows, Meadows, & Randers, 1992; Meadows, et al., 1972; WCED, 1987; Lele's "Sustainable development: a critical review"); global reports about compelling issues (e.g., MEA, 2005, and the climate change reports from IPCC); papers about the development and sociology of science (Lubchenco's "Entering the century of the environment: a new social contract for science" or Kates, et al., 2001, on sustainability science); policy documents (e.g., "The World Conservation Strategy," the Rio Declaration and Agenda 21); and a number of publications dealing with a variety of topics such as the valuation of ecosystem services (e.g., Daily, 1997; Costanza, et al., "The value of the world's ecosystem services and natural capital"), ecosystem resilience (e.g., Berkes' et al. "Navigating socioecological systems," Holling's "Resilience of terrestrial ecosystems" or Walker's et al. "Resilience, adaptability and transformability in socioecological systems"), environmental, ecological and development economics (e.g., Pearce's et al. "Blueprint for a green economy," Costanza and Daly's "Natural capital and sustainable development," Adams' "Green development" or Norgaard's "Development betrayed"), environmental impacts (e.g., Wackernagel's et al. "Tracking the ecological overshoot of the human economy," Vitousek's et al. "Human appropriation of the products of photosynthesis" or von Weizsäcker's et al. "Factor four"), urban sustainability (Breheny's "Sustainable development and urban form"), governance of natural resources (Ostrom's "Governing the commons"), and political science (Hajer's "Politics of environmental discourse" or Dryzek's "Environmental discourses").

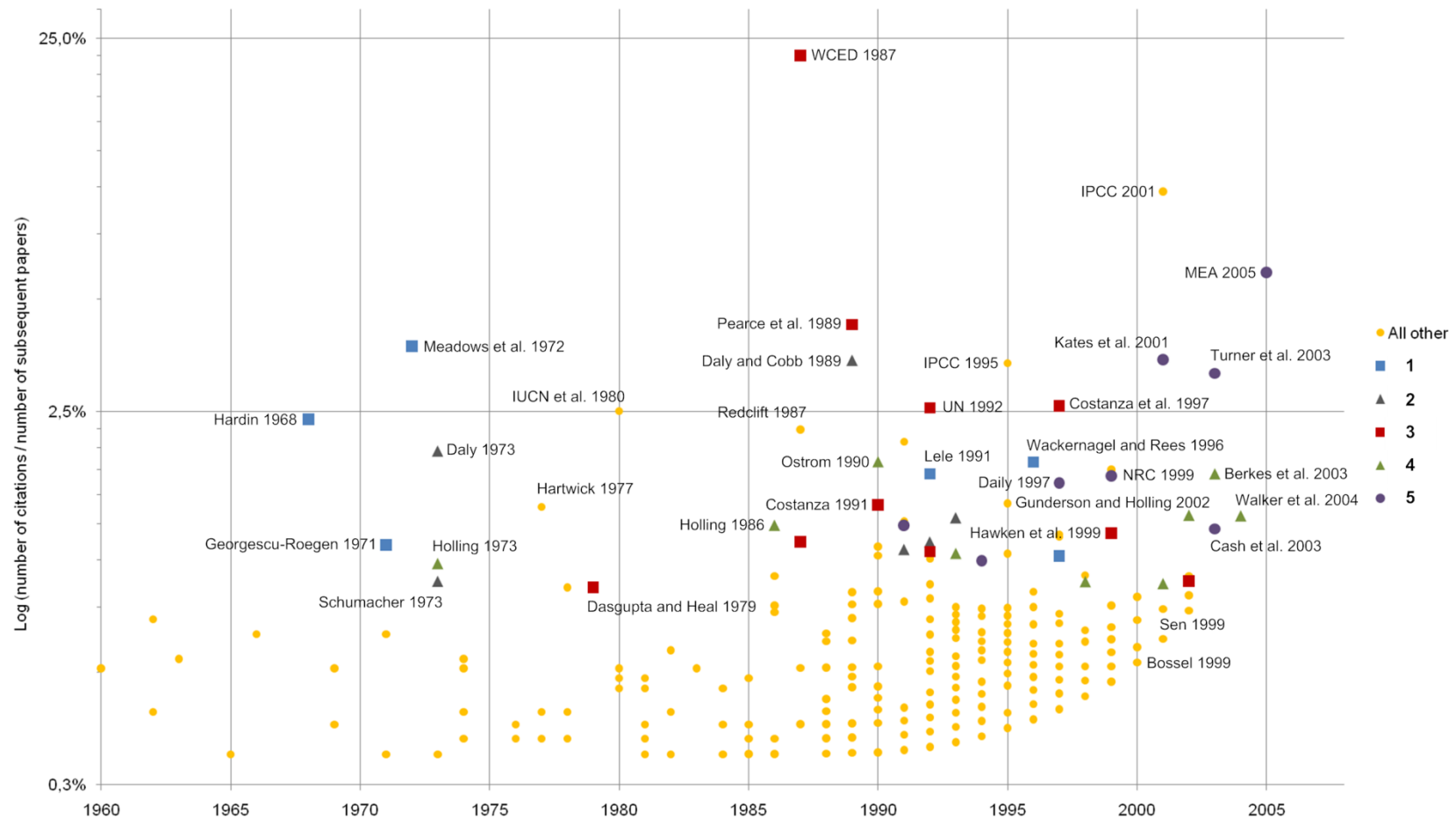


Figure 2.6-2: Publications with 10 or more citations in papers containing “sustainable development” or “sustainability science” in their title, abstract or keywords (1960–2005). 1: the limits approach; 2: the means and ends approach; 3: the needs and capabilities approach; 4: the complexity approach; 5: the consilience approach. Source: own work based on ISI, (2008).

More importantly, most of the references listed in annex A.I could be assigned to the organizational framework used in section 2.4, although in many cases the distinction between categories was not straightforward: seven publications mostly convey the idea of limiting natural resources, five publications introduce the division between means and ends, 10 go further and conceptualize sustainable development as a number of needs that must be satisfied independently, nine endorse the concept of complexity and of adaptive cycling, and eight constitute a step towards scientific consilience since they integrate many of the referred approaches and cannot be classified as one of them.

2.6.3 Influential authors and journals

The most cited primary individual authors are North American (e.g., Robert Costanza, Herman Daly, C. S. Holling, Robert Ayres, Donella Meadows) and English (e.g., David Pearce, Michael Redclift, Timothy O'Riordan) – see Table 2.6-2. Institutional authors (e.g., WCED, World Bank, European Commission, United Kingdom's Department of the Environment, Transport and Regions, IPCC, United Nations, OECD) dominate the list of most cited references, as would be expected from their huge resources and numerous extensively distributed publications – of which many are especially fit to capture the broad scope of sustainability, such as the *World Development Report* series published by the World Bank. Some authors are extensively cited but do not appear that much in the list of the 380 references with 10 or more citations. Lester Brown, for instance, is cited 158 times, but only 10% of these citations are in that list. An extreme situation happens with OECD: none of its publications even appear in the in the top 380. This happens when authors are very prolific but their individual publications get a modest number of citations. They contrast with authors such as WCED, IPCC, David Pearce, Herman Daly, Robert Costanza and Donella Meadows whose influence is more expressive because at least some of their publications are highly cited.

Table 2.6-2: Most relevant institutional and individual authors. The first 10 most cited institutional authors and the 15 most cited individual primary authors in papers containing “sustainable development” or “sustainability science” in their title, abstract or keywords are shown.

Author	Background	Citations	In the main list*	Publications
<u>Institutional authors</u>				
WCED		744	100%	1
World Bank		616	29%	194
European Commission		387	7%	175
UK's Dept. Env. Trans. Regions		371	6%	179
IPCC		358	84%	27
United Nations		325	6%	140
OECD		307	0%	155
Food and Agriculture Organization		282	0%	141
IUCN		171	73%	25
World Health Organization		158	0%	81
<u>Individual primary authors</u>				
Pearce, D.	Economy	493	57%	93
Daly, H.	Economy	416	67%	55
Costanza, R.	Economy	298	65%	33
Meadows, D.	Environ. sciences	205	87%	14
Redclift, M.	Sociology	199	54%	35
Holling, C.	Ecology	196	52%	28
Fearnside, P.	Ecology	179	14%	44
Ayres, R.	Economy	167	33%	38
Brown, L.	Environmentalism	158	10%	45
Rees, W.	Ecology	153	44%	38
Solow, R.	Economy	150	62%	28
Wackernagel, M.	Environmentalism	147	51%	31
Berkes, F.	Ecology	142	47%	38
O'Riordan, T.	Political sciences	140	18%	38
Norgaard, R.	Economy	139	60%	26

* Proportion of citations that are included in the list of the references with 10 or more citations. Authors with more than 30% of their citations in that list appear shaded.

The list of the most cited journals is dominated by *Ecological Economics*, a specialist journal in the field of sustainable development, followed by *Science*, *Nature* and *World Development*, which are more generalist (Table 2.6-3). Some of the highly cited journals have also published

influential papers. *Ecological Economics*, *Science*, *World Development*, *American Law and Economic Review*, and the *Proceedings of the National Academy of Sciences of the United States*, all have at least 20% of their citations in the list of the 380 most influential publications.

Table 2.6-3: Most relevant journals. The first 20 most cited journals in papers containing “sustainable development” or “sustainability science” in their titles, abstracts, or keywords.

Journal	Citations	In the main list*
Ecological Economics	1402	23%
Science	1316	22%
Nature	696	15%
World Development	591	22%
Conservation Biology	524	16%
Ambio	449	0%
Energy Policy	430	0%
Environmental Conservation	384	18%
Bioscience	362	11%
Environmental management	334	12%
Global Environmental Change	324	12%
American Law and Economics Review	306	34%
Agriculture, Ecosystems & Environment	273	0%
Proceedings of the National Academy of Sciences of the USA	272	21%
Climatic Change	261	8%
Ecological Applications	260	5%
Environment and Planning A	258	4%
Environment	241	0%
Futures	221	19%
Journal of Environmental Economics and Management	219	8%

* Proportion of citations that are included in the list of the references with 10 or more citations. Publications with more than 20% of their citations in that list appear shaded.

2.6.4 Scientific disciplines

Scientific underpinnings of sustainable development are diverse. While this multidisciplinaryity is indisputable, it masks the relative contribution of the different fields of science. Bibliography referenced by the sustainable development literature covers a broad range of disciplines, ranging from economics, sociology and political science to the natural sciences. There is nevertheless an overrepresentation of economical (particularly ecological economical) and ecological sciences literature. Half of the list of the 60 most influential publications (cf. annex

A.I), for instance, can be classified as coming from the social sciences; a third of the list is multidisciplinary and 15% come from the life sciences. A comparison of the present research with the results of Ma & Stern (2006) and Costanza, et al. (2004) shows that the dominance of economics in their lists and, consequently, the uniformity of the topics covered, are even more pronounced. In spite of the predominance of economics in the publications shown in annex A.I, the list is remarkably multidisciplinary.

The list of the most influential authors and journals presented in Table 2.6-2 and Table 2.6-3 is also dominated by economy (authors: David Pearce, Herman Daly, Robert Costanza; journals: *Ecological Economics*, *American Law and Economics Review*, *Journal of Environmental Economics and Management*) and ecology (authors: Crawford Holling, Philip Fearnside, William Rees, Fikret Berkes; journals: *Nature*, *Conservation Biology*, *Ambio*, *Environmental Conservation*). A smaller but still significant contribution comes from sociology, political sciences and planning (authors: Michael Redclift, Timothy O'Riordan; journals: *World Development*, *Environment and Planning A*, *Futures*).

Figure 2.6-3, instead of analyzing the bibliography cited by the sustainability literature, looks into that literature itself. Each paper was classified into one main branch of science or as multidisciplinary. Aside from the yearly fluctuations, it is possible to discern a downward tendency for the social sciences, although – as for the latest available period, 2001–2005 – they still represent as much as 27% of all the papers published, a proportion just below to that of life sciences and multidisciplinary papers. Together, these three fields account for 70% of the sustainability literature recorded by the Web of Science (ISI, 2008). Another group of scientific disciplines includes the earth sciences, physical sciences, and technology. Their proportions range from 5 to 16%, jointly representing 30% of all the papers. The relative contribution of multidisciplinary papers is increasing significantly since 2001, while that of the earth sciences is decreasing.

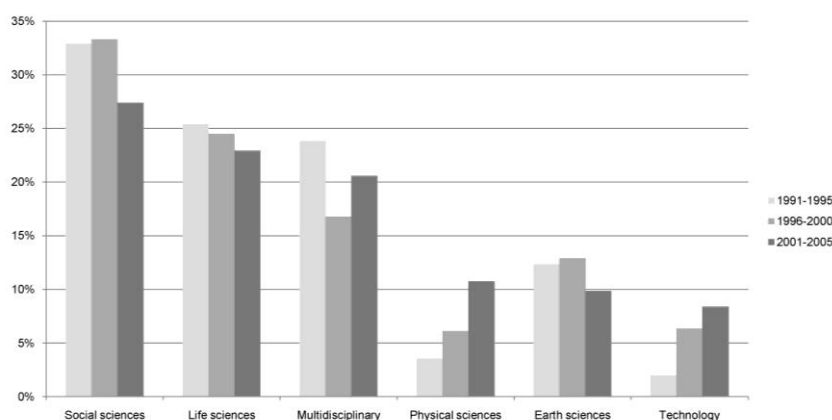


Figure 2.6-3: Evolution of relative contribution of different scientific fields in the sustainable development literature (1990–2005). Source: own work based on ISI (2008).

2.7 Sustainability indicators

2.7.1 Introduction

The use of sustainability indicators is extremely common and essential for most sustainability approaches. For instance, a search in the IISD's Compendium of Sustainable Development Indicator Initiatives (IISD, 2009) yielded as much as 841 results. *Indicators* are quantitative measures designed to assess progress toward or away from a stated goal (Moldan & Dahl, 2007; Parris & Kates, 2003a). They are, however, proxies, or indirect measures of the true condition that is being studied, which means that no ideal indicators that fully encompass all the desired qualities exist (Cobb, 2001; Meadows, 1998). Indicators can also be important instruments to measure the performance of a system (McCool & Stankey, 2004); to enable a community to identify its values and priorities, and to engage people in achieving those goals (Portney, 2003); and to establish routines and guarantee that data concerning relevant issues is gathered and analyzed (Meadows, 1998). According to Parris, much of the literature in the field adopts the old axiom "what gets measured, gets managed." The inverse is probably true as well: what is not measured, is not managed. A less obvious corollary of these propositions is that the selection of indicators also influences the way society perceives sustainability problems. The role of indicators as tools for awareness raising (particularly that of politicians), and capable of triggering responses when they are needed should not be dismissed (Meadows, 1998). In spite of this, Cobb (2001) and Portney (2003) suggest that there is no systematic evidence that indicator projects contribute to the path towards sustainability, and that indicators are seldom used even when they are developed.

Parris & Kates (2003a) distinguished indicators from driving forces. However, their proposals have not been followed in practice, in part because technically a variable may act a driving force in some situations and an indicator in others. Education, for instance, is a driving force in the sense that it influences the progress towards many desired goals, but may also become an indicator if specific educational targets are set. Therefore, some confusion will probably remain which can only be resolved case wise. The distinction between indicators, goals and targets is more clear-cut and should be systematically followed as a useful reference lexicon: *goals* are broad but specific qualitative statements about objectives chosen from the major categories of what to sustain and what to develop (cf. Figure 2.4-6), whereas *targets* use indicators to make goals specific with endpoints and timetables (cf. Table 2.3-2 for some of the most important targets pertaining sustaining development). Targets may be used as benchmarks in the calculation of distance-to-target indicators.

2.7.2 Selecting indicators

Literature is full of recommendations about how to select indicators. The most coherent and complete set of criteria developed so far is probably the so-called *Bellagio principles*. They serve as guidelines for the whole assessment process including the choice and design of indicators, their interpretation and communication of results (Hardi & Zdan, 1997). Annex A.3 presents a compilation of those principles. According to the most commonly referred criteria (see, e.g., Bell, 2001; Böhringer & Jochem, 2007; Bossel, 1999; Button, 2002; Dodds, 1995; Karlsson, et al., 2007; Meadows, 1998; Moldan & Dahl, 2007; Pintér, Hardi, & Bartelmus, 2005; Segnestam, 2002) – and in addition to the general questions mentioned in the beginning of this section – the selection of indicators:

- *must* have direct relevance to its objectives (indicators must capture the essential characteristics of the system and show a scientifically verifiable trajectory of maintenance or improvement in system functions);
- *must* be legitimate in the eyes of users and stakeholders, and salient or relevant to decision makers (this requires that indicators can be effectively communicated to their target audience);
- *must* be scientifically sound (the calculation method must be scientifically rigor, valid and transparent so that computations can be verified and performed whenever necessary by another party);
- *should* be based on a theoretical framework (indicators should be related with some underlying philosophical understanding of human well-being and sustainable development; see also Dasgupta, 2001, p. 178);
- *should* be included only when data collection is guaranteed according to technical and budgetary constrains;
- *should* be comparable with policy targets, scientific benchmarks or thresholds (the comparison of indicator values with some other reference is essential for their interpretation);
- *would preferably* indicate the timely approximation of turning points or thresholds (if possible, indicators should function as early warnings of problems ahead);
- *should, whenever possible*, be quantifiable (to avoid unnecessary subjectivity, indicators should preferably be quantifiable according to scientific sound methodologies).

Robèrt, et al. (1997) and Ness, Urbel-Piirsalu, Anderberg, & Olsson (2007) mention more general criteria that could be used to judge the quality of sustainability methods and tools – of which indicators are an example. Relevant questions include: (a) is the model based on a scientifically acceptable conception of the world? (b) does the model contain a scientifically

supportable definition of sustainability? (c) does the model integrate nature and society? (d) is the model applicable at different scales, (e) does the model address both the short and long-term perspectives? (f) does the model provides interpretable and transparent results?

Several authors stress the need to complement expert based approaches to the construction of indicators with participation processes. Not only are community driven indicators often simpler and cheaper than those proposed by experts (Reed, Fraser, Morse, & Dougill, 2005), they also propitiate the fundamental debate about priorities for decision-making and about the trade-offs between conflicting policies (Portney, 2003). By systematically involving people and the different actors of society, public participation is able, if carried out ethically and correctly, to ensure the legitimacy of the indicator selection process. Unfortunately, there are very few examples where countries or institutions have provided a full and detailed documentation of how they have elaborated and selected their indicators (Joint United Nations Economic Commission for Europe/OECD/Eurostat Working Group on Statistics for Sustainable Development, 2008).

In spite of all recommendations, researchers agree on attesting that, to date, “no indicator sets are universally accepted, backed by compelling theory, rigorous [in] data collection and analysis, and influential in policy” (Parris & Kates, 2003b, p. 559). Parris & Kates (2003b), NRC (1999) and Pintér, et al. (2005) suggest that the influence of indicators is hindered by (a) the ambiguity of sustainable development; (b) the lack of agreement on what to develop, what to sustain, and for how long; and (c) the confusion of terminology, data, and methods of measurement. These reasons probably explain as well why so many indicators sets have been assembled but none widely implemented (Moldan & Dahl, 2007). Table 2.7-I provides a state-of-the-art in the development of indicators as to their capacity to meet selection criteria and other conceptual challenges (Karlsson, et al., 2007). It is noteworthy that indicators ready for implementation are not available for a number of important sustainability issues.

Table 2.7-1: Stage of development in indicators in meeting conceptual challenges. Source: Karlsson, et al., 2007.

Sustainability			Process and Universality		
Challenge	Stage of Development		Challenge	Stage of Development	
Measuring sustainability and sustainable development	In general	I	North–South issues	For strengths of countries	I
	Some indicators capturing some components of sustainability	II		For Northern development bias	II
	Biodiversity indicators	III		For indicator definitions	III
Frameworks		II	Country comparability		III
Linkages between pillars	Economy–environment linkage	III	Cultural diversity	International	I
	Social–environment linkage	I		National (some countries)	II
Temporal and spatial scales	In general terms	I	Equity	Environmental equity	I
	In individual cases	III		Social and institutional equity	II
				Economic equity	III
Strong–weak sustainability	Where applicable	I	Democracy		II–III
Planetary limits		I	Acceptability		II
Vulnerability–resilience	Environmental systems	II			
	Social and economic systems	I			
Irreversibility		I			

Note: The stages of indicator development are classified as follows: I, research stage; II, in development, some progress made; III, ready for implementation.

2.7.3 Indicator frameworks

Indicators can be classified into different groups according to specific and nonoverlapping criteria. The first distinction that could be made is between indicators that are derived from a solid conceptual framework and indicators that are selected by other methods (usually less theory related or even *ad-hoc*). Examples of conceptual frameworks include the capital approach, the pressure-state-response, Meadows' pyramid (cf. section 2.4) and more complex accounting systems such as the Integrated Environmental and Economic Accounting (SEEA). Indicator sets not adhering to one of these frameworks (explicitly or implicitly) are usually arranged pragmatically into domains, themes or specific issues. With respect to the target audience and the method of selection, indicators can be adopted by politicians to monitor the progress toward policy goals; can be adopted by scientists to access trends and conditions associated with relevant stocks and processes; or can be adopted by the public – through participation processes – usually to address relevant topics at the local or regional scales. Most often, however, one indicator can serve multiple target groups or be adapted so that it can fit the expectations of them (that is, I think there is no need to develop different indicator sets for scientists, politicians and citizens, because that would probably create a number of difficulties and solve no problems). In addition, indicators sets are scale-dependent, although one challenge is precisely the development of indicators that are able to adapt to different scales and places.

Pressure-state-response

OECD developed in 1993 one of the most widely known sustainable development indicator frameworks: the pressure-state-response. This model was later extended by EEA in 1995 to form the driving force-pressure-state-impact-response (DPSIR) framework (Gabrielsen & Bosch, 2003; Figure 2.7-1). Both models remain in use today by their founding organizations. The meaning of each model component is as follows: *driving forces* describe the social, demographic, and economic development in societies and the corresponding lifestyles and overall levels of consumption and production patterns; *pressure* indicators describe rates or amounts of release of substances, physical and biological agents, the use of resources, and the use of land; *state* indicators give a description of the quantity and quality of physical, biological and chemical phenomena in a certain area; *impact* indicators are used to describe the relevance of changes in the state of the environment; *response* indicators refer to responses by groups and individuals in society and government attempts to prevent, compensate, ameliorate, or adapt to changes in the state of the environment (Stanners, et al., 2007). The whole DPSIR model thus reflects a causality chain from the root causes of a problem (or the indirect drivers of change, in the terminology of the MEA, 2005), which result in proximate causes (or the direct drivers), which affects the environment's quality, which in turn cause impacts and demand responses.

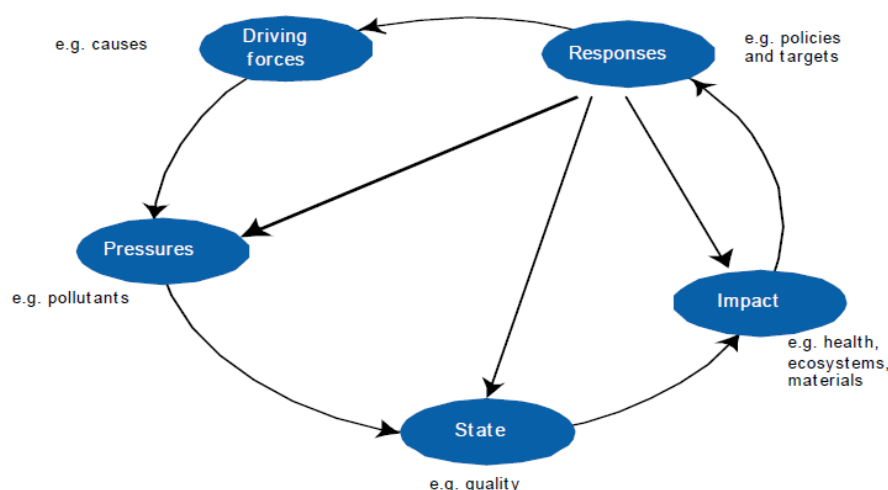


Figure 2.7-1: The DPSIR framework for reporting on environmental issues. Source: Gabrielsen & Bosch, 2003.

The model is appealing but has been considered overly simplistic (Bell, 2001). Specifically, I would add that the DPSIR model fits well the explanation of concrete problem-issues, but its systemic representation of sustainable development is far less elegant because causes and consequences frequently change positions through complex relationships. Moreover, most of

the constitutive components of sustainable development are relegated by DPSIR to the category of driving force, which is in direct contradiction with the theses of, e.g., Sen (1999/2003) and Dasgupta (2001).

Capital approaches

Capital approaches to sustainability indicators stem from the interpretation of sustainable development as the maintenance of wealth through time (Dasgupta, 2001). The model attempts to calculate national wealth as a function of different stocks and flows of capital, including not only financial capital and produced capital goods, but also natural, human, social, and institutional capital. This requires that all forms of capital be expressed in common units (usually monetary) (United Nations - Department of Economic and Social Affairs, 2007a). The simplicity of aggregating different domains into a single measure goes against the beliefs of ecological economics and finds strong opposition from many scientists (e.g., Daly, 1996; Dasgupta, 2001; Munda, 2008; cf. section 2.4). The Joint United Nations Economic Commission for Europe/OECD/Eurostat Working Group on Statistics for Sustainable Development has therefore recommended that a practical set of capital-based indicators should include monetary indicators for those stocks that can be meaningfully valued using existing data and methods, and other indicators for those capital stocks that cannot or should not be valued (Joint United Nations Economic Commission for Europe/OECD/Eurostat Working Group on Statistics for Sustainable Development, 2008).

Accounting frameworks for societal metabolism

Nineteenth-century biology described *metabolism* as an exchange of matter between an organism and its environment; for Marx and Engel, the concept also meant a material exchange between humans and nature but implied their mutual interdependence as well. In the words of Fischer-Kowalski & Weisz (1999, p. 226), metabolism as applied to society “appears to be not completely alien to the traditions of social theory.” The modern concept, however, is much more entrenched in the biological than in the sociological perspective, even if several philosophical lessons can be drawn. Metabolism has ramifications into a variety of fields and methods such as industrial ecology and life cycle assessments. The expression *urban metabolism*, coined in 1965 by the scientist Abel Wolman, has been used to refer to the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste (Kennedy, Cuddihy, & Engel-Yan, 2007). The basic rationale is to consider a city as a highly complex dissipative structure which, in order to maintain its characteristics, requires the influx of materials and energy. The framework goes well beyond this simplistic view and accounts for the interrelation between stocks and flows of information, knowledge, money, products, and wastes (Rotmans, van Asselt, & Vellinga, 2000).

Newman (1999) proposed the inclusion of the liveability and sociability of urban areas in addition to the physical and biological processes already captured by the basic metabolism model. Rotmans, et al. (2000) and Ravetz (2000b) proposed similar frameworks, the latter also clearly inspired in the DPSIR structure (Figure 2.7-2).

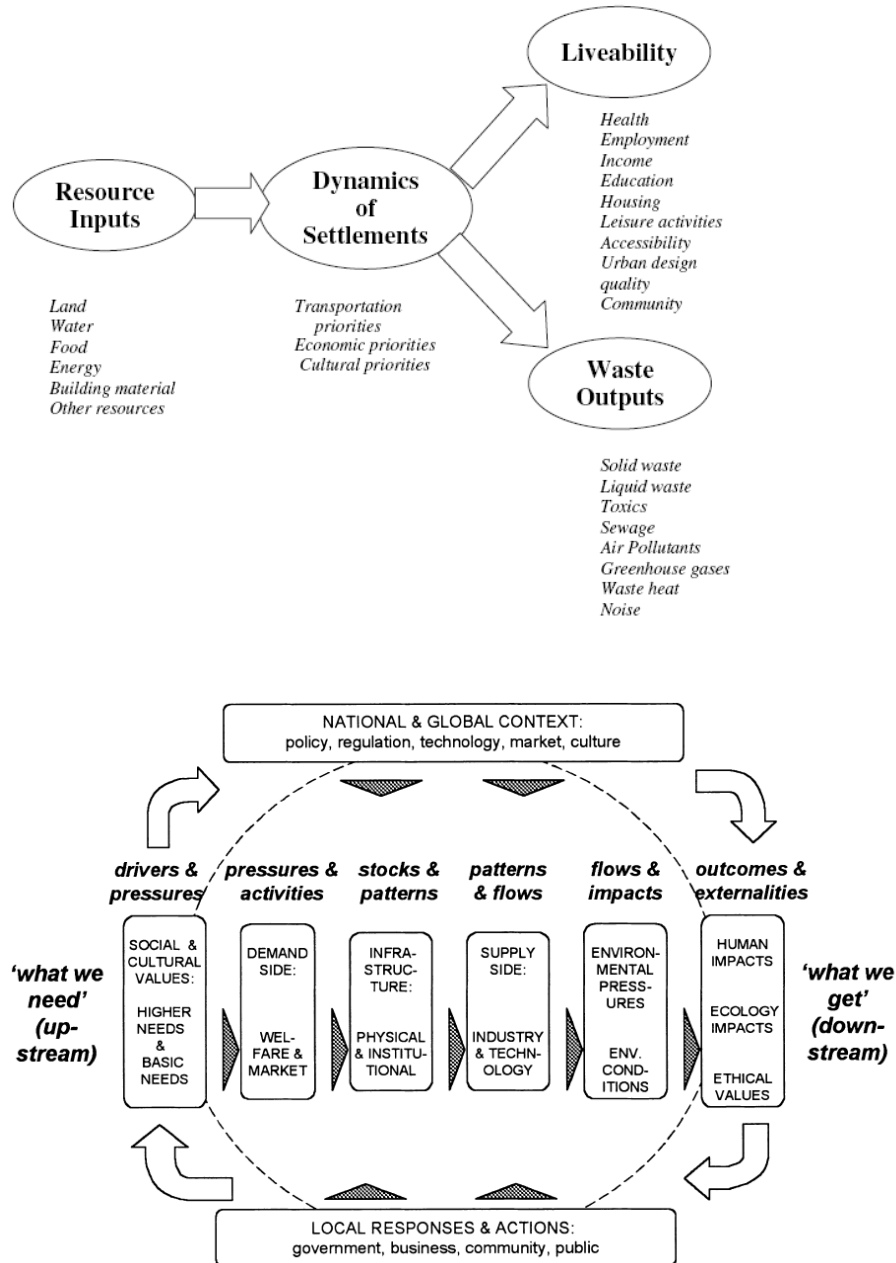


Figure 2.7-2: The extended metabolism model (top) and the integrated assessment framework (bottom). Source: Newman, 1999 (top) and Rotmans, et al., 2000 (bottom).

The bottom line is that both models attempt to extend the basic metabolic considerations to provide an integrated assessment of cities. However, it is not clear that the framework is able to deal with and to unveil the complex links between system's processes as effectively as truly integrated assessments.

A deeper effort towards integrated environmental and economic assessments is provided by systematic accounting frameworks. After 30 years since the material and energy flow accounting first appeared, a harmonized system of environmental and economic accounting is at last taking its place and will become an international statistical standard by 2010 if the deadlines are met (United Nations - Statistics Division, 2009).

Material flow and energy accounting comprises various descriptive and analytical tools to understand the functioning of the physical basis of societies, the interlinkages of processes and product chains, and the exchange of materials and energy with the environment in order to understand the interaction of human activities and the environment (Moll, Bringezu, & Schütz, 2005). Material flow and energy accounting treats socioeconomic processes as biophysical processes that can be regarded as a compartment of the biosphere and hence is compatible with the pre-analytic vision of ecological economics (cf. section 2.4). Material inputs into the economy consist primarily of extracted raw materials and produced biomass that has entered the economic system, whereas material outputs consist primarily of emissions to air and water, wastes deposited in landfills and dissipative uses of materials (Eurostat, 2001). Several indicators can be derived from the accounting framework. They are usually divided into three groups (Hinterberger, Giljum, & Hammer, 2003; see also Figure 2.7-3):

- input indicators: *direct material input* comprises all materials which have economic value and are directly used in production and consumption activities; *total material input* equals direct material input plus the unused domestic extraction; *total material requirement* includes total material input and the indirect flows associated to the imports of an economy;
- output indicators: *domestic processed output* equals the outputs to nature plus all outflows of used materials from domestic or foreign origin; *total domestic output* includes, in addition to the domestic processed output, the unused domestic extraction;
- consumption indicators: *domestic material consumption* measures the total quantity of materials used within an economy excluding indirect flows. Domestic material consumption is calculated by subtracting exports from direct material input; total material consumption includes, in addition to domestic material consumption, the indirect flows associated to imports and exports. These flows are generally not available from official sources and must be estimated.

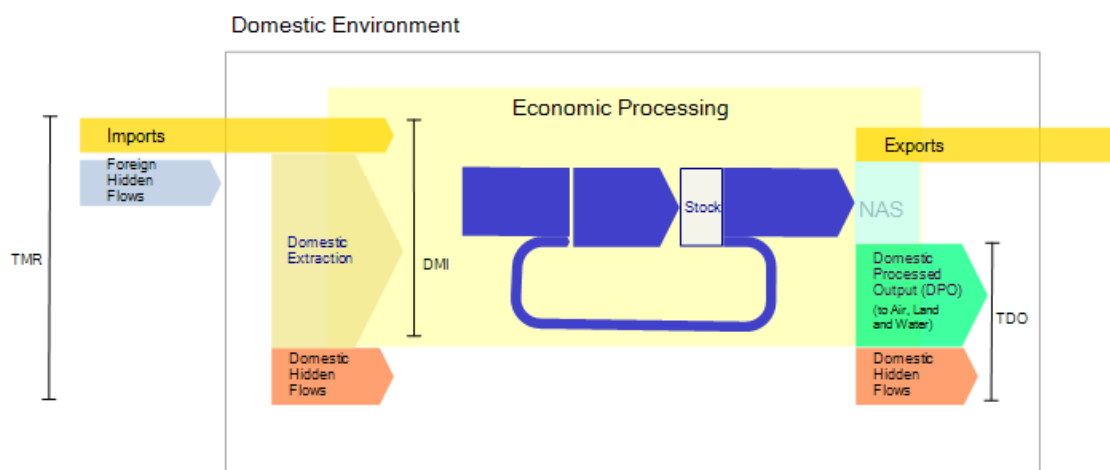


Figure 2.7-3: Indicators used in economy-wide material and energy flow accounting. TMR: total material requirement; DMI: direct material input; NAS: net addition to stocks; DPO: domestic processes output; TDO: total domestic output. Source: Wikipedia, 2009b.

More recently, the United Nations, the European Commission, the International Monetary Fund, OECD and the World Bank have jointly published the 2003 version of SEEA. SEEA 2003 is a step towards the harmonization of concepts and methods in environmental-economic accounting. Four categories of accounts are included: physical data relating to flows of materials and energy; expenditures relevant to the good management of the environment; environmental assets measured in physical and monetary terms; and adjustments to existing system of national accounts to correct for the impact of the economy on the environment (United Nations, European Commission, International Monetary Fund, OECD, & World Bank, 2003).

Both material flow and energy accounting and SEEA frameworks appear to have the rigor that many indicator sets are short of, but they are still mainly concerned with the environmental dimension of sustainability and thus need to be complemented with other of indicators. Moreover, the link between indicators derived from both accounting frameworks and the environmental consequences of material, energy and monetary flows is not yet well understood, which precludes the possibility of drawing policy-making recommendations (Eurostat, 2001; Hinterberger, et al., 2003). Methodologies are being refined to account for flows presently not captured or whose estimation is complex.

2.7.4 Indicator sets

Progress has been made in the last years with some indicator sets that seem to be slowly gaining acceptance, even if their geographical scope or target audience is limited. The most widely applied indicators sets are those developed by international organizations. The United

Nations Commission on Sustainable Development has issued its third revision of sustainability indicators, now composed by a core set of 50 indicators and a larger set of 96 (United Nations - Department of Economic and Social Affairs, 2007a); the United Nations Millennium Development Goals have associated a set of 60 indicators to measure progress towards those objectives (United Nations - Statistics Division, 2009); the Joint United Nations Economic Commission for Europe/OECD/Eurostat Working Group on Statistics for Sustainable Development has published a report to assist national governments and international organizations in the design of their own indicator sets and proposed a capital based indicator set made up by 15 stock and 15 flow indicators to be used in future country-to-country comparisons (Joint United Nations Economic Commission for Europe/OECD/Eurostat Working Group on Statistics for Sustainable Development, 2008; see Table 2.7-2); the Global Reporting Initiative's framework has been used by over 1500 organizations to report on their economic (nine indicators), environmental (30 indicators), and social performances (14 indicators) (Global Reporting Initiative, 2006); Eurostat has adopted in 2007 a reviewed set of indicators arranged in a multilevel framework to support the European Union sustainable development strategy: 11 headline indicators (level 1), 33 general policy performance indicators (level 2), 78 detailed policy efficiency indicators (level 3) and 11 contextual indicators (European Commission, 2007); still at the European level, the Commission maintains since 2003 the *Urban Audit*, a project that provides about 300 urban statistics for 321 cities (at three geographical levels) and across 27 countries. Although focused on specific sustainability domains or issues, two initiatives are worth mentioning: UNEP's core set of 21 environmental indicators, which aid in the annual writing of the "Global Environmental Outlook" reports (UNEP, 2007); and the Transport and Environmental Reporting Mechanism, a set of 40 indicators initiated in 2000 for the 32 EEA member countries which links transports, climate change and other impact categories relevant for policy (EEA, 2009).

Table 2.7-2: Set of capital-based sustainable development indicators proposed by the Joint United Nations Economic Commission for Europe/OECD/Eurostat Working Group on Statistics for Sustainable Development. Source: idem, 2008.

Stock indicators	Flow indicators
<u>Monetary indicators</u>	
Real <i>per capita</i> economic wealth	Real <i>per capita</i> genuine economic savings
Real <i>per capita</i> net foreign financial asset holdings	Real <i>per capita</i> investment in foreign financial assets
Real <i>per capita</i> produced capital	Real <i>per capita</i> net investment in produced capital
Real <i>per capita</i> human capital	Real <i>per capita</i> net investment in human capital
Real <i>per capita</i> natural capital	Real <i>per capita</i> net depletion of natural capital
Real <i>per capita</i> social capital (place holder)	Real <i>per capita</i> net investment in social capital (place holder)
<u>Physical indicators</u>	
Temperature deviations from normal temperatures	Greenhouse gas emissions
Ground-level ozone and fine particulate concentrations	Smog-forming pollutant emissions
Quality-adjusted water availability	Nutrient loadings to water bodies
Fragmentation of natural habitats	Conversion of natural habitats to other uses
Percentage of the population with post-secondary education	Enrolment in post-secondary educational institutions
Health-adjusted life expectancy	Changes in age-specific mortality and morbidity (place holder)
Membership in local associations and networks	Change in membership in local associations and networks
Trust and adherence to norms	Flow indicators of trust/adherence to norms and collective action (place holder)

International organizations are also the most common holders of data used in the preparation of periodical reports about sustainable development and human well-being. The UNDP publishes annually their “Human Development Reports” which rely on numerous indicators covering the various aspects of the subject (United Nations Development Program [UNDP], 2007); similarly, the World Bank monitors and analyzes about 800 indicators to prepare the “World Development Reports” (World Bank, 2007); the Worldwatch Institute assembles 30 sustainability trends in five categories which are aid in the compilation of the “State of the World” reports; WRI’s Earth Trends portal gathers data about more than 600 variables covering 220 countries (WRI, 2008) which are used in the preparation of the “World

Resources” reports; and the United Nations Habitat manages a database containing several urban development indicators which aids in the preparation of their flagship reports “The Global Report on Human Settlements” and “The State of the World’s Cities” (United Nations Center for Human Settlements, 2001b).

At a national level, the efforts of the United Kingdom, Germany, Sweden, and Belgium must be given credit, as all of them pioneered the efforts of establishing indicator sets by the end of the nineties (Joint United Nations Economic Commission for Europe/OECD/Eurostat Working Group on Statistics for Sustainable Development, 2008). The latest revision of the United Kingdom’s set is formed by 68 indicators selected to supporting the monitoring of national sustainable development policies (United Kingdom Department for Environment, 2009). More recently, other countries have also built their own indicator suites – which are often linked to the respective national sustainable development strategies. In Portugal, the practice of environment reporting is already established. Since 1999, the Portuguese Environmental Agency has been publishing yearly environmental assessments. The next step will probably be the merging of these routine reports with the 2007 version of the National System of Sustainable Development Indicators to produce sustainability assessments. The Portuguese set is composed by 118 indicators, 30 of which are classified as key (Agência Portuguesa do Ambiente, Marcelino, Espada, & Vilão, 2007).

There are in addition several local sustainable development indicator initiatives. The most commonly referred places are in the United States: the Sustainable Seattle Project, the Willapa Bay Indicators, the Hamilton-Wentworth’s Community Indicator Project and the Oregon Benchmarks Project (Roseland, 2005). Outside the United States, the efforts carried out in Sydney (Newman, 2006), Leicester, Birmingham (Beatley, 2000), Melbourne, Toronto, Vancouver and Barcelona (IISD, 2009) are worth mentioning. In Portugal data is lacking, but continuous indicator projects seem to be very rare. From the interviews carried out with 82 heads of municipality in 2003/2004, Schmidt, Nave, & Guerra (2006) received only eight answers that might indicate such cases – more precisely, municipalities involved in LA21 processes that reported being in the implementation, monitoring or reviewing phases. In 2002, Quental & Silva (2003) sent a questionnaire to all Portuguese municipalities and yielded a worse result: none of the 20 respondents was monitoring their LA21 or environmental plans. Although in both cases no questions specifically directed to indicators were asked, results are suggestive of the lack of importance given to the regular and transparent monitoring of sustainable development. The project “Eco XXI,” coordinated by Associação Bandeira Azul da Europa, seems promising in changing that situation. A set of 23 local level sustainability indicators were developed and applied in 2008/2009 to the 43 municipalities that have voluntarily enrolled in the project (Associação Bandeira Azul da Europa, 2009). But the project

has still to gain wider public and media attention before it can turn into a sustainability assessment tool capable of stimulating a healthy competition among municipalities. I have coordinated an ambitious collection of indicators for the Metropolitan Area of Porto in 2005 (Quental, 2005) on behalf of the strategic planning process *Futuro Sustentável*. The report incorporates a wide variety of longitudinal information at the municipal level and, additionally, foreign data when the comparability of indicators was ensured. Since then, however, no updates have been released.

2.7.5 Composite indices

Research on composite indices is one of the most active in the indicators community. Literature distinguishes between *aggregated indicator*, *composite indicator* and *index*, but the distinctions are not particularly useful and may be misleading. For simplicity, the term *composite index* was preferred to designate indicators that combine two or more components (sometimes of very different nature) into a single score. Development of composite indices is requested on the grounds of improved data meaningfulness and of better communication capabilities (Bauler, et al., 2007), but the task is fraught with conceptual and technical difficulties.

Conceptual difficulties stem from the irreducible character of sustainable development (cf. section 2.4), which should in principle refrain scientists from looking for a magic number capable of aggregating all the different sustainability domains. When sustainability indices are developed, and contrary to the recommendations put forward before, seldom they are backed up by a compelling theory about what should be measured and why (Böhringer & Jochem, 2007; Graymore, Sipe, & Rickson, 2008; Parris & Kates, 2003b). That is, composites become in these situations a mixture of indicators with a variable level of discretion.

Technical difficulties arise when different issues (measured on different units) need to be converted to a common unit (which is called *normalization*) so that they can be aggregated. However, technical difficulties may just be the result of a conceptual dysfunction. Because sustainability encompasses social, environmental, economic and institutional issues, a common and obvious measuring scale is not available. A frequent choice is the use of monetary units, but valuation methods are still highly subjective and cannot properly attach a value to several sustainability domains (e.g., Munda, 2008). Normalization is facilitated when composite indices have very specific objectives and when the process follows scientifically valid methods. The global warming potential and the ozone depletion potential, for instance, are two indices that effectively aggregate information concerning the relative impact of several molecules; eco-indicator 99, although still suffering from several methodological deficiencies, converts the impacts caused by products over their life cycle into a common unit called milli-point (Ministry

of Housing Spatial Planning and the Environment, 2000). Without an underlying theory it becomes quite difficult, if not impossible (as Arrow proved in his impossibility theorem; cf. OECD, 2008), to construct indices with a perfect aggregation method. In addition, Zhou, Ang, & Poh (2006) and Böhringer & Jochem (2007) claimed that the most correct aggregation method – the geometric mean of indicator values – is seldom used in favor of simple arithmetic means. Because of these difficulties, OECD published a guide to aid in the development of composite indicators. Several methods, including statistical procedures such as factor analysis, were explained and compared so that an informed choice can be made (OECD, 2008). Graymore, et al., (2008) referred about the lack of transparency in the calculation methods of many composite indices, which should be a basic requirement. After preparing Table 2.7-3, which presents some of the most widely used composite indicators that deal with sustainability issues, I have to agree with Graymore.

There are many other indices besides the one indicated in Table 2.7-3. They include the *gross national happiness* (based on the subjective well-being of individuals), the *Dow Jones sustainability index* (tracks the performance of sustainability-driven companies), the *index of social health* (monitors the social well-being of American society), the *city power index* (seeks to capture the relative weight of cities within national governance systems), the *sustainable cities index* (applied only once in selected United Kingdom cities), the *urban governance index* (a tool to measure progress in achieving good urban governance; United Nations Center for Human Settlements, 2009), and the *commitment to development index* (rates 22 rich countries on how much they help poor countries build prosperity, good governance, and security).

Table 2.7-3: Some of the most common or promising composite indicators that deal with sustainable development.

Index and similar*	Characteristics [†]	Description	Strengths and criticisms
<u>Sustainable development</u>			
Well-being Index (2001)	(a) Capabilities (b) Strong commensurability (c) Elements, indicators and indices are combined according to a complicated hierarchical process; in each step, normalization is carried out by transforming indicator scales into barometer scales which are based on performance criteria; weighting methods are highly variable	The well-being index is the graphical intersection of two sub-indices: the human wellbeing index (a composite of 36 indicators of health, population, wealth, education, communication, freedom, peace, crime, and equity) and the ecosystem wellbeing index (a composite of 51 indicators of land health, protected areas, water quality, water supply, global atmosphere, air quality, species diversity, energy use, and resource pressures) (Hák, Moldan, & Dahl, 2007). Prescott-Allen (2001), who developed the indices instructed by IUCN, published an extensive assessment of 180 countries.	Because each indicator is also published as user-friendly maps and diagrams (including the so-called <i>eggs of well-being</i>), information is preserved during the complicated aggregation method if the user is careful enough to consult the range of data available (Moldan & Dahl, 2007). Aggregation uses several techniques (unweighted averages, weighted averages, and vetoes) which could be controversial (UNDSD, 2001). The specific methods chosen in each case lack a strong theoretical justification.
Taking sustainable cities seriously index (2003)	(a) Not applicable (b) Weak commensurability (c) Indicators (the sustainability programs under consideration) are equally weighted; the final score is given by summing up all sustainability programs practiced in each city.	The index measures the extent to which cities seem to take sustainability seriously. The analysis focuses on the policies, programs, and activities of cities that would seem to be consistent with an overall effort for cities to become more sustainable. The index is calculated from data regarding 34 of those programs (Portney, 2003).	The index has a clear and specific goal and the calculation method fits the intention. Improvements in the weighting scheme and in the scaling of each indicator value would be beneficial.

Table 2.7-3 (continued)

Index and similar*	Characteristics [†]	Description	Strengths and criticisms
<u>Greened GNP</u>			
Index of sustainable economic welfare (1989) <i>Similar:</i> Sustainable national income (1991); genuine progress indicator (1995); sustainable social net national product (1996); environmentally adjusted domestic product (1998)	(a) Utilitarian (b) Weak commensurability (c) Terms are monetarized, given equal weights, and summed	ISEW is focused on improving the gross domestic product and accounting for some of the externalities it does not consider (UNDSD, 2001). The starting point is the inflation-adjusted consumption of households. Consumption is adjusted by five categories to obtain an index which is more appropriate for measuring social welfare: distribution of income, economic activities not counted in the conventional gross national income, time adjustments, damage caused by economic activity, and the consideration of net capital endowment of foreign investors (Böhringer & Jochem, 2007).	Could replace the GDP as the main economic indicator. Valuation methods are not standardized yet and enough data to calculate environmental degradation costs is usually lacking. ISEW's theoretical validity is questionable (Zylicz, 2007; Gasparatos, El-Haram, & Homer, 2008). "If GNP were a cigarette, then ISEW would be that cigarette with a charcoal filter" (Daly, 1996, p. 97).

Table 2.7-3 (continued)

Index and similar*	Characteristics†	Description	Strengths and criticisms
Genuine savings or genuine investments (1993)	(a) Utilitarian (b) Weak commensurability (c) Terms are monetarized, given equal weights, and summed	Genuine savings aim to represent the value of the net change in the whole range of assets that are important for development: produced assets, natural resources, environmental quality, human resources, and foreign assets. The extend standard national accounts calculations by deducting the value of depletion of natural resources, deducting pollution damages, treating current expenditure on education as saving rather than as consumption, deducting net foreign borrowing and add net official transfers, and deducting the value of resource depletion (Everett & Wilks, 1999). Savings must be greater than depreciation on all assets for an economy to qualify as potentially sustainable. Savings minus depreciation equal genuine savings (Pearce, 2002).	It is difficult to uniquely determine all of the ways in which capital contributes to well-being. Those that cannot be identified cannot be valued. Even for those contributions that can be identified, it is sometimes difficult to translate their value into dollars (Joint United Nations Economic Commission for Europe/OECD/Eurostat Working Group on Statistics for Sustainable Development, 2008). Controlling for the effect of population growth is needed in order to correctly interpret the indicator (Dasgupta, 2001).

Table 2.7-3 (continued)

Index and similar*	Characteristics†	Description	Strengths and criticisms
<u>Human development</u>			
Human development index (1990)	(a) Capabilities (b) Weak commensurability (c) Each indicator is calculated for the country i as $\frac{x_i - x_{min}}{x_{max} - x_{min}}$, where x_{max} and x_{min} are goalposts determined by the UNDP; sub-indices are then averaged	HDI is reported annually as part of the Human Development Reports. HDI is a composite of two indicators and one sub-index: life expectancy, the education index (which relies on two indicators), and GNP (Böhringer & Jochem, 2007). Each indicator represents the distance between the level of attainment in a country and the target level (Cobb, 2001). Countries with a HDI higher than 0,8 belong to the high human development group, between 0,5 and 0,8, countries belong to the medium human development group, and below 0,5 countries are considered in the low human development group (Hák, et al., 2007).	HDI has been gaining worldwide acceptance and notoriety. The index would be strengthened if some measure of income distribution (Cobb, 2001) and public participation (Dasgupta, 2001) were included in the calculation. It does not serve as an indicator of sustainable development because neglects environment issues (Dasgupta, 2007; Moldan & Dahl, 2007).
City development index (2001)	(a) Capabilities (b) Weak commensurability (c) Each indicator is calculated for the city i as $\frac{x_i - x_{min}}{x_{max} - x_{min}}$, where x_{max} and x_{min} are goalposts determined by the United Nations Center for Human Settlements; sub-indices can be arithmetic means of their constituting indicators or, alternatively, weights can be obtained by principal components analysis	The CDI was developed as a prototype for Habitat II to rank cities according to their level of development (United Nations Center for Human Settlements, 2001b). It consists of five sub-indices: an infrastructure index, a waste index, a health index, an education index, and a city product index. Each sub-index is a composite of a variable number of indicators. Indicators are normalized on a distance-to-target basis. (Böhringer & Jochem, 2007).	The five indices measure relevant aspects but other important issues are left out (UNSD (2001). Environmental considerations are only superficially considered. The CDI correlates strongly with the HDI if both are applied at the same level.

Table 2.7-3 (continued)

Index and similar*	Characteristics†	Description	Strengths and criticisms
Creativity index (2002)	(a) Capabilities (b) Weak commensurability (c) Terms are averaged	The Creativity Index is a composite indicator used by the economist Richard Florida to describe how members of the so-called <i>creative class</i> are attracted to a city. The index combines four elements: the share of the workforce classified as creative, innovation, high tech industry, and diversity (measured by the gay index, a reasonable proxy for an area's openness). Florida argues that using this index, cities can be rated and ranked in terms of innovative high tech centers (Florida, 2004).	Some researchers have found no relationship between the creativity index and measures such as economic growth. Other researchers point out that creativity is the result of fundamental characteristics that are present in dynamic cities ⁵ .
Freedom in the world (1972)	(a) Capabilities (b) Weak commensurability (c) The scores obtained for political rights and civil liberties are averaged and determine the overall country's status as free, partly free, or not free	Individual countries are evaluated based on a checklist of 10 questions on political rights and 15 civil liberties that are derived in large measure from the Universal Declaration of Human Rights. Each country is assigned a rating for political rights and a rating for civil liberties based on a scale of 1 to 7, with 1 representing the highest and 7 the lowest level of freedom (Hák, et al., 2007).	Freedom in the world has been published and widely publicized yearly for 192 countries and 14 territories by the organization <i>Freedom House</i> . Ratings have some degree of subjectiveness. Methodological changes warn against temporal comparisons.

⁵ Wikipedia, 2009a.

Table 2.7-3 (continued)

Index and similar*	Characteristics†	Description	Strengths and criticisms
<u>Environmental</u>			
Ecological footprint (1992) <i>Similar:</i> Human appropriation of net primary productivity (1986); environmental space (1992); water footprint (2002)	(a) Not applicable (b) Strong commensurability (c) Each impact category is either directly assigned to a bioproductive area type or converted to one according to scientific standards; all terms are in area units (usually ha) and can be easily summed-up to yield the total footprint	Ecological footprint accounts act as balance sheets by documenting for a given population the area of biologically productive land and sea required to produce the renewable resources this population consumes and assimilate the waste it generates, using prevailing technology. Human impacts are estimated from official statistics as six main bioproductive area types: cropland, grazing land, forest, fishing ground, built-up land and energy land. The resulting Ecological footprint can be compared with the available bioproductive land to conclude about the level of environmental sustainability (Wackernagel, Kitzes, Moran, Goldfinger, & Thomas, 2006).	Ecological footprint has achieved the highest popularity among environmental indicators, partially because of its intuitive results. WWF has been publishing country estimates biennially since 1998 in their “Living Planet Reports.” Ecological footprint has been severely criticized ever since it was created. Researchers base their criticism in the calculation method’s lack of transparency and of scientific validity (Graymore, et al., 2008; Moldan & Dahl, 2007; Munda, 2006; van den Bergh & Verbruggen, 1999), the loss of information during the aggregation process (Graymore, et al., 2008; Moldan & Dahl, 2007), the poor adequacy for regional scale assessments (Graymore, et al., 2008; Lewis & Brabec, 2005; Zuindeau, 2006), the fact that land use is regarded to be associated with single impact categories (van den Bergh & Verbruggen, 1999), the incidence only on the environmental pillar of sustainability (Moldan & Dahl, 2007; UNDSO, 2001), and the irrelevance for policy-making (Newman, 2006).

Table 2.7-3 (continued)

Index and similar*	Characteristics†	Description	Strengths and criticisms
Living planet index (1997)	(a) Not applicable (b) Weak commensurability (c) Each sub-index is constructed by averaging its population's annual rates of change according to a hierarchy of several lower-level indices; each of these individual component indices was set at 100 in 1970; sub-indices are gradually averaged until the final index is achieved	LPI is based on trends in nearly 5000 populations of 1686 species of mammal, bird, reptile, amphibian, and fish from around the globe. LPI is the aggregate of two sub-indices: the temperate index and the tropical index (Hails, Humphrey, Loh, & Goldfinger, 2008).	Like has been happening with the ecological footprint, the LPI has benefited from the publicity given by WWF in the "Living Planet Reports." Böhringer & Jochem (2007) claim that the index appears rather questionable because it presumes substitutability of species. Can be a proxy of ecosystems' health although land cover is not included.
Environmental performance index (2002) <i>Similar:</i> Environmental sustainability index (1999)	(a) Not applicable (b) Weak commensurability (c) Each indicator is calculated for the country i as $\frac{x_i - x_{min}}{x_{max} - x_{min}}$, where x_{max} and x_{min} are targets determined according to scientific literature, experts or policy documents, or the boundary value of the original variable obtained by statistical winsorising (to recode outliers); sub-indices are weighted according to a weight matrix and gradually added until the final index is achieved	EPI is a composite index of current national environmental protection efforts that can be linked to policy targets. EPI builds on two core objectives: reducing environmental stresses to human health and protecting ecosystems and natural resources. Twenty-five indicators are arranged in a tree-like hierarchical framework creating a number of sub-indices that progressively join together to form the final index. Indicators are calculated on a distance-to-target basis (Esty, et al., 2008).	EPI has been gaining media attention. The calculation method requires a number of steps but it is presented with high clarity and transparency. The index is restricted to the environmental domain of sustainability.

Table 2.7-3 (continued)

Index and similar*	Characteristics [†]	Description	Strengths and criticisms
Material input per service unit Energy return on (energy) input Emergy	(a) Not applicable (b) Strong commensurability (c) Terms are normalized, given equal weights, and summed	These indicators are usually applied in the context of life cycle assessments but can be used in other contexts, including urban systems. All of them convey information about the efficiency of a system – but do it in different ways. MIPS relate all the materials directly and indirectly used for production in an economy (the <i>ecological rucksack</i>) with the services provided by that economy (Funtowicz, 1999). It is therefore an indicator of the material intensity of a system. The MIPS concept has been the starting point for the strategic discussions on the Factor 4 and Factor 10 goals (Ness, et al., 2007). EROI and emergy are similar indicators that express the energy efficiency and intensity of a process. EROI is the ratio of usable energy acquired from a particular energy source to the amount of energy expended to obtain that energy (Conselho Nacional do Ambiente e do Desenvolvimento Sustentável, 2007). Emergy is the available energy of one kind (usually solar) that has to be used up directly or indirectly to make a product of service (Odum & Odum, 2006).	These indicators provide valuable information about the efficiency and intensity of an economy, process or product, and allow both time and geographical comparisons. EROI is particularly useful to compare different energetic resources. MIPS and emergy are more directed to product assessments (their application to larger scales is conceptually similar to the ecological footprint). In MIPS and emergy, difficulties arise when services have to be determined. Which services? and how to estimate the materials and energy they require? Efficiency indicators are restricted to a very specific part of the environmental and economical domains of sustainability. They cannot provide information about the scale of material and energy use, for example.

Table 2.7-3 (continued)

Index and similar*	Characteristics†	Description	Strengths and criticisms
Environmental vulnerability index	(a) Not applicable (b) Strong commensurability (c) Raw indicator values are transformed into a vulnerability scale according to expert judgment and scientific literature; normalized indicators are then averaged to form the sub-indices and the eventually the final index.	EVI provides a measure of the vulnerability of the natural environment of a country. EVI is a composite of three sub-indices: the risk exposure index (made up by 32 indicators), the resilience index (made up by eight indicators), and the vulnerability index (made up by 10 indicators) (Pratt, Kaly, & Mitchell, 2004).	EVI is backed by an understandable goal and by a scientific model of vulnerability. As a result, the computation method is also scientifically sound. Because of its specificity, only covers a part of the environmental domain of sustainability.

* Creation date is shown in parenthesis.

† (a) Rationale¹, (b) comparability of values², (c) normalization, weighting and aggregation³.

¹ Following Cobb's (2000) assertions and the literature review presented in section 2.5.

² According to Funtowicz's (1999) framework.

³ According to Böhringer & Jochem (2007) specifications.

2.8 Synthesis

2.8.1 International politics and policy

The political analysis of the present chapter aimed at revealing the main developments and cycling patterns of political activity concerning sustainable development, and at identifying the most important sustainability goals and targets. The cycling patterns reported in Figure 2.3-I combined with the uneven time distribution of the milestones identified in Table 2.2-I convey the powerful message that political efforts are indeed characterized by measurable ups and downs. Moreover, the fact that the peaks in political activity coincide with the decennial Earth Summits (particularly UNCED and WSSD, and to a lesser degree UNCHS) is suggestive of their influence as catalysts of more profound societal and political action.

In a “starting up” stage until the seventies, the first significant efforts for environmental protection were undertaken. At the national level, governments started to approve general legislative frameworks, to establish environmental ministries and to create protected areas. At the global and regional scales, multilateral treaties aiming at the conservation of species (Conference on International Trade in Endangered Species of Wild Fauna and Flora) and ecosystems (Ramsar Convention), the protection of human rights and cultural heritage (World Heritage Convention), and the control of pollution (Convention on Long-Range Transboundary Air Pollution) were agreed. The Stockholm Conference in 1972 was a recognizable milestone and resulted in the creation of UNEP.

A second stage, characterized by a stagnation of sustainable development policy, followed and extended until around 1986. Although at the national level the creation of protected areas continued to grow, multilateral efforts in the environmental area refrained due to a shift for economic prosperity as a solution for development problems. Besides this less favorable atmosphere, the World Conservation Strategy (in 1980) gave visibility to the concept of sustainable development. However, the concept appeared for the first time in 1976 (in text of the “Agreement Establishing the South Pacific Regional Environment Program,” according to a search in Mitchell, 2008) with a meaning similar to the one coined later, in 1987, by the Brundtland Commission.

The decade from around 1987 until 1995 represented another period of significant efforts of the international community to push for sustainable development. The Brundtland Commission set the stage in their report “Our common future.” Sustainable development entered definitely the lexicon and became a popular expression receiving the agreement of almost everyone. The 1992 UNCED was another obvious breakthrough, as supported by peaks in all indicators of Figure 2.3-I around this date and by the impressive number of political milestones that

followed: environmental agreements (Convention on Biological Diversity, United Nations Framework Convention on Climate Change), institutional arrangements and financial mechanisms (United Nations Commission on Sustainable Development, Global Environment Facility) and acknowledged “soft law” (Rio Declaration, Agenda 21). The balanced position offered by WCED was neglected during UNCED, whose agenda was significantly “greener.” During the nineties, governance issues such as transboundary cooperation and public participation were finally addressed by multilateral agreements.

The fourth period that started around 1996 was marked by a decline in global sustainable development policy. The fear of terrorism and the globalization of economy are probable reasons, but a short peak in political indicators around 2000 – certainly related with the coming of WSSD – turn the conclusions less straightforward. But even WSSD as a milestone was not as influential as UNCED, if the judgment is based on their outcomes (Table 2.3-2). For instance, no agreements, institutional arrangements or financial mechanisms followed WSSD; and although several targets were approved, Røpke (2005) remarked the notable “implementation deficit” that the international community seems unable to counteract. As already proposed by UNEP (2007), perhaps a new stage of sustainable development policy is emerging that shifts the attention to the implementation of existing norms and policies, including the growing number of national sustainable development strategies, which already amount to 82 (UNSD, 2008).

Topics and goals addressed at the global level by multilateral agreements and by other political milestones have been in constant evolution depending on the perception relevancy and urgency of the problems, on disasters or specific events, and on influences from the scientific realm. Analysis of Table 2.3-2 reveals a transition from single issues to more complex and integrated frameworks. Ecosystem concerns succeeded species conservation initiatives, and it was not until the nineties that governance issues were directly addressed by multilateral environment agreements. Since 2000, the interest about the institutional dimension of sustainable development seems to have continued, at least in the discourse of the Millennium Declaration and of WSSD, although it has not been accompanied by implementation mechanisms. Recently, Governments have been approving treaties to regulate new topics that pose specific threats such as the genetically modified organisms and the persistent organic pollutants. Several targets have been agreed by the international community, namely through the Millennium Development Goals. These commitments are meritorious but at the same time biased towards human development, since these are significantly more detailed and in a larger number than the environmental protection goals. Sustainability concerns shifted from an emphasis on pollution and availability of natural resources to a more balanced position that

puts human and social development – particularly freedom and the expansion of individual capabilities – at the center.

2.8.2 Scientific approaches to sustainability

One of the goals of the present chapter was to reveal the main developments in the scientific arena of sustainable development and to determine the most relevant influential publications in the field. Complementary methods (literature review and analysis of bibliometric data) were used for that purpose. Four traits were identified as the most important of modern sustainability research, namely in ecological economics and sustainability science:

- From a static view of environmental limits and human impacts, sustainability approaches progressed to a dynamic and integrative vision of them. Carrying capacity is not an attribute of the natural systems but instead of the coupled socioecological systems. Far from static, carrying capacity can be increased through better technology or more efficient management and institutional regimes. Specific concepts such as risk, resilience and vulnerability have been proposed to convey this rationale;
- Sustainability concerns shifted from an emphasis on human impacts and availability of natural resources to a more balanced position that puts human and social capital – particularly freedom – at the center. The economic and institutional settings became increasingly valued as well, also because of their instrumental and facilitating role in moving towards sustainability;
- From an end-state and fixed concept, sustainability is nowadays seen as more of a transition or as a collective work-in-progress towards desired goals. Because it is problem driven and embedded in the larger scale of policy priorities, sustainability science pays great attention to the relationship with society. The research process must therefore respect the rules of saliency, credibility and legitimacy in order to accomplish its purposes;
- Sustainability is not only vague in its definition and broad in its scope. It is also struggling between two complementary rationales. On one side, sustainable development is somehow related to every important goal of society, from protecting nature to developing human rights. Any partial analysis or development of each of those topics is relevant for the sustainability debate. On the other side, and contrasting to this multitude of objectives, sustainability science is nowadays a specific field of study that embraces or unites several disciplines. That is, sustainability is intrinsic to various disciplines, but it also is a discipline on its own joining a multitude of contributions.

The findings of the bibliometric study complement the conclusions from the literature review by allowing the identification of the most influential publications of the sustainability literature. The references ranking higher are those with a global dimension and large diffusion, such as

WCED (1987) – which is unquestionably the most cited publication –, IPCC's third assessment report (2001) and MEA (2005), but classics follow thereafter (e.g., Pearce's et al. "Blueprint for a green economy" and D. Meadows, Meadows, Randers, & Behrens "Limits to growth"). Visual interpretation of Figure 2.6-1 suggests a pattern of landmark studies that frame the core of sustainability thinking about every five years and which somewhat trickle down into many less cited, although still influential, works.

Scientific literature dealing with sustainability is dominated by the economics and by ecology (cf. the most cited references in annex A.1, the leading authors and journals in Table 2.6-2 and Table 2.6-3, and the disciplinary evolution of papers in Figure 2.6-3). A smaller but still significant contribution comes from sociology, political sciences, and planning. Nevertheless, the core of cited references and a growing number of papers are in fact multidisciplinary – especially since 2000, just a year before the Amsterdam Declaration that proclaimed the sustainability science. There is no doubt that sustainable development, at least as a catchword, has entered the scientific lexicon. Since around 1990 there has been an impressive growth in the number of papers containing that expression in the title or abstract (Figure 2.6-2).

As a final synthesis, the primal roots of sustainability thinking lie in relatively narrow focused analysis of the seventies that emphasized environmental and resource constraints to human economy. Later, since the eighties, a broader perspective was favored by ecological economics. Ecological economics also regards the economy as embedded in the biosphere, but goes further by dismissing the simplicity of utilitarianism and replacing it with a larger set of welfare criteria that includes equity and the intrinsic value of nature. Uncertainty and complexity were acknowledged as two fundamental system characteristics. The rise of the global economy particularly since the nineties came along with a growing call for individual values and rights. Sustainability incorporated this message by devoting a more prominent attention to both human and social development. The new century brought what some scientists consider to be a new branch of science: sustainability science. Sustainability science is a new step towards consilience, a tentative to bring together scholars from different backgrounds in order to create meaningful and integrated thesis. In this sense, rather than being discarded, previous approaches to sustainability were reclaimed and integrated. Since the first steps of the sustainability science have just been given, its potential is still to be further released.

3. Urban sustainability and sustainable territorial structure

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3. Urban sustainability and sustainable territorial structure

3.1 Introduction

The previous chapter concentrated on sustainable development in its broadest sense. In this chapter, I present the issues and approaches to sustainability specifically dealing with urban systems so as to continue the journey from the global to the borough scale. Section 3.2 starts with general perspectives on urban sustainability drawn from policy documents and scientific literature. Section 3.3 details the concepts of territorial structure, urban form, urban growth, and sprawl. Empirical data concerning these issues is also provided. Section 3.4 represents a close-up of the relationships between territorial structure and selected sustainability domains. A particular emphasis is given to mobility patterns because of their importance for this thesis. I end up with section 3.5, which synthesizes the chapter.

3.2 Different perspectives on urban sustainability

This section starts with a selection of definitions for *sustainable city* found in the literature. Then, I present urban sustainability goals as they are expressed in policy declarations and in scientific literature. Goals are grouped into four components: environmental sustainability, urban planning, social and economic development, and governance. These dimensions are based on the scheme proposed by Campbell (1996), who devised a simple triangular model to understand the divergent priorities of planning.

3.2.1 Definitions

The definitions for *sustainable city* are vague – just like the definitions for sustainable development. Two central and general urban sustainability policies are consensual: improving quality of life, and respecting the carrying capacity of the planet. Another dimension of great importance is also found in most definitions: the idea of equity, either intragenerational or intergenerational. The geographic dimension of equity was analyzed in detail by Zuindeau (2006). In the following paragraphs, I illustrate urban sustainability with various definitions coming from different backgrounds.

“A sustainable city is organized so as to enable all its citizens to meet their own needs and to enhance their well-being without damaging the natural world or

endangering the living conditions of other people, now or in the future” (Girardet, 1999/2007, p. 16).

“A sustainable city is one which its people and business continuously endeavor to improve their natural, built and cultural environments at neighborhood and regional levels, whilst working in ways which always support the goal of global sustainable development” (Haughton & Hunter, 1994, p. 27).

“The path to sustainability lies in transforming our cities so that they are based on the patterns and processes of natural, sustainable ecosystems, achieving ecological regeneration, healthy communities, and viable economies within their bioregions. Cities work best at bioregional and community scales, not just at the global scale where much of the economy is taken them” (Newman & Jennings, 2008, p. 7).

“The role of planners is therefore to engage the current challenge of sustainable development with a dual, interactive strategy: to manage and resolve conflict; and to promote creative technical, architectural, and institutional solutions. Planners must both negotiate the procedures of the conflict and promote a substantive vision of sustainable development” (Campbell, 1996).

“A sustainable city is a city in which agglomeration economies should possibly be associated with positive environmental externalities and social network externalities, and in which at the same time negative effects stemming from the interaction of the three different environments are kept within certain threshold conditions associated with the urban carrying capacity on the urban environmental utilization space” (Nijkamp and Opschoor, 1995, as cited in Camagni, Capello, & Nijkamp, 1998, p. 108).

“In order for the development of land use, patterns of built-up land and infrastructure in an area to be characterized as sustainable, it must secure that the inhabitants of the area can have their vital needs met in a way that can be sustained in the future, and is not in conflict with sustainable development at a global level” (Næss, 2001, p. 505).

3.2.2 Goals expressed in policy declarations

A compilation of charters, declarations, and guiding principles for urban sustainability mainly for European countries is presented in Table 3.2-2. From a normative point of view, Europe has been in the forefront of urban sustainability concerns. The efforts of European Commission date back to 1991 when the “Green Paper on the Urban Environment” was published. This report eventually led in 1993 to the launch of the European Sustainable Cities and Towns Campaign with the overall objective of promoting urban sustainability and supporting European local authorities in implementing related policies. The campaign has been particularly active in the promotion of Local Agenda 21 (LA21) processes. Since the inaugural conference in 1994 – where the landmark Aalborg charter, already signed by 2030 municipalities, was approved – other conferences were regularly organized and resulted in similar, though less important, declarations. The highly quoted “Sustainable Cities Report” was published in 1996. In 2006, the Commission released the Thematic Strategy on the Urban Environment but, in spite of the rather minimalist goals and contained ambition, no further developments since then are visible. Another major initiative at the European Union level is the European Spatial Development Perspective (ESDP). The strategy was approved in 1999 and comprises three main policy options: promote a polycentric spatial development and a new urban-rural relationship; stimulate parity of access to infrastructure and knowledge; and implement a wise management of natural and cultural heritage. Excepting for the lack of planning goals in the Lisbon Action Plan (1996) and the lack of environmental goals in the New Charter of Athens (2003), goals expressed in Table 3.2-2 are quite balanced. Those exceptions are probably the result of a background bias of the participants and, as such, do not seem to carry any deeper significance.

Portugal

In Portugal, the guiding policy concerning sustainability is presented in the National Strategy for Sustainable Development (ENDS), which spans through the period of 2005–2015. One of its major goals is creating an urban dynamics that are more inclusive and less destructive to the environment. Territorial planning and policy is dictated by Act 48/98, which defines main national guidelines. It establishes, *inter alia*, objectives such as the rational use and management of natural resources, the maintenance of the environmental equilibrium, the humanization of cities, and the functionality of the built-up spaces. A bottom-up approach is under construction for a complex national planning system (Table 3.2-1). It started in the beginning of the nineties when all Portuguese municipalities were required to prepare land use plans for the entirety of their territories. The National Program for the Territory and Land use Policies (PNPOT) – the upper layer of the system – however, was only approved in September 2007. It consists of a

strategic national guidance document which shall be incorporated into territorial plans at the regional level and articulated with other national level strategies like the ENDS. The program is structured around five main objectives, two of which are highlighted: (a) conserving biodiversity, natural and cultural heritage, as well as using energy and geological resources sustainably; and (b) promoting a polycentric territorial development and strengthening the infrastructure that supports territorial integration and cohesion. Regional territorial plans covering the entire country (one for each of the five NUT II regions) are still being prepared. There are a number of thematic plans that complement the broad spectrum plans mentioned above. They include such specific areas as nature conservation, forestry, and water basin planning. However, plans often remain in the domain of intentions. In a review of the Portuguese planning and governance systems, I have concluded that several dysfunctions are hampering their proper functioning (Quental, 2006c, 2006d).

Table 3.2-1: Main territorial plans in Portugal.

Name	Type	Main theme	Level
National Program for the Territory and Land use Policies (PNPOT)	Strategic	General	National
Regional territorial plans (PROT)	Strategic	General	Regional
Forestry plans	Forestry land use and management	Forests	Subregional
Protected areas master plans	Land use	Nature conservation	Subregional
Natura 2000 plan	Land use	Nature conservation	Subregional
River basin plans	Land use	Water	Subregional
Local land use plans (PDM)	Strategic and land use	General	Municipal

Table 3.2-2: Comparison of goals as expressed in selected policy declarations dealing more directly with urban sustainability.

Sustainability milestone	Environmental sustainability	Urban planning	Social and economic development	Governance
The European Urban Charter (1992) Signatories: Member States of the Council of Europe	.Protect nature and green spaces .Adopt policies to prevent pollution	.Base political decisions on urban and regional planning .Manage natural resources in a rational manner .Redevelop older housing .Provide adequate infrastructure .Maintain the residential character of the city centre .Ensure diversity and mobility in housing .Reduce the volume of private car travel .Promote different forms of travel .Recover streets as a social arena .Design towns in such a way that all citizens have access to all places .Integrate disabled persons	.Guarantee a secure home for every family .Safeguard city centers .Enhance cultural pluralism .Promote sporting and recreational activities .Adopt nondiscriminatory policies .Develop an urban security policy .Stimulate economic development .Maintain and revive specialized crafts	.Stimulate cooperation between authorities and community groups .Devise original financial mechanisms and partnerships .Adopt sound information policies .Increment citizen participation in local political life .Consult citizens over all major projects affecting the future of the community .Ensure effective participation by immigrants

Table 3.2-2 (continued)

Sustainability milestone	Environmental sustainability	Urban planning	Social and economic development	Governance
Charter of European Cities & Towns Towards Sustainability, or Aalborg Charter (1994) Signatories: Local authorities	.Conserve the remaining natural capital .Stabilize and reduce emissions of greenhouse gases .Undertake every effort to see that further pollution is stopped and prevented at source .Increase the end-use efficiency of products and energy	.Embrace the strategic environmental assessment of all plans .Effective land use and development planning .Provide efficient public transport .Improve accessibility and urban lifestyles with less transport .Stop promoting the unnecessary use of motorized vehicles .Give priority to ecologically means of transport	.Seek opportunities for education and training for sustainability .Create jobs which contribute to the sustainability of the community .Encourage the creation of long-term jobs and long-life products in accordance with the principles of sustainability	.Take advantage of a wide range of management and information instruments .Resolve problems by negotiating outwards .Ensure that all citizens and interested groups have access to information and are able to participate in local decision-making processes
Lisbon Action Plan: from Charter to Action (1996) Signatories: Local authorities	.Adopt the Aalborg Charter .Carry out systematic action planning to move from analysis to action .Integrate environmental with social and economic development to improve health and quality of life for our citizens .Use advanced tools for sustainability management		.Establish programs to raise awareness among our citizens, interest groups, as well as politicians and local government officers of sustainability issues	.Seek to get our own house in order .Involve the entire local authority in the process of LA21 .Gain strength through interauthority alliances: associations, networks and campaigns .Enter into consultation and partnerships with the various sectors of our community

Table 3.2-2 (continued)

Sustainability milestone	Environmental sustainability	Urban planning	Social and economic development	Governance
Istanbul Declaration on Human Settlements (1996)	.Build sustainable human settlements .Minimize vulnerability to disasters .Change unsustainable consumption and production patterns, particularly in industrialized countries	.Provide basic infrastructure and services	.Provide adequate shelter for all .Ensure gender equality .Fight growing security and violence .Reduce unemployment	.International cooperation .Financing human settlements .Enablement and participation .Access progress
European Spatial Development Perspective (1999)	.Development of the Natura 2000 ecological network - Creative restoration of landscapes	.Effective methods for reducing uncontrolled urban expansion .Reinvigorated urban-rural relationships .Promotion of towns and countryside - Integrated spatial development strategies .Maintenance of basic services and public transport .Better coordination of spatial development policy and land use planning with transport and telecommunications planning	.Diversified development strategies for rural areas .Support for sustainable and multifunctional agriculture .Education, training, and creation of nonagricultural jobs .Environmental friendly tourism	.Greater use of economic instruments to recognize the ecological significance of protected and environmentally sensitive areas

Table 3.2-2 (continued)

Sustainability milestone	Environmental sustainability	Urban planning	Social and economic development	Governance
Guiding principles for sustainable spatial development of the European Continent (2000) Signatories: Ministers for Spatial Planning of the European Council	.Limit the impacts of natural disasters .Carefully manage the urban ecosystem, particularly with regard to open spaces, water, energy, waste and noise .Reduce environmental damage .Enhance and protect natural resources and the natural heritage	.Control de expansion of urban areas .Develop energy resources while maintaining safety .Promote more balanced accessibility .Develop effective but at the same time environmentally-friendly public transport	.Regenerate deprived neighborhoods and produce a mix of activities and social groups within the urban structure .Enhance cultural heritage as factor for development .Promote territorial cohesion through a more balanced social and economic development of regions and improved competitiveness .Encourage high quality, sustainable tourism	.Encourage development generated by urban functions .Improve the relationship between town and countryside .Develop networks of towns .Establish planning bodies across local authority boundaries between individual towns and communes .Develop access to information and knowledge

Table 3.2-2 (continued)

Sustainability milestone	Environmental sustainability	Urban planning	Social and economic development	Governance
Hannover Call (2000) Signatories: Local authorities	.Incorporate social and environmental considerations into policies .Introduce management systems for local sustainability and environmental performance .Introduce policies for green purchasing of products and services .Provide stronger support for the implementation of Agenda 21 and of the Habitat Agenda .Support the European Sustainable Cities & Towns Campaign .Stop labor and environmental dumping by incorporating social and environmental standards in international and multilateral agreements on trade	.Introduce an energy tax and stop subsidies for air traffic as a key instrument for internalizing social and environmental costs of energy use and providing an incentive for sustainable energy use and energy efficiency	.Engage in the development and implementation of health action plans and sustainable development plans .Understand that prospects for increasing profit and shareholder value may be severely jeopardized if the sustainable development of cities and the wellbeing of citizens as consumers are not guaranteed .Integrate environmental, health, safety and risk considerations into corporate strategies .Engage in the growing market of sustainable products and services, and to profit from first mover opportunities on these markets	.Develop, jointly with local government associations and networks, a culture of partnership between the European Commission on the one side, and local authorities and their associations on the other side .Allocate subsidies and grants to local and regional authorities, in particular in the fields of urban development and renewal, as well as transport, only on the condition that sustainability criteria are being met .Eradicate debt through remission programs .Provide adequate funds to international financing facilities for sustainable development

Table 3.2-2 (continued)

Sustainability milestone	Environmental sustainability	Urban planning	Social and economic development	Governance
Melbourne Principles for Sustainable Cities (2002)	.Recognize the intrinsic value of biodiversity and natural ecosystems, and protect and restore them .Enable communities to minimize their ecological footprint .Build on the characteristics of ecosystems in the development and nurturing of healthy and sustainable cities .Promote sustainable production and consumption, through appropriate use of environmentally sound technologies and effective demand management		.Achieve long-term economic and social security .Recognize and build on the distinctive characteristics of cities, including their human and cultural values, history and natural systems	.Provide a long-term vision for cities based on: sustainability; intergenerational, social, economic and political equity; and their individuality .Empower people and foster participation .Expand and enable cooperative networks to work towards a common, sustainable future .Enable continual improvement, based on accountability, transparency and good governance

Table 3.2-2 (continued)

Sustainability milestone	Environmental sustainability	Urban planning	Social and economic development	Governance
New Charter of Athens (2003) Signatories: Member of the European Council of Town Planners		.Analyze existing features and trends, consider the wider geographic context and focus on long-term needs .Elaborate alternative potential solutions for specific problems and challenges .Adopt strategic management approaches to spatial development processes rather than just plan making to serve bureaucratic administrative requirements .Develop and elaborate spatial development visions showing opportunities for the future .Maintain an appropriate knowledge of contemporary planning philosophy, theory, research, and practice .Encourage healthy and constructive criticism about the theory and practice of planning	.Contribute to training and education .Strive to protect the integrity of the natural environment, the excellence of urban design and endeavor to conserve the heritage of the built environment for future generations .Respect the principles of solidarity, subsidiary and equity in decision-making, in planned solutions and in their implementation .Suggest and elaborate operational legislative tools to ensure efficiency and social justice in spatial policies .Expand choice and opportunity for all, recognizing a special responsibility for the needs of disadvantaged groups and persons	.Think in all dimensions, balancing local and regional strategies within global trends .Monitor plans in order to adjust unforeseen outcomes, propose solutions or actions, and ensure a continuous feedback linkage between planning policy and implementation .Stimulate partnerships between public and private sectors .Collaborate with and coordinate all involved parties .Facilitate true public participation and involvement between local authorities, decision-makers, economic stakeholders and individual citizens .Convince all involved parties to share a common and long term vision for their city or region, beyond their individual interests and objectives

Table 3.2-2 (continued)

Sustainability milestone	Environmental sustainability	Urban planning	Social and economic development	Governance
Aalborg Commitments (2004) Signatories: Local authorities	.Assume responsibility to protect, to preserve, and to ensure equitable access to natural common goods .Adopt and facilitate the prudent and efficient use of resources .Assume global responsibility for peace, justice, equity, sustainable development and climate protection	.Promote a strategic role for urban planning and design in addressing environmental, social, economic, health and cultural issues for the benefit of all .Recognize the interdependence of transport, health and environment and are committed to strongly promoting sustainable mobility choices	.Protect and promote the health and wellbeing of our citizens .Secure inclusive and supportive communities .Create and ensure a vibrant local economy that gives access to employment without damaging the environment	.Implement effective management cycles, from formulation through implementation to evaluation. .Strengthen decision-making processes through increased participatory democracy
Thematic Strategy on the Urban Environment of the European Commission (2006)		.Implement sustainable urban transport plans		.Promote integrated environmental management
Leipzig Charter on sustainable European cities (2007) Signatories: Ministers of the Member States of the European Union	.Improve energy efficiency	.Creating and ensuring high-quality public spaces .Pursuing strategies for upgrading the physical environment .Promote efficient and affordable urban transport .Modernize infrastructure networks	.Build proactive educational policies .Build proactive innovation policies .Pay special attention to deprived neighborhoods .Strengthening the local economy and local labor market economy	.Make greater use of integrated urban development policy approaches

3.2.3 Goals expressed in scientific literature

Urban sustainability goals were also tracked in selected scientific references according to the organization scheme already used, which consists of environmental sustainability, urban planning, social and economic development, and governance (Table 3.2-3). Different authors emphasize specific sustainability concerns, confirming the ambiguous and ambivalent nature of the concept. Lynch (1960/1999), for instance, proposed five general dimensions and two meta-criteria to illuminate the basic characteristics of city form: *vitality*, *sense*, *fit*, *access*, *control*, *justice*, and *efficiency*. Lynch then explained how each dimension should be assessed. This conceptualization of the city may be useful for sustainability thinking, although the environmental considerations were not at the center of Lynch's concerns. Rogers & Gumuchdjian (1997/2001) envisioned seven dimensions related not only to urban form but also with city prosperity and ecology. Calthorpe & Fulton (2001) proposed a spatial model for a city-region comprised by four main units: *centers*, the main destiny of the neighborhood, city or region; *districts*, areas with special vocations and dominated by a specific function; *reserves*, open spaces and green areas that should be connected by corridors in order to form a network; and *corridors*, the elements linking natural areas and the transportation infrastructure such as avenues and rail tracks. Finco & Nijkamp (2001), profiting from the traditional triangular image of sustainable development, put urban sustainability at the center of three pillars (social, economic and physical) and policies (long-term allocative efficiency, environmental equity, and distributive efficiency – cf. Figure 3.2-1). The remainder authors mentioned at the Table 3.2-3 suggested several explicit political actions that would gear the city towards sustainability. They are interesting for the purposes of identifying the most relevant urban sustainability issues, but unlike the contributions of Lynch, Rogers and Calthorpe & Fulton, those suggestions are seldom rooted on some form of a sustainable city theory.

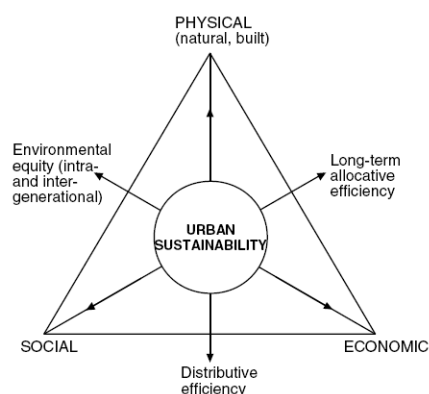


Figure 3.2-1: The main goals of sustainable urban development according to Finco & Nijkamp (2001).

A synthesis and simple organization of the various urban sustainability goals is presented in section 3.5.

Table 3.2-3: Comparison of goals as expressed in selected scientific references dealing more directly with urban sustainability.

Reference	Environmental sustainability	Urban planning	Social and economic development	Governance
Lynch, 1960/1999	.Efficiency	.Access	.Vitality .Sense .Justice	.Fit .Control
Maclaren, 1996	.Living within the carrying capacity of the natural environment .Minimal use of nonrenewable resources		.Intergenerational equity .Intragenerational equity .Economic vitality and diversity .Community self-reliance .Individual well-being .Satisfaction of basic human needs	
Alberti, 1996	.Minimize the direct transformation of habitats .Efficient use of natural resources .Minimize the emission of air pollutants and of waste		.Guarantee human health and well-being	
Rogers & Gumuchdjian, 1997/2001	.Ecological city	.Compact and polycentric city .Beautiful city .City of easy contact and mobility	.Creative city .Diverse city .Just city	

Table 3.2-3 (continued)

Reference	Environmental sustainability	Urban planning	Social and economic development	Governance
Satterthwaite, 1997	.Minimizing use or waste of nonrenewable resources .Sustainable use of finite renewable resources .Biodegradable wastes not overtaxing capacities of renewable sinks .Nonbiodegradable wastes not overtaxing capacity of local and global sinks to absorb or dilute them without adverse effects		.Social, cultural and health needs .Economic needs	.Political needs
Camagni, et al., 1998	.Limits on the use of specific polluting technologies .Marketable emission rights .Pricing on scarce resources .Incentives do use less polluting transport means .Tax on energy resources	.Incentives to reuse derelict areas .Change in urban form .Regulations for unused lands .Land development regulations .Incentives to mass transit use .Regulation for congested areas .Change in mobility patterns and modal choice .Mass transit development .Long distance transport means provision	.Incentives to R&D in environment-benign technologies	.Discriminatory pricing in regulated services

Table 3.2-3 (continued)

Reference	Environmental sustainability	Urban planning	Social and economic development	Governance
Girardet, 1999/2007	.Life cycle assessments .Wildlife refugees .Tropical timber avoided .Prevention and recycling of waste .Sustainable energy system	.Bioclimatic architecture .Integration of transports and pedestrians	.Environmental education .Green jobs .Ecological firms	.State of environment reporting .
Rees, 1999	.Strive for zero-impact development	.Capitalize on the multifunctionality of green areas	.Integrate open space planning with other policies to increase local autonomy	
Calthorpe & Fulton, 2001	.Reserves	.Centers .Corridors	.Districts	
Næss, 2001	.Minimize the conversion of natural areas for food production .Minimize the consumption of harmful construction materials .Replace open-ended flows with closed loops relying to a higher extent on local resources .Provide a sound environment for the city's inhabitants, without pollution and noise damaging to the inhabitants' health, and with sufficient green areas .Reduce the energy use and emissions			

Table 3.2-3 (continued)

Reference	Environmental sustainability	Urban planning	Social and economic development	Governance
Finco & Nijkamp, 2001			.Long-term allocative efficiency .Distribution efficiency .Environmental equity	
McGranahan & Satterthwaite, 2003	.Interspecies equity (in protecting ecosystems and biodiversity) .Intergenerational equity (in helping to conserve resources)		.Intergenerational equity (in access to basic services) .Procedural equity (grounded in a legal system and in political praxis)	
Gaffron, Huismans, & Skala, 2005	.City in balance with nature .City contributing to closed water cycles .City as power station of renewable energies .City of minimized energy consumption .City of reduction, re-use and recycling of waste	.City of minimized demand for land .City of balanced mixed use .City of qualified density .City with public space for everyday life .City as network of urban quarters .City of urban scale and urbanity .City with integrated green areas .City of accessibility for everyone .City integrated with surrounding region .City for pedestrian, cyclists and public transport .City of short distances	.City of sustainable lifestyles .City of health, safety and well-being .City of cultural identity and social diversity .City of strong local economy .City integrated into global communication networks	.City built and managed with inhabitants

Table 3.2-3 (continued)

Reference	Environmental sustainability	Urban planning	Social and economic development	Governance
Kenworthy, 2006	.The natural environment permeates city's spaces .There is extensive use of environmental technologies for water, energy and waste management	.The city has a compact, mixed-use urban form .The central city and sub-centers absorb a high proportion of employment and residential growth .Freeway and road infrastructure are de-emphasized in favor of transit, walking and cycling	.The economic performance of the city and employment creation are maximized through innovation, creativity and the uniqueness of the local environment, culture and history, as well as the high environmental and social quality of the city's public environments	.All decision-making is sustainability-based, integrating social, economic, environmental and cultural considerations .Planning for the future of the city is a debate and decide, not a predict and provide, computer-driven process .The city has a high quality public realm throughout that expresses a public culture, community, and equity and good governance
Egger, 2006	.Natural water body quality .Natural resource efficiency .Climate change .Air quality	.Integrated planning .Regional infrastructure .Accessibility	.Innovation .Education .Health .Culture and leisure .Economic position .City-region development .Economic diversity and output .Work .Social capital .Shelter security	.Political structure .Open society

Table 3.2-3 (continued)

Reference	Environmental sustainability	Urban planning	Social and economic development	Governance
Lee, 2007	.Lower environmental impacts .Increased recycling of materials .Use of energy with growing efficiency		.Improvement of public health .Improvement of well-being	
Fernandes, 2007		.Reduce sprawl .Renew derelict areas .Implement urban design techniques to foster high-quality public spaces		
Newman & Jennings, 2008	.Urban bioregional processes and biodiversity are maintained and enhanced through a system of reserves throughout the bioregion .Urban systems progressively reduce their impact and begin to form ecologically and socially regenerative systems .Urban values respect the intrinsic value of all life	.City form is designed to encourage human interaction, and to restore and maintain ecological processes .Urban infrastructure is designed to mimic or use natural processes .Infrastructure maximizes social interactions and minimizes land and energy use	.Urban lifestyles are equitable, conserving, varied, and enriched by a strong sense of place and community .Urban production and consumption activities focus on meeting genuine human needs	.Urban institutional structures are polycentric and bioregional as well as being linked globally, involving processes that are participatory, cooperative, and based on adaptive management .Urban governance is based on creating hope through leadership, innovation, participation, and the demonstration of practical and symbolic sustainability projects

3.2.4 Urban sustainability projects

Several implementation projects dealing with urban sustainability are underway, but they will not be reviewed here in detail⁶ (Table 3.2-4).

Table 3.2-4: Relevant initiatives dealing with urban sustainability.

Title	Topic	Coordinating institution
European Sustainable Cities and Towns Campaign	General	ICLEI – International Council for Local Environmental Initiatives
Healthy Cities	General	World Health Organization
LA2I	General	United Nations
Sustainable Cities Program	General	United Nations Center for Human Settlements
Smart growth initiatives	Land use planning	Smart Growth Network
CIVITAS Initiative	Transports	European Commission
C40 Cities	Climate change	Clinton Foundation
Cities for Climate Protection	Climate change	ICLEI – International Council for Local Environmental Initiatives
Covenant of Mayors	Climate change	European Commission
Energy-Cités	Energy	

LA2I processes have gained a prominent role as sustainability initiatives at the urban level. In Portugal, the number of such processes has been steadily increasing. Quental & Silva (2003) reported just one municipality starting the process, although the contemporary Second LA2I survey counted 27 (International Council for Local Environmental Initiatives, 2002); a few years later, Schmidt, Nave, & Guerra (2006) made reference to 13 municipalities engaged with a LA2I; and recently, Pinto (Pinto, Macedo, & Macedo, 2009), building on the data systematically collected by the LA2I web portal⁷, referred 139. The problem with these figures is that they were based on information provided by the municipalities, and usually there was no on the ground evaluation to check if the claimed actions were in fact being implemented. Moreover, municipalities whose processes have been discontinued have not been deleted from the database. Still, these figures are surely a sign of greater openness among city councilors and technical staff. This idea is corroborated by Fidelis & Pires (2009), who carried out a detailed

⁶ A recent MSc thesis has concentrated on this subject (Gomes, 2009).

⁷ <http://www.agenda21local.info/index.php>.

review about the implementation of LA2I in Portugal. On one side, they found signs of “surrender” to the potential of LA2I to improve local governance for sustainable development, as municipalities have been showing increasing interest for participatory processes. On another side, they found signs of “resistance” to the adoption of new government strategies, evidenced by the “limited long-term and integrated view of sustainable development, the weak development of partnerships, and the limited flows of information and strategic collaboration between local departments and between local councils and communities” (p. 516).

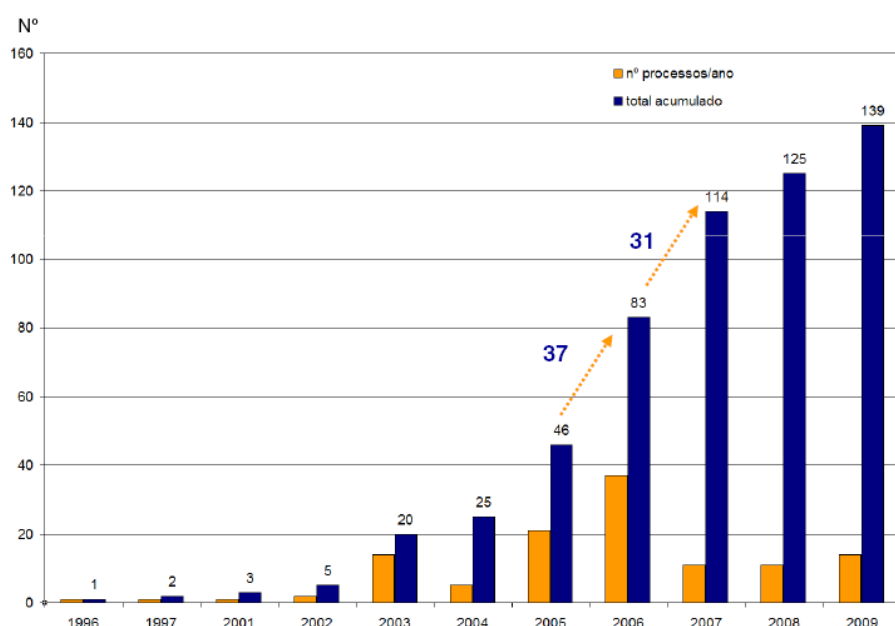


Figure 3.2-2: LA2I processes in Portugal (new processes per year and running total). Source: Pinto, et al., 2009.

I have actively participated in a regional Agenda 21 called *Futuro Sustentável* as part of my professional activity. The process started in 2003 and involved, in a first stage, nine municipalities of the Metropolitan Area of Porto (the same municipalities represented in this thesis). Later, in 2007, the project was enlarged to the entire metropolitan region, which comprises, nowadays, 16 municipalities. After dozens of meetings with different actors such as borough’s representatives, nongovernmental organizations, and citizens, a diagnosis and an action plan were issued in 2008. The plan was centered around four themes: water, education for sustainable development, territorial planning, and mobility (Figure 3.2-3). Implementation will follow, hopefully. A picturesque representation of the long-term vision for the sustainability of the region was prepared by a talented member of the technical staff (Figure 3.2-4).

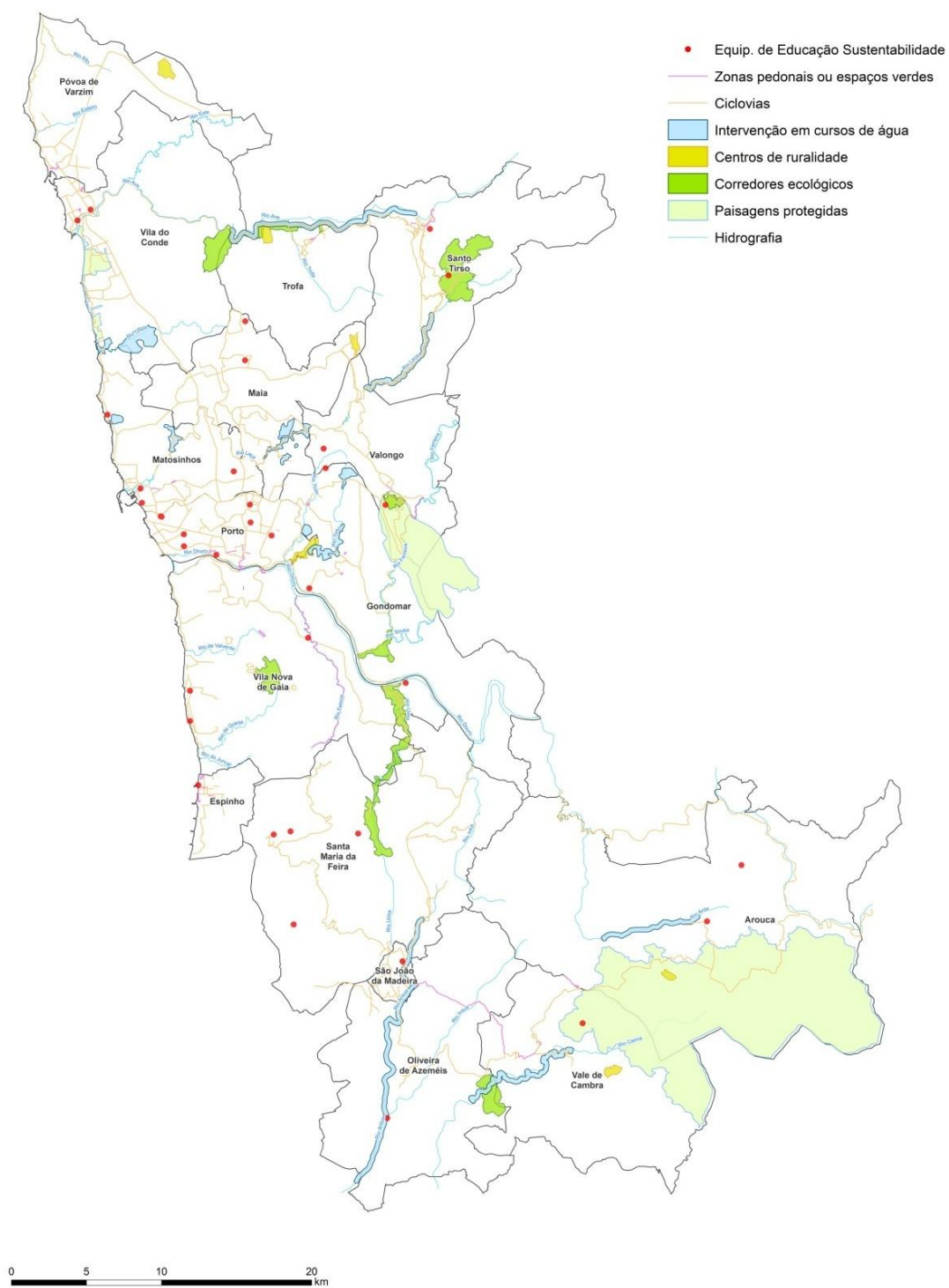


Figure 3.2-3: Main actions planned by *Futuro Sustentável*. Source: Escola Superior de Biotecnologia - Grupo de Estudos Ambientais & Lipor, 2009.

“Uma região com rios e ribeiros limpos, onde a água é usada de forma eficiente. Uma região com mais espaços verdes, vegetação natural e áreas protegidas. Uma região com mobilidade para todos, onde é fácil circular de transportes públicos, a pé e de bicicleta. Uma região que investe em educação para a sustentabilidade num patamar de maior qualidade. Uma região com maior cooperação entre entidades e participação efectiva dos cidadãos, investindo na qualidade de vida.”



Figure 3.2-4: Artistic representation of the vision for sustainable development endorsed by *Futuro Sustentável*. Source: Escola Superior de Biotecnologia - Grupo de Estudos Ambientais & Lipor, 2009. Artwork by Pedro Fernandes.

3.2.5 The contribution of urban planning

Planning theory

Patrick Geddes (1854–1932), a Scottish philosopher and biologist, is credited as the “father” of regional planning (Hall, 1988/2002). Based on the ideas of the Garden City developed by Ebenezer Howard (1850–1928), Geddes envisioned an impressive and comprehensive model of the city. Jane Jacobs referred, in her famous book “The Death and Life of Great Cities” (1961/2001, p. 20) that the goal of regional planning was to “decentralize great cities, thin them out, and disperse their enterprises and populations into smaller, separated cities or, better yet, towns”. The ideas of Howard and Geddes have been actively widespread by visionaries like Lewis Mumford and Clarence Stein, who added to the original ideas the necessary accuracy of urban design. The Garden City model was partially applied in the towns of Letchworth (1904), Hampstead (1909) and Welwyn (1919). Patrick Abercrombie integrated these cities into the Greater London Plan (1944), which proposed the decentralization of population by small clusters around a prosperous central core. However, a number of factors, mostly related with political ideologies, interrupted the natural development of regional planning theory and practice in the United Kingdom. Only in the nineties, with the emergence of the new regionalism, regional planning gained renewed acceptance. In the United States, the influence of the Garden City was more visible from the twenties on (Hall, 1988/2002).

In the early twentieth century, the organic models and the Garden City began to be questioned. The International Congress of Modern Architecture and the Athens Charter, drafted in 1933 and publicized only in 1941, developed a model of city radically different.

Taking advantage of technological advances in the field of civil engineering, the cities were to be transformed into clusters of tall buildings surrounded by public spaces and green areas. Mobility would be possible through a number of large avenues. A functional city emerged from this scenario. Living, working, leisure and mobility should be segregated through zoning. José Lamas argued that

“(…) the methodology of modern design is completely different. In the traditional city, the size and organization of accommodation resulted from the shape of the building, and consequently from the shape of the parcel and their position on the block. For modern urbanism, the housing-cell is the key element of the city framing. Housing-cells are grouped to provide buildings, and these are grouped to form neighborhoods (...). Grouping housing-cells determine the shape of the building and grouping buildings determine the shape of the neighborhood⁸” (Lamas, 2000).

Le Corbusier occupies a prominent place in the modern movement and is considered the mentor of a new model of city: the *Cité Radieuse*. The models of Garden City and the *Cité Radieuse*, although with profound differences in their morphology, shared the saving of large spaces for public enjoyment. In the early sixties the first criticisms to the modern movement appeared. In fact, despite the good intentions of the mentors and the high architectural quality of buildings, the modern city was designed on a large scale and lacked humanized places. It was a kind of standardized mass production. As a result, people could not appropriate existing public spaces and occasional conviviality in the streets became difficult. Jane Jacobs strongly criticized what she called “a sort of Radiant Garden City Beautiful”:

“He [Le Courbusier] proposed underground streets for heavy vehicles and deliveries, and of course like the Garden City planners he kept the pedestrians off the streets and in the parks. His city was like a wonderful mechanical toy. Furthermore, his conception, as an architectural work, had a dazzling clarity, simplicity and harmony. It was so orderly, so visible, so easy to understand. It said

⁸ “(...) a metodologia da concepção moderna é completamente diferente. Na cidade tradicional, a dimensão e a organização do alojamento resultavam da forma do edifício, e este da forma do lote e da sua posição no quarteirão. Para o urbanismo moderno, a célula habitacional é o elemento-base de formação da cidade. Agrupa-se para constituir edifícios, e estes agrupam-se para formar bairros (...). O agrupamento de células habitacionais determina a forma do edifício e o agrupamento de edifícios determina a forma do bairro” (Lamas, 2000).

everything in a flash, like a good advertisement. This vision and its bold symbolism have been all but irresistible to planners, housers, designers, and to developers, lenders and mayors too. No matter how vulgarized or clumsy the design, how dreary and useless the open space, how dull the close-up view, an imitation of Le Corbusier shouts one's achievement. But as to how the city works, it tells, like the Garden City, nothing but lies" (Jacobs, 1961/2001, p. 23).

With the criticism of the modern movement, the interest for urban design reappears, as the work of Gordon Cullen and Kevin Lynch exemplify (Lynch, 1960/1999).

These were the foundations for the emergence, later on, of the *New Urbanism*. Worried with the evolution of the city, with the spread of suburbs and with citizen alienation from public issues, a group of technicians with different academic backgrounds founded in 1993 the Congress for the New Urbanism. Its Charter contains a set of principles that, once applied at the regional, district and building level, would prevent the spread of the city, stimulate its renewal, make housing more affordable, and promote public transportation. At the center of the New Urbanism ideology is, therefore, a critique of the low-density American suburbs. It also incorporates some of the formal urbanism values (e.g., detail, organicism, vitality) lost with the Modern Movement, and incorporates principles of environmental sustainability (reducing consumption of energy, water and other resources, and protecting the regenerative capacity of natural assets). New Urbanism argues for fiscal harmonization among the local authorities of a region to avoid destructive competition for revenues and promote cooperation for common strategies (Calthorpe & Fulton, 2001). Calthorpe & Fulton schematically divided the region into four distinct units: centers, the prime destiny of the neighborhood, city or region; districts, areas with special vocations and dominated by a specific function; reserves: open spaces and green areas which shall be connected by corridors shaping a network; and corridors, the elements linking natural areas and the transit infrastructures such as avenues and rail tracks. A regional map would consist of a mosaic of well-articulated four basic elements, taking into account the relationships between the various parts. In the United States, this theory has been put in place through "smart growth" initiatives.

Factors influencing the success of planning

Júlia Lourenço (2003) attempted to understand the development of a planning process for urban growth areas, particularly the fundamental success factors underlying plan implementation. The institutional context in which plans were prepared, including the logics of public and private action, were taken into account. Underlying factors were divided between two groups: determinant and critical factors. Persistence on aims and perception of innovations were identified as the critical factors (Table 3.2-5). A detailed analysis according to

the matrix of determinant and critical factors was performed on seven plan-processes. These case studies were selected because they envisioned proposals of difficult implementation in Portugal.

Table 3.2-5: Determinant and critical factors for the success of the plan-process.

Determinant factors		
Biophysical	Technical	Cultural
Land use	Plan proposals	Public participation
Soil morphology and ground composition	Viability studies	Policy measures
Accessibility	Urban management	Land policies
Ownership patterns	Fees	Institutional arrangements
Critical factors		
Persistence on aims		
Perception of innovations		

The assessment of the plan-processes was carried out having as reference their “ideal” behavior (Figure 3.2-5). The model suggests a logical sequence of three cycles: planning efforts, action (measured by the investment on urbanization, public infrastructures and equipments), and living. Ideally, the rate of planning decreases significantly on the target area after 10 years of planning production and reaches a minimum level after 20 years; the actions and living curves start from a low level and increase significantly over time, having peaks at 20 and 40 years later, respectively. Lourenço's (2003) model is basically a tool for monitoring a plan-process. When the real curves of planning, actions, and living depart from their ideal behavior, the perception of innovations by the relevant actors can usually explain those differences.

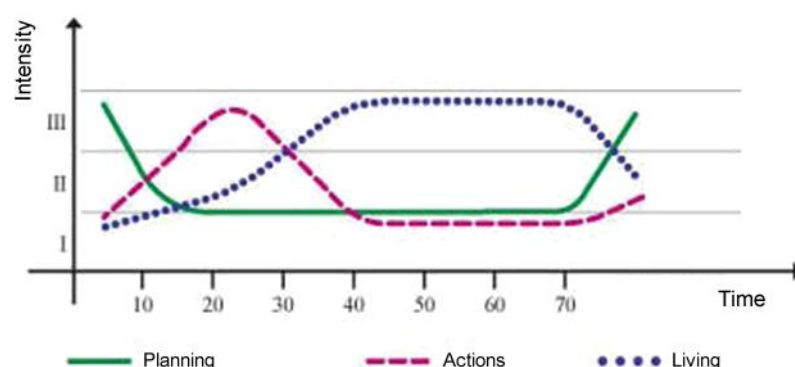


Figure 3.2-5: Ideal behavior of a plan-process. Source: Lourenço, 2003.

3.3 Urban form, growth and sprawl

3.3.1 Urbanization and population trends

The transition from a rural to an urban society is called *urbanization*. Statistically, urbanization reflects an increasing proportion of the population living in settlements defined as urban, primarily through net rural to urban migration. The level of urbanization is the percentage of the total population living in towns and cities while the rate of urbanization is the rate at which urban population grows (United Nations Population Fund [UNFPA], 2007).

The British Census of 1851 showed that, for the first time in history, more people were living in urban areas than in rural areas (Giddings, Hopwood, Mellor, & O'Brien, 2005). For the world as a whole, the breakthrough occurred in 2008 (UNFPA, 2007; see also Figure 3.3-1). The European Union, Australia, New Zealand and Northern America are considerably more urbanized: about 80% of the citizens already live in places with more than 10 000 inhabitants (United Nations - Department of Economic and Social Affairs, 2008) (Figure 3.3-2).

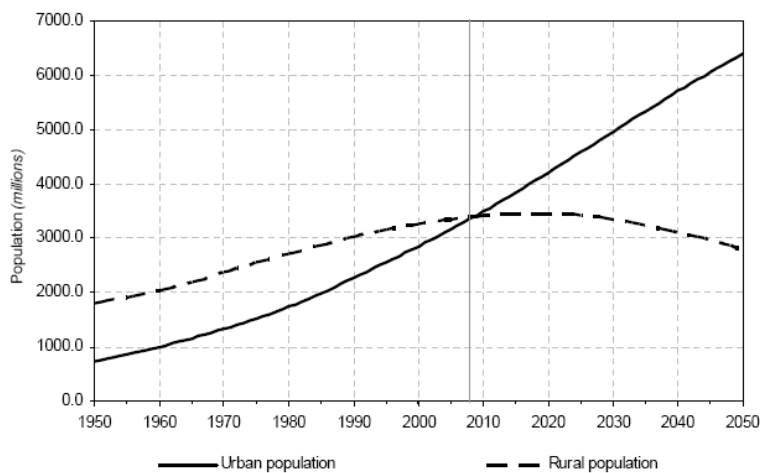


Figure 3.3-1: Urban and rural populations of the world (1950–2050). Source: United Nations - Department of Economic and Social Affairs, 2008.

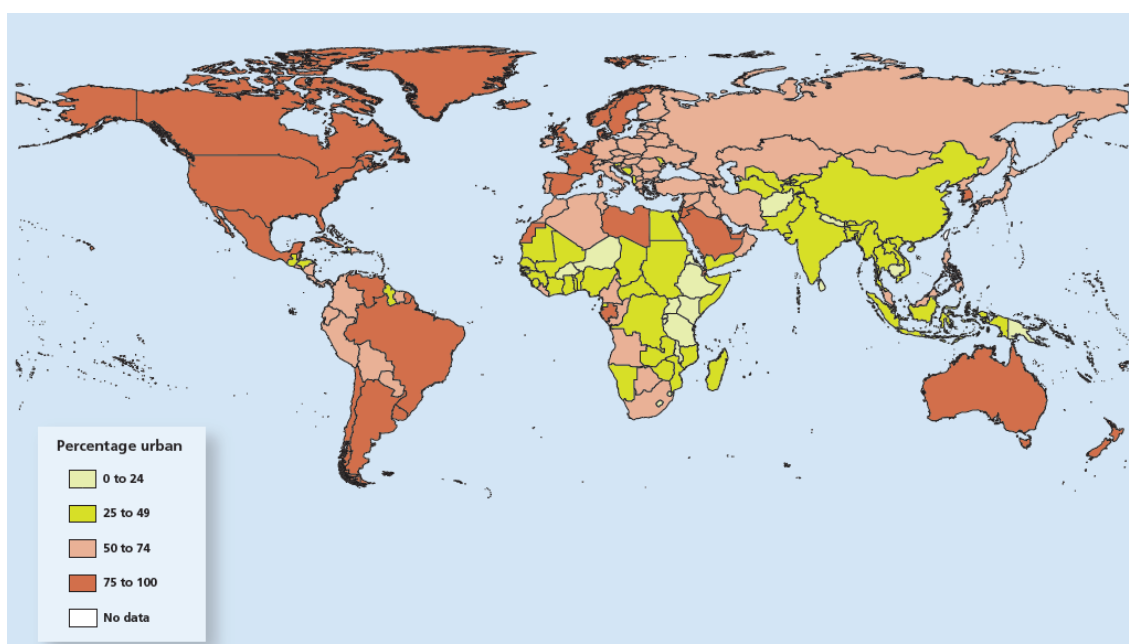


Figure 3.3-2: Urban population (2007). Source: United Nations - Department of Economic and Social Affairs, 2007b.

The first wave of urbanization began in Europe and North America as a consequence of the Industrial Revolution, which demanded large amounts of workforce (O'Meara, 1999). Over the course of two centuries (1750–1950), these regions experienced an economic and demographic transition from rural to mostly urban societies. A second wave of urbanization is taking place since the past half-century in the less developed regions of the world (UNFPA, 2007). China, for instance, will probably surpass the 50% mark of urban dwellers in 2010 (McNeill, 2007). The fact that countries are experiencing different development phases explains the highly uneven growth rates of urban population across regions (Figure 3.3-3).

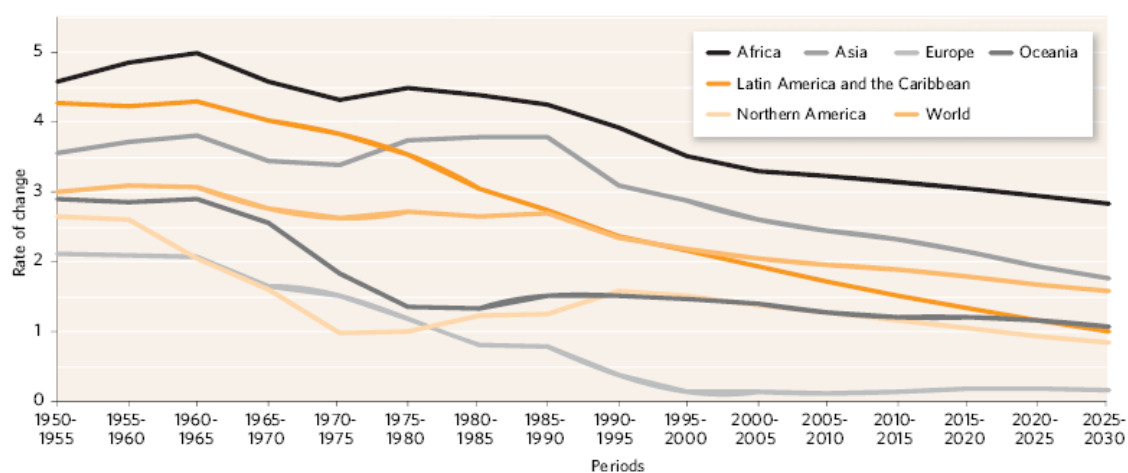


Figure 3.3-3: Average annual rate of change of the urban population by region (1950–2030). Source: UNFPA, 2007.

Overall, world urban population grew from less than 30 million in 1800 to the current 3,4 billion inhabitants, and is expected to rise to 6,5 billion in 2050. Between 1950 and 2007, the growth rate averaged 2,6% per year and is expected to slow down to 1,8% during 2007–2025, which still represents a doubling of the urban population in 38 years. Virtually all the population growth in the next four decades will be concentrated in urban areas (United Nations - Department of Economic and Social Affairs, 2008)

The pattern of population distribution is also changing: people are increasingly concentrated in large urban areas (Figure 3.3-4). There are presently 19 cities with more than 10 million people (megacities), 22 cities with five to 10 million, and 370 cities with one to five million (United Nations Center for Human Settlements, 2001b)

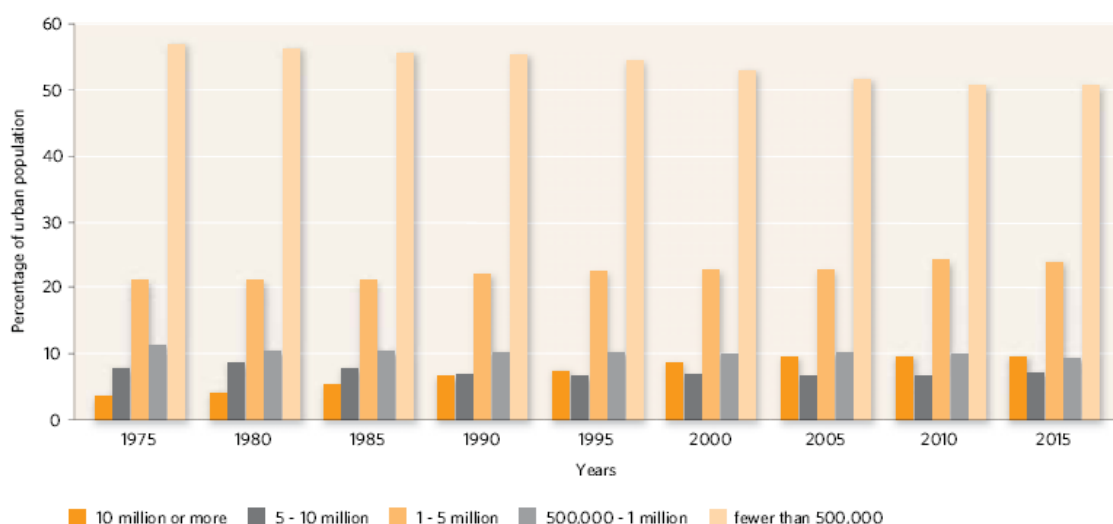


Figure 3.3-4: Urban population by size class of settlement (1975–2015). Source: UNFPA, 2007.

Global population rate of growth peaked around 1970 at 2% per annum and has been steadily falling since then. Declining birth rates will probably result in zero growth by 2050–2070 (McNeill, 2007). But growth rates can mask considerable absolute changes in population. For instance, the 1,5% annual population growth rate in India represent as much as 18 million new citizens every year. Therefore, although falling birth rates in the most populous countries can be seen as a step towards sustainability, absolute increments may still represent a serious burden for the planet.

The transition from highly fertile societies to societies characterized by low birth rates and long life expectancies was fueled by urbanization and related developments in sectors such as women education, political liberties and public health (Sen, 1999/2003). Although urbanization implies considerable environmental impacts, it also fuels several socioeconomic trends essential for sustainable development – even if the net environmental result is negative because of citizens' more intensive consumption patterns.

Drivers of urbanization

Urbanization has been primarily caused by the perception that cities provide greater diversity of opportunities and quality of life for citizens (Newman, 1999). Haughton & Hunter (1994) claim that the process is very much guided by the political structures and by existing social and economical conditions, but it can still be regarded as a natural movement of people searching for better jobs, education and freedom. Migration from rural to urban areas (the rural exodus) is the “traditional” cause of urbanization, but other phenomena of great importance exist, such as the migration from cities to other, usually more developed, cities.

Girardet (1999/2007) and McGranahan & Marcotullio (2005) enumerate several factors that account for the growing urbanization in the world: globalization, technological change, political and democratic shifts, concentration of political and financial power in the cities, economic development, and cheap energy. These drivers are experienced differently in different parts of the world (McGranahan & Marcotullio, 2005) which partially explains the distinct patterns of urbanization across regions.

3.3.2 Urban forms and patterns

Anderson, Kanaroglou, & Miller (1996) defined *urban form* as the spatial configuration of fixed elements within a metropolitan region, including the spatial pattern of land uses and their densities, as well as the spatial design of transport and communication infrastructure. Handy (2006) calls this *built environment*. *Territorial structure* is a more encompassing concept consisting of human capabilities, urban form, transportation system, and economy. At the neighborhood scale urban form could be confused with the concept of *urban design*, which usually refers to small scale arrangements and to the appearance of public spaces.

Different spatial patterns of land use reflect the evolution of urban form during decades or centuries (Carvalho, 2003). Kevin Lynch (1960/1999) defined four basic urban development forms that have been thereafter rethought and published under a variety of names in the literature (Lewis & Brabec, 2005). Table 3.3-1 synthesizes these main archetypal forms of urban development as well as later additions, and Figure 3.3-5 graphically depicts some of the most common.

Table 3.3-1: Archetypal forms of urban growth at the metropolitan level.

	Nuclear	Polycentric	Linear	Stellar	Leapfrog	Uniform sprawl
	A dense urban center is surrounded by a low density, rural matrix	A group of interrelated centers joined by transport that form a functional whole	Urban development along a corridor such as a railroad or a road	Two or more fingers of growth extend from the center	An urban center growing outwards discontinuously through small patches	Largely uniform land uses and densities across the region
Lynch, 1960/1999	Nuclear	Constellation	Linear	Stellar		
Ewing, 1994		Scattered			Leapfrog	
Anderson, et al., 1996	Concentric	Multinucleated				
Cervero, 1998	Strong-core cities	Adaptive cities	Hybrid	Hybrid	Adaptive public transit	Adaptive public transit
Holden, 2004	Compact cities	Decentralized concentration			Urban sprawl	Green city
Nordregio, 2005	Monocentric	Polycentric			Sprawl	Sparsely populated
Lewis & Brabec, 2005						Sprawl
Tsai, 2005	Monocentric	Polycentric	Strip	Strip	Leapfrog	Decentralized sprawl

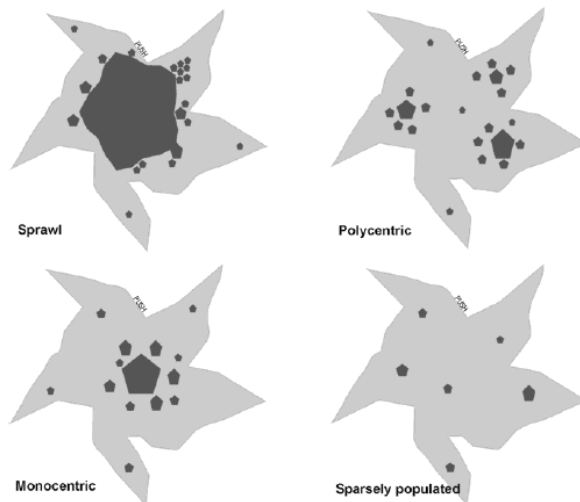


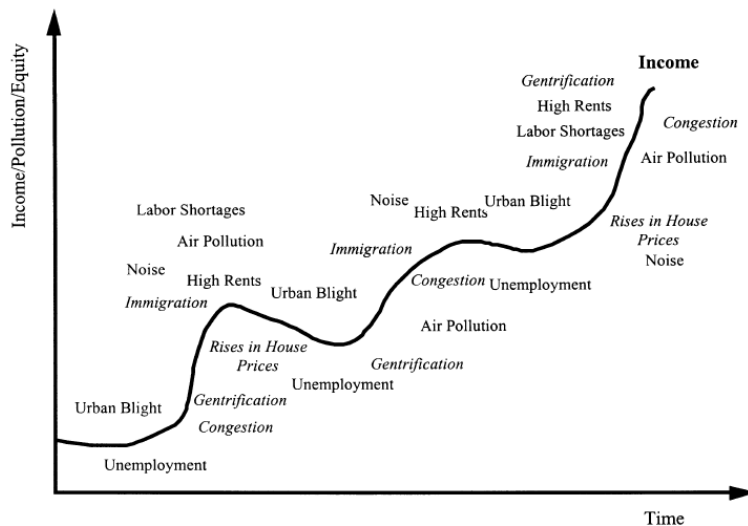
Figure 3.3-5: Different patterns of urban growth. Source: Nordregio, 2005.

Analysis of Table 3.3-I shows that consensual definitions are lacking and lexicon is prone to misunderstandings. What one author considers *sprawl*, for instance, another author may call it *leapfrog development*. Chin (2002) and Tsai (2005) suggest that the polycentric, linear and stellar forms could also be considered as special types of sprawl, but this would just blur the concepts and add to the confusion. The typology suggested by Cervero (1998) classifies cities according to the relationship between the spatial patterns of land use and the structure of the public transportation networks. It is more inclusive, but the rationale is similar to the other classifications mentioned. The header of each column in Table 3.3-I represents the most common perception of each archetypal urban form.

The six typical urban forms presented can be understood as a continuum of increasing uniformity in the distribution of population across the territory. All forms remain identifiable in some urban landscapes, but 20th century growth patterns have diluted their unique signature (Lewis & Brabec, 2005). The nuclear city is the traditional form: a dense nucleus, usually where the central business district is located, surrounded by a rural matrix with a clear boundary between the two (in the medieval times, walls protected cities from invaders and established a physical segregation). Polycentric metropolises have been gaining consensus as a desirable urban form (e.g., Calthorpe & Fulton, 2001; Camagni, Gibelli, & Rigamonti, 2002; Catalán, Saurí, & Serra, 2008; EEA, 2006b) and was explicitly recommended by the European Spatial Development Perspective. When compared with monocentric urban systems or dispersed small settlements, polycentric regions are claimed to be more efficient, equitable and competitive (EEA, 2006b). In addition, Catalán, et al. (2008) contends that polycentric regions restrain urban dispersion and encourage a relatively compact growth. Linear, stellar, leapfrog and uniform sprawl represent increasing degrees of sprawl: the urban-rural segregation disappears and is replaced by an indistinct landscape of houses, gardens and agricultural fields.

3.3.3 Urban life cycle

Metropolitan urban forms evolve with time. Several authors agree on an urban transition characterized by cycles of urbanization, suburbanization, counter-urbanization and reurbanization (e.g., Button, 2002; Capello & Faggian, 2002; Chin, 2002; Couch, Leontidou, & Petschel-Held, 2007; EEA, 2006b; Haughton & Hunter, 1994; Ravetz, 2000a; Turok & Mykhnenko, 2007). In the first phase, the urban center experiences a faster population growth than the surrounding areas; in the second phase, the urban fringe develops faster than the core area and residential land use in the centre is replaced by tertiary activities; in the third phase, the metropolitan area as a whole loses population; in the last phase, the core ring areas decline faster than the core, which may even increase its population. Economists have been trying to explain and model these transitions (Figure 3.3-6).



Key: Economic factors in plain type, social welfare factors in *italics*, and environmental factors in shadow.

Figure 3.3-6: Urban life cycle: links between economic, environmental and social welfare trends. Source: Button, 2002, p. 228.

Urban growth and decline rest on the tension between agglomeration economies and diseconomies (Munda, 2006), or between *centripetal* and *centrifugal* forces (Krugman, 1999). Centripetal forces include market size effects, thick labor markets and pure external economies, and centrifugal forces include immobile factors, land rents and pure external diseconomies (Krugman, 1999). During urbanization, agglomeration economies result in growing densities in the center. As time passes, demand for land pushes rents up and the increase in other diseconomies, such as soaring pollution, diminish the attractiveness of the center to business and residents. Facilitated by improved public and private transports, suburbanization arises (Haughton & Hunter, 1994) and may even lead to the formation of edge cities (Garreau, 1991). An edge city is characterized by large concentrations of office and retail

space developing near the nodes of major highways in places which 30 years ago did not have urban characteristics. The next phase, counter-urbanization (Berry, 1976), emerges as people react to the diseconomies of large cities (congestion, high land prices, environmental decay, etc.). A last phase of reurbanization may happen as the centrifugal forces dwindle and the attractiveness of the center is reestablished. A simultaneous movement of people towards rural areas situated in or near protected natural areas may be present. This phenomenon, coined as *naturbanization* by Prados (2005), finds its roots in people who are discontent with the urban lifestyle and value a higher contact with nature.

The urban life cycle received some theoretical support from the so-called *environmental Kuznet's curve*. In 1955, the Nobel laureate Simon Kuznets suggested that income disparities increased with economic development during a first phase, but started to decrease as the economic development crossed a determined threshold. An extension of this model proposed a similar U shaped curve relating income and environmental quality. The argument for the environmental Kuznet's curve is the following: as the economy develops and income *per capita* rises, society takes greater care with the quality of environmental amenities (Lambin, 2004); at the same time, the economic transition from an industrial to a post-industrial phase triggers environmental improvements (Camagni, et al., 1998). This cycle of environmental degradation followed by environmental amelioration partially explains the agglomeration economies and diseconomies embodied in the urban life cycle.

Nevertheless, Haughton & Hunter (1994), Capello & Faggian (2002) and Turok & Mykhnenko (2007) warned about the simplistic nature of the cycle, which remains empirical and lacks solid theoretical grounds. It describes the patterns of population movement but does not provide a solid explanation for them. In addition, the trajectory of the environmental Kuznet's curve is

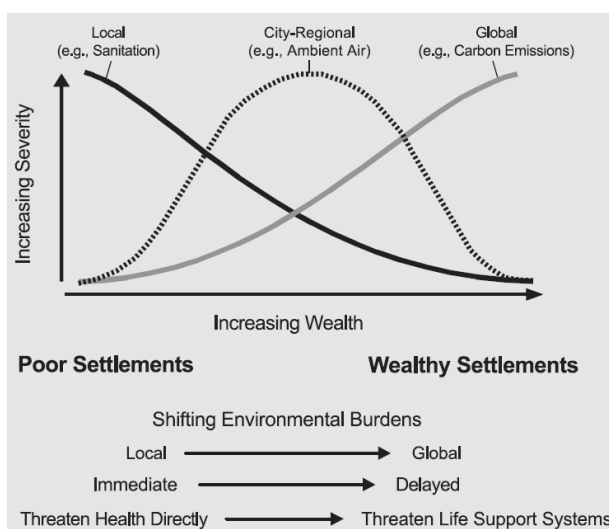


Figure 3.3-7: Environmental Kuznet's curve at different scales as adapted by McGranahan & Marcotullio. Source: McGranahan & Marcotullio, 2005.

verified only under particular conditions, namely for local and short-term problems (Lambin, 2004). Figure 3.3-7 exemplifies how the improvement of local conditions is accompanied by the worsening of other issues at larger scales. In China, Van Dijk & Mingshun (2005) reported similar patterns of environmental degradation at the city level caused by economic growth.

Urban life cycles probably explain the emergence of the metropolitan area during the 20th century as a new form of human settlement. Metropolis emerged with the expansion and sprawl of nuclear cities. Yet, the complexity of urban systems probably explains why different phases of the cycle may co-exist simultaneously. Couch, et al. (2007) argue that the coincidence of re-urbanisation with urban sprawl constitutes one of the most important changes in European urban material cultures over the past two decades.

Sprawl and land cover changes

Despite the vast literature about urban sprawl and an agreement about its general characteristics, a more technical and quantified definition is still lacking (Chin, 2002). The wide range of meanings found in literature requires caution when comparisons between different research methodologies are made. Still, definitions can be grouped according to the characteristics they emphasize. Fulton, et al. (2001) and Ewing, Pendall, & Chen (2002) consider a territory as *sprawling* when land is being consumed at a faster rate than population growth and as *densifying* when population is growing more rapidly than land is being consumed for urbanization. On the other hand, Transportation Research Board (2002) ignores the rate of land consumption as an indicator and considers as sprawling only nonurban counties with an “outlier” position in terms of population or employment growth. Specifically, they employ the following sets of criteria:

1. (a) the county's growth rate is in the upper quartile of the economic area's annual county household and employment growth rates; (b) the county's growth rate exceeds the average annual national county growth rate; and (c) the county's absolute level of growth exceeds 40 percent of the average annual absolute county growth; or
2. The county's absolute level of growth exceeds 160 percent of the average annual absolute county growth.

It is important to note that the aforementioned criteria exclude urban areas from sprawling by definition. Another possibility adopted by other researchers is to classify sprawl according to its density and spatial development patterns. The following characteristics are mentioned by Ewing, et al. (2002), Chin (2002) and Frenkel & Ashkenazi (2008): a population that is widely dispersed in low-density, scattered, and discontinuous expansion development (“leapfrog”); segregation of land uses; a network of roads marked by huge blocks and poor access; and lack of well-defined, thriving activity centers. Frenkel & Ashkenazi (2008) include what could be considered, in principle, a consequence of sprawl and not a defining characteristic: the massive use of private vehicles. The density gradient from the city center was employed by Lewis & Brabec (2005) and Couch, et al. (2007) to distinguish urban growth from urban sprawl: all other things being equal, urban growth will cause the density gradient line to shift to the right whilst retaining the same gradient, whereas urban sprawl will result in a less steep gradient line

(Figure 3.3-8). Couch, et al., classified metropolitan regions through the comparative analysis of population trends in the core city and in the suburbs. *Sprawl* occurs when density growth in the suburbs outpaces that of the center, or when density declines faster in the center than in the suburbs; *containment* occurs in the remaining cases. This definition defies the common sense in the case of a declining region that is in addition classified as sprawling.

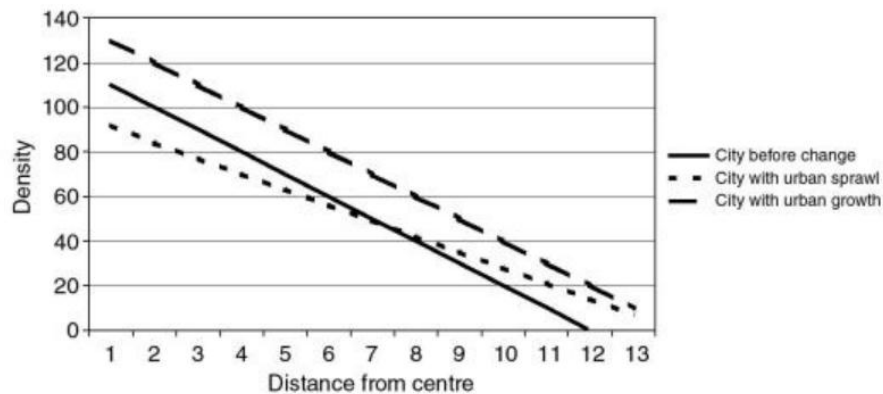


Figure 3.3-8: Distinguishing urban sprawl from urban growth. Source: Couch, et al., 2007, p. 6.

Although it is not possible to state which of the definitions mentioned above for sprawl is the most correct, the combined analysis of at least population and land use trends is recommended to honor the majority of literature. The definition depends on what is being measured and for which purposes: it may change if the intention is to describe landscape evolution or, on the contrary, to illuminate the patterns of spatial development often associated with particular socioeconomic conditions and travel behaviors. Perhaps a more promising option is to regard the concept as a continuous scale (Lewis & Brabec, 2005) instead of fixing specific thresholds to distinguish sprawl from densification. When a consensus method of calculation is agreed on – even if some arbitrariness is inevitable – a higher rigor will probably be achievable when investigating the consequences of sprawl.

Drivers of urban sprawl

Urban sprawl can be understood differently depending on the scale of analysis. At a national level, the trend – at least in Portugal – is clearly towards the concentration of people in larger metropolitan regions (Marques, 2004). The influx of inhabitants in cities requires new housing and therefore the expansion of cities' boundaries. But most cities losing population are still expanding physically and increasing their urban area (Couch, et al., 2007), so other factors must account for the observed trends. In this section, the multilevel structure of urban sprawl proposed by Couch, et al., will be employed as guidance through the main drivers of this process (Figure 3.3-9).

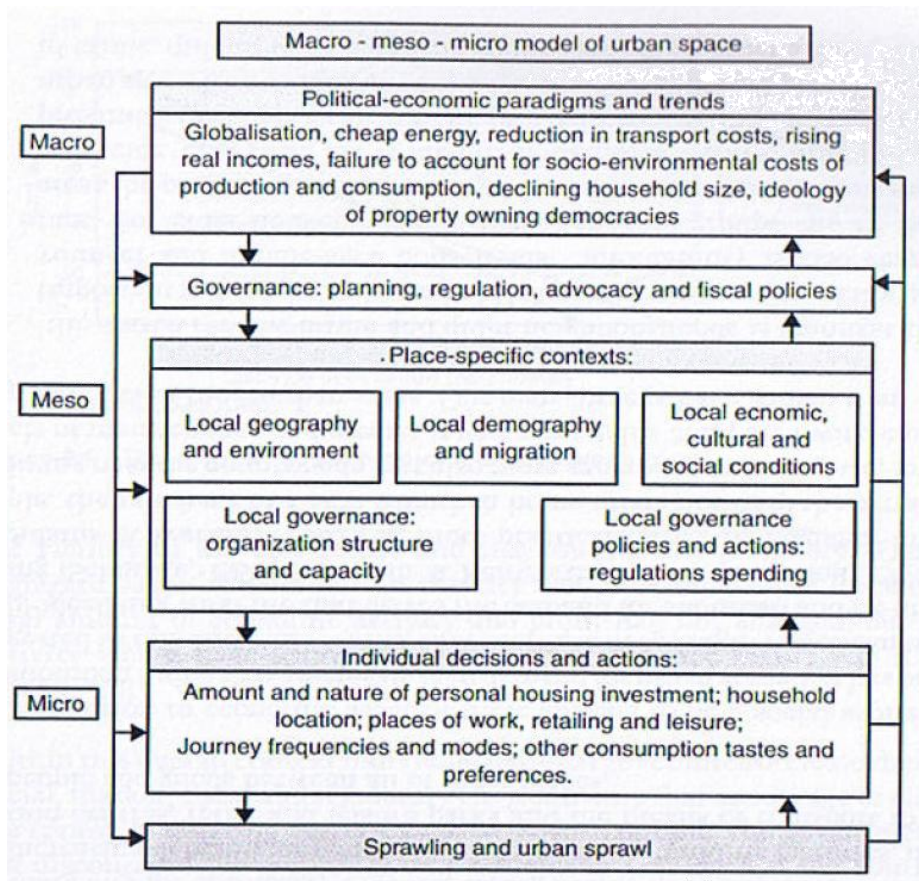


Figure 3.3-9: Multilevel theory of urban sprawl. Source: Couch, et al., 2007.

❑ Drivers of urban sprawl > Economic context

Kates & Parris (2003) anticipated a number of trends that will characterize the XXI century. Globalization, economic growth and the facilitated movement of people are among those trends. The positive feedback loop between globalization, economic growth and urbanization is well established (see, e.g., Haughton & Hunter, 1994; Schneider, 2006; UNFPA, 2007). Contrary to the expectation that technology would allow people to spread through rural territories and adopt distance working, human concentrations within the new global economy are increasingly important (McGranahan & Marcotullio, 2005). The influence of economic growth on urban sprawl is therefore exerted via the stimulus given to people to migrate to cities, where most of the opportunities and power are concentrated. In cities, immigrants increase the demand for cheap housing in the periphery and consequently stimulate urban sprawl.

The influence of globalization is also exerted through structural changes in economy. Globalization has been driving to higher economies scale in the sectors of distribution and retail over the past decades. In the fifties, most shops were small and mixed with other uses in the urban matrix – a typical pattern in the traditional Mediterranean cities. Commercial and transport areas are nowadays usually located in the outskirts of the city near highway nodes

where they act as prime motors of sprawl. Artificial areas devoted to these uses have, on average, grown twice as fast as residential areas (EEA, 2006b).

Banking plays a fundamental enabling role in urban sprawl as well. The availability of long-term mortgage has dramatically increased the number of families being able to enter the real estate market, inflating prices and demand for new suburban housing (Couch, et al., 2007).

❑ Drivers of urban sprawl > Historical origins

Sprawl in the United States and in Europe share many common characteristics but have also dissimilarities. Because of Europe's ancient human occupation, cities in Western Europe usually conserve the distinct urban forms built during each historical and development period (see, e.g., Lamas, 2000).

Before the nineteenth century, suburbs in Europe "housed the poor, artisans, watermen, noisy malodorous trades, cheap inns, posting-houses, stables for post horses, porter's lodgings" (Braudel & Reynolds, 1992). Chaucer's *Canterbury Tales* described them as "corners and blind alleys where robbers and thieves instinctively huddle secretly and fearfully together." This is in striking contrast with the prevailing view of suburbs as qualified places in most of Europe and United States (perhaps not so much in Portugal, where suburbs remind the bad feelings of ghettos and alike).

Falkowski (2004) pointed out that African-American soldiers in the United States were segregated from white soldiers during World War II and worked in factories to support the war effort. To help reintegrate veterans of war back into society, the Congress passed new laws facilitating the purchase of single-family houses outside of urban centers. The growth of suburbs was actively stimulated as it symbolized the American dream (McHarg, 1969; UNFPA, 2007). The fact that African-Americans were not eligible for the housing subsidies initiated a "white flight" and inadvertently increased the racial segregation of America – a problem that remains extremely severe in most United States metropolitan areas nowadays (Altshuler, Morrill, Wolman, & Mitchell, 1999).

In Northern Europe, sprawl is associated with pastoral utopias, *i.e.*, anti-urbanism cultural representations which favored the movement of elites and middle classes to the detached houses in the countryside. This is especially visible in Malmö and around Stockholm. In Eastern Europe, because of the legacy of state-controlled economy, sprawl has been greatly regulated and only after the collapse of the Soviet Union did investments started in the periphery. Investments were made primarily in shopping and retail centers and only to a lesser extent in housing (Couch, et al., 2007).

□ Drivers of urban sprawl > Social factors

Migration to the cities not only drives urban growth, but is also a fundamental cause of suburbanization. Many immigrants, either coming from other countries or from other cities in the same country, usually seek opportunities for a better standard of living and cannot bear the costs of living in the center (Satterthwaite, 2005). Therefore, they tend to settle in the suburbs, where housing is affordable (Couch, et al., 2007). Rural migrants often bring a legacy of higher fertility levels and contribute to the growth in the numbers of young people coming of age, forming their own households, and using land for dwelling units and for some type of productive activity (Lambin & Geist, 2006). In Portugal, particularly in the municipalities around Lisbon, this is obvious given the high concentration of African people living in social housing (Ferreira & Vara, 2002).

Sprawl is also stimulated by the desire of many families to live in a larger house surrounded by a rural ambiance, and far from the problems typical of urban settings (criminality, social problems, pollution, noise, traffic congestion, stress, poor aesthetic quality) (EEA, 2006b; Lambin & Geist, 2006; McGranahan & Marcotullio, 2005). Catalán, et al. (2008) argued that this was especially true in the first industrial cities, which were overload with congestion, pollution and disease. The built-up environment may also be considered unattractive because of poor urban planning, with areas lacking green open space and sports facilities (Camagni, et al., 2002; EEA, 2006b). In addition, most people value the increased privacy they can achieve in a detached house of their own (Chin, 2002). This is related with the distribution of amenities, a subject studied with particular attention by Wu (2006). His results suggest that urban sprawl and jurisdictional fragmentation are more likely to occur in a society with a high degree of income inequality and a large variation in environmental amenities. Curiously, Irwin & Bockstael (2007) found that proximity to the Chesapeake Bay was negatively associated with fragmentation, suggesting that an attraction effect associated with the natural amenity has led to a more compact pattern of development.

The decrease in household size is another driver of urban sprawl. In the United States and Europe, the average household size has shrunk to fewer than three, and the proportion of single-person households has risen to 25% in Europe and 20% in the United States (McGranahan & Marcotullio, 2005). In Portugal, very much the same has happened: according to INE – Statistics Portugal (INE), single person households have increased from 13,8% in 1991 to 17,3% in 2001. In Europe, new households are expected to account for the construction of 12,5 million dwellings in the period 2000–2005, and another 11,5 million in 2005–2010 (McGranahan & Marcotullio, 2005). Even in face of natural population decrease or a stagnant urban population, new household formation is leading to continued urban expansion and to higher pressures on the environment (Piracha & Marcotullio, 2003).

□ Drivers of urban sprawl > Fiscal system and institutional factors

Land prices and land speculation can be powerful drivers of sprawl (EEA, 2006b). The extremely low price of agricultural land compared to the price of already urbanized land creates an incentive for agents to urbanize the former and retain the significant surplus value created by urbanization. Profits are much greater when cheap undeveloped land is urbanized compared with urban renewal projects of conversion of brownfields (Camagni, et al., 2002; Conselho Nacional do Ambiente e do Desenvolvimento Sustentável, 2004; EEA, 2006b). Lambin & Geist (2006) noted that newly urbanized land was often of great quality for agricultural purposes. In Portugal this is a well-known fact, as renewal⁹ projects, according to INE, account for less than 20% of all real estate projects. Agricultural land is pulled into the market when accessibility is increased through the construction, for instance, of a highway. At the same time, in the urban center, land is often retained undeveloped and its price placed above its current market value in anticipation of future demand for higher value uses (Roseland & Soots, 2007). Chin (2002) remarks that, over a long time period, land speculation creates an efficient allocation of land uses because land is later developed at higher densities as infill development or is used for higher value commercial uses. The difference between effective land prices and their market values thus determines if development occurs primarily as infill in the center or as sprawl in the periphery. Fiscal policies may be set to curtail the surplus values retained by the speculator, reducing the gradient of prices between the center and periphery and effectively combating dispersion (UNFPA, 2007). At the same time, because policies against speculation cause a reduction in land prices, housing becomes cheaper as well.

Fiscal policies at the national level often conduce to undesirable outcomes, but coordination between those policies at different levels of government is another important, yet commonly overlooked, cause of suburbanization (National Round Table on the Environment and the Economy, 2003). As the message sent to buyers and investors is contradictory, it is likely that effective urban planning is undermined.

Roseland & Soots (2007) added that land-use planning rarely addresses long-term or life cycle costs, and as a result taxpayers often end up paying the hidden costs of development infrastructure (roads, sewage, etc.) and equipments (schools, health centers, etc.). As developers do not have to bear the costs of urbanization, there is an awkward incentive to sprawl instead of to direct investments to urban centers, where infrastructure and equipments are already in place.

The role of institutional factors in the process of suburbanization must also be emphasized. Competition is great among adjacent municipalities for tax revenues, jobs, and services. Thus,

⁹ Includes restoration, extension and conversion constructions.

many municipalities relax controls on the development of agricultural land and offer tax benefits for those who make large investments in the municipality (Camagni, et al., 2002; Chin, 2002; EEA, 2006b). Often, this competing behavior of municipalities is encouraged by inadequate fiscal bylaws at higher levels of governance.

Sprawl is still promoted by existing plans advocating excessive zoning and segregation of land uses (Couch, et al., 2007). Ideologies such as *La Ville radieuse*, legacy of the modernist movement inspired by Le Corbusier and by the Charter of Athens (1933), much contributed to the creation of functional zones far from each other and mainly accessible by car (Hall, 1988/2002).

□ Drivers of urban sprawl > Transports and communications

Australian economic historian Frost (1991), as cited in Newman (1999), divided the Western cities in the nineteenth and twentieth centuries into two distinct types, according to their spending on infrastructure: the traditional high-density cities of Europe, east coast North America, and east coast Australia (London, Paris, Berlin, Saint Petersburg, New York, Philadelphia, Chicago, Sydney), which directed a high proportion of their capital into industry and less into urban infrastructure; and the new frontier towns of western and southern North America and Australia (Los Angeles, San Francisco, Seattle, Denver, Melbourne, Perth, Adelaide), which, on the contrary, directed a higher proportion of their wealth into infrastructure. The traditional cities promoted human and industrial concentration, while the new frontier cities stimulated low-density development and sprawl. As a result, sprawl in the traditional European cities started much later than in the new frontier cities, although later sprawl was still associated with developments in the transport sector. These advances in the transport and communication systems have spurred the emergence of new urban forms that would have been unconceivable with older infrastructure and technology (Altshuler, 1979, as cited in Mindali, Raveh, & Salomon, 2004). Medieval cities, whose reticulate of paths and buildings still amaze citizens today, were designed for walking distances because walking and horse-drawn carriages were the main transport mean at the time (Anas, et al., 1998). The introduction of horse drawn and then the electric streetcars between 1830 and 1900 enabled a number of people, especially from the middle and upper classes, to move from the center, which was shared by different socioeconomic classes at the time.

Although current perception would hardly consider sprawl the first wave of city expansion, it was in fact the very beginning of a continuing trend of population decentralization across vaster territories. The construction of suburban railways, in the second half of the nineteenth century, substantially accelerated the process (Couch, et al., 2007). In London, suburbanization started with the extension of the rail network in the 1860s, producing a radial pattern of urbanization along the routes. The latter development of a more widely spread, circular

pattern of growth was a consequence of the bus network, which complemented the rail in reaching territories not served by the main infrastructure (Chin, 2002). Dissemination of the automobile started in the early twentieth century and brought, especially after the World War II, a change even more profound in the urban structure than the one caused by the train (Anderson, et al., 1996; Newman, 1999). Because cars and trucks were twice as fast, and because their variable costs were half of those of the horse and wagon, people and industry moved further away from the center where land and commuting costs were lower (Anas, et al., 1998; Deal & Schunk, 2004; McGranahan & Marcotullio, 2005). It was the advent of the *automobile city* (Newman, 1999). It is interesting to note that, along with the evolution of transports, geography became less and less important in constraining which places were to be urbanized. Older cities essentially relied on walking, even when served by the railway, and proximity between people and businesses was necessary. Cars somewhat delinked people from the geographical constraints: for the first time, the automobile provided its owner with the freedom to choose residential locations far removed from the workplace, and allowed for the development of areas not served by public transportation (Anderson, et al., 1996). In the United States, this prompted the emergence of a new form of automobile city near the nodes of express highways: the *edge cities* (Anas, et al., 1998; Garreau, 1991).

More recently, the globalization of information technologies such as the internet has motivated a debate about their future impact on urban forms. Some authors contend that information technologies will drive urban development towards an even more sprawled future (Audirac, 2005), but others consider that there is little evidence to support it (Gillespie, 1992, as cited in Anderson, et al., 1996). Rather than leading to the dispersal of cities, information technologies could instead be associated with the concentration of urban activities into nodal centers (United Nations Center for Human Settlements, 2001b).

The link between sprawl and transportation is explained by a surprising evidence: no matter how the accessibility is changed, an average commuting time of about 30 min seems consistent across different city types, regions and modal shares (Newman, 1999; Poulit, 2007). In Portugal, travel times from home to work have been stable at around 20 min as observed in the 1991 and 2001 Census, despite the enormous investment in highways since the eighties. Instead of promoting faster commuting times, increased accessibilities trigger the movement of people and jobs to new locations maintaining about a half-hour travel time (Newman, 1999). Also, because larger territorial areas become accessible to people, densities are pushed downwards.

Improvement of the transport infrastructure may not decrease travel times but these investments are far from being a zero sum equation. Poulit (2007) has shown that travel time and job attractiveness are related through an exponential function: an increase in travel time of

10 min is enough to reduce the attractiveness of a job by more than one-half, and an increase of 20 min by more than five times. At the end, the consequence of improved accessibility – even considering the influence of sprawl – is a region with a larger catchment area extending its influence over vaster territories.

Econometric models

Numerous factors influencing urban sprawl have been described. However, is it not easy to relate them in a meaningful way. The model suggested by Couch, et al. (2007), for instance, constitutes a useful list of relevant variables at different levels, but does not explain nor provide insights into the relationship between factors, their role or their relative importance in causing sprawl. That is hardly a surprise given that scientists such as Éric Lambin recognize that no consistent theory explaining land use changes exist (Lambin, 2005). Over the last years, however, there has been a tremendous effort in modeling land use changes in urban settings, and novel approaches such as cellular automata or agent based models are yielding promising results (Lambin & Geist, 2006). The rationale for agent-based models is that different actors behave differently and have their specific motivations. An example is that families with small children are most likely to move to suburban areas outside the city; and that, in contrast, the elderly and single are least likely to leave the urban center (McGranahan & Marcotullio, 2005). Modeling the behavior of specific groups of people has also been carried out by Couch, et al. (2007).

Classical models are more helpful in illustrating the relevant relationships between the drivers of urban sprawl. The classical von Thünen's bid-rent theory and the Lotka-Volterra predator prey model have been adapted to such cases (Capello & Faggian, 2002). According to these researchers, who employed a panel model relating population change and urban rent, urban rent plays the role of spatial resource allocator because it influences location choices. An increase in urban rent pushes residential and production activities towards the periphery, which is characterized by lower land prices. The inverse is also true: house prices are influenced by demographic changes in the previous period. This is because a household chooses the residential location that provides the best tradeoff between land costs and commuting costs. Wealthier households live in suburbs because the income elasticity of demand for housing is larger than the income elasticity of commuting costs (Wu, 2006). The bid-rent theory has obvious connections with the urban cycle described before, which includes the process of sprawl. Capello & Faggian's results provide an econometric explanation for it. In brief, an increase in the demand for housing raises urban rents and pushes population out of the core areas; this causes a decrease in urban population, lower rents, and the birth of a new cycle (the reurbanization phase in Berry's model).

Other empirical models lacking a solid theoretical framework have also been applied. Fulton, et al. (2001) analyzed all metropolitan areas in the United States between 1982 and 1997 and concluded that those areas growing more rapidly in population, relying more heavily on public water and sewer systems, and having higher levels of immigrant residents, tended to consume less land for urbanization relative to population growth; metropolitan areas tended to consume more land for urbanization if they were already characterized by high population densities and if they had fragmented local governments. Nielsen (2007) cited the results of three econometric models at the regional or city level with the similar purpose of explaining urban land use (Table 3.3-2). Because urban land use, and not the change in urban land use, was modeled, population appears as an important explanatory variable in the three models. Schneider (2006), in simple bivariate analysis performed with data from several cities around the globe, has found a limited relationship between urban expansion and population change. Nielsen has also performed a multiple logistic regression to explain the change in urban land cover in either NUTS II or NUTS III regions (so that the size of units would be as similar as possible). Results are shown in Table 3.3-3 and suggest that, holding the other variables constant, urban growth is higher in less urbanized, dense, and wealthier regions.

Table 3.3-2: Comparative studies of drivers of urban growth at the regional level. Source: Nielsen, 2007.

Source:	Reginster et.al, 2006: Scenarios of future urban land use in Europe	Angel et.al, 2005: The dynamics of global urban expansion	Alig et.al., 2004: Urbanization on the US landscape: looking ahead in the 21 st century
Data coverage, time and units:	European NUTS2 regions, PELCOM land cover data	Sample of 90 cities across the world, Landsat data, 1990 & 2000	US counties, NRI data, four years (data points) from 1982 to 1997
Dependent variables:	Percentage of urban land use, 2000	Urban land use in sq. km 1990; 2000 (two data points per city) Change in urban land 1990-2000.	Proportion urbanized (logit transformed),
Independent variables:	Population GDP per capita Unemployment rate Participation rate	Population Per capita GDP National share of IP addresses Air linkages Maximum slope Agricultural rent Cost of fuel Cars pr. capita Ground water 3 climate dummies	Population density Per capita income Value of agri. pro. Metropolitan 7 regio-dummies
Analysis:	OLS	OLS, linear and log- linear	OLS GLS
Conclusion with respect to drivers:	Population+ GDP per capita+	Population + Income + Share of IP addresses + (Air links +) (Maximum slope -) (Agricultural rent -) (Cars per capita +) Shallow ground water + Climate differences +/-	Population density + Per capita income + Metropolitan + Regional differences +/-
Level of explanation:	Adjusted R-square in OLS regression= 0,911	R-square in cross- sectional analysis of urban land=0,79; in loglinear analysis of urban expansion=0,89	Adjusted R-square in OLS regression= 0,60

Table 3.3-3: Predictors of urban land cover growth between 1990 and 2000. Variables are ordered by their importance. Source: Nielsen, 2007.

Growth in urban land cover 1990-2000			
	EU25	EU15	N10
1	Urban land 1990 (-)	Urban land 1990 (-)	Urban land 1990 (-)
2	GDP/capita (+)	Population density (+)	Growth in population (+)
3	Growth in tourist beds (+)	Maximum slope (-)	
4	Gross value added/Ha (+)	Growth in population (+)	
5	Population density (+)	Growth in cars/capita (+)	
6	Growth in population (+)		
7	Maximum slope (-)		
8	Growth in GDP/capita (+)		
9	Growth in agricultural output per Ha (-)		
10	Growth in Cars/capita (+)		

Similarly, Hu & Lo (2007) performed a spatially explicit logistic regression (resolution = 225 m) to identify the demographic, economic and biophysical forces driving urban growth between 1987 and 1997 in the Atlanta Metropolitan Area. They identified two groups of factors influencing the probability of a cell being converted to urban use: distance to the central business district, number of urban cells within a 7×7 cell window, cell not being urbanized, and UTM northing coordinate, all with odds ratios higher than 1; and population density, distance to the nearest urban center, and high or low density urban uses, all with odds ratios lower than 1. Hu's and Nielsen's results may seem contradictory, but the different scale of analyses do not allow straightforward comparisons.

Models are extremely important in helping us joining several components together, but it can be cumbersome to detect relevant missing variables or to collect the necessary data to run them. For instance, Hu's model failed to consider the spatial distribution of amenities that Wu (2006) identified as relevant in predicting urban growth.

Empirical data about urban cycles, urban growth and sprawl

It is estimated that built-up or impervious surfaces occupy roughly between 2% to 3% of the Earth's land surface (Lambin & Geist, 2006). This may seem a small proportion, but artificial surfaces already amount to 470 million ha and are rising fast due to suburban sprawl (Alberti, et al., 2006). Cities are expanding faster than their population, and some cities are expanding their territory despite experiencing a population decline. Between 2000 and 2030, world urban population is expected to grow 72%, while built-up areas in cities with 100 thousand or more inhabitants shall increase by 175%. As a consequence, during the last decade, the average population density in cities declined at a annual rate of 1,7% in the developing countries, and at a rate of of 2,2% in developed countries (UNFPA, 2007). Some of the most rapidly growing cities can be found in Eastern and Southeastern Asia and South America (cf. Figure 3.3-10 and Figure 3.3-11). In China, for instance, Seto et al. (2002), as cited in Lambin & Geist (2006),

estimated that the region of Pearl River Delta increased its artificial surfaces by 364% between 1988 and 1996; Bangkok's built-up area expanded from 67 km² in 1953 to 426 km² in 1990 (UNFPA, 2007).

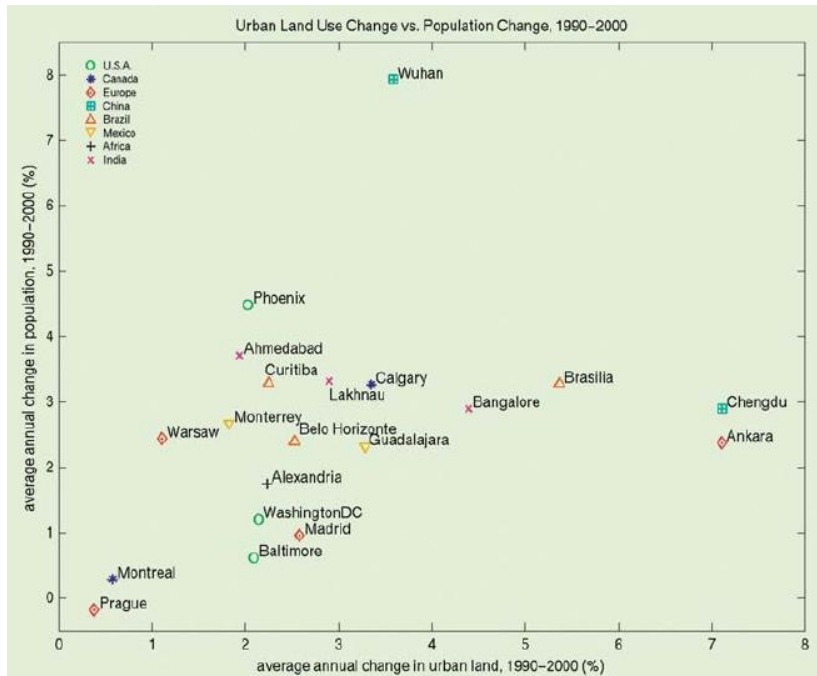


Figure 3.3-10: Annual change in urban land against the annual change in population for several cities (1990–2000). Source: Schneider, 2006.

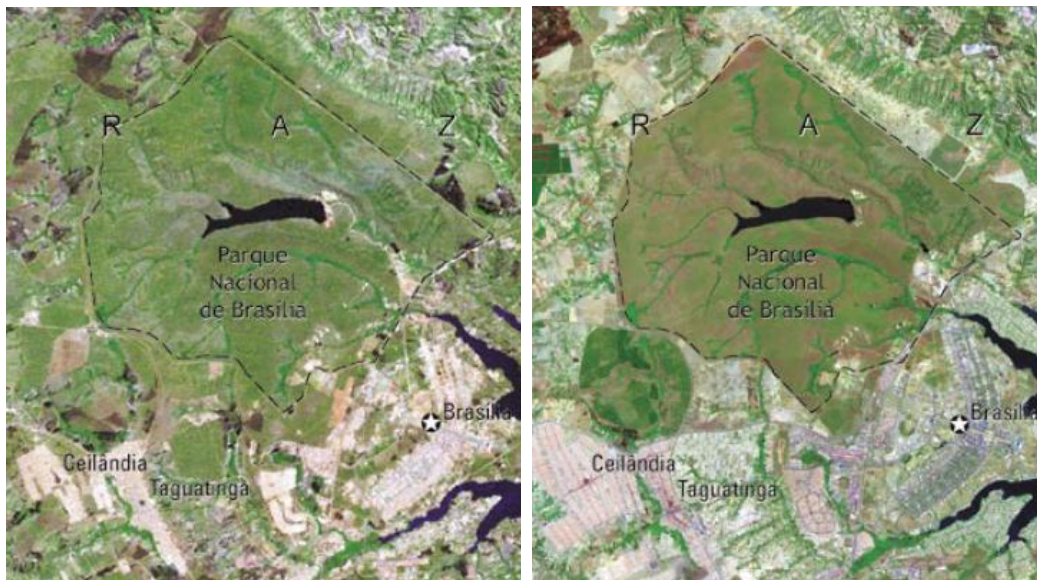


Figure 3.3-11: Urban expansion around Brasilia (left: 1973; right: 2001). Source: UNEP, 2005.

□ Empirical data about urban cycles, urban growth and sprawl > Flows between land use classes

Expansion of cities must be made at the expense of previous land uses. Lambin & Geist (2006) referred that a large share of urban growth is likely to take place on prime agricultural land located in coastal plains and in river valleys. This leads to the concept of land use flows, which refer to the gains and losses of land area between different land use types (EEA, 2006a).

In developing countries, Döös (2002), as cited in Lambin & Geist (2006), estimated that one to two million ha of cropland are taken out of production every year to meet the demand for urban and industrial uses. The pattern in the United States is similar: suburban roads and houses supplant more the one million ha of farmland per year (O'Meara, 1999). In China, Seto et al. (2002), as cited in Lambin & Geist, found that about 70% of the urban expansion between 1988 and 1996 in the region of Pearl River Delta was converted from farmland.

Land conversion to urban uses in Europe is much slower than in the United States. A detailed study by EEA (2006a) with data obtained from the Corine Land Cover project has shown that, in 24 countries, agricultural land lost to urban uses amounted to 811 thousand ha between 1990 and 2000 (Figure 3.3-12 and Figure 3.3-13). This must be added to the 150 thousand ha of forests, semi-natural vegetation and open spaces that were also converted to artificial areas.

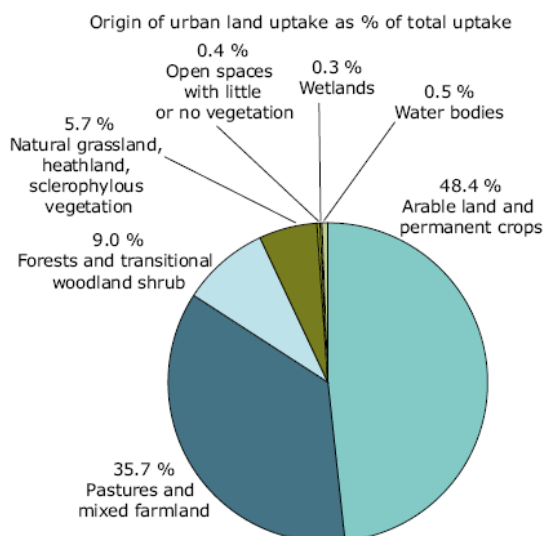


Figure 3.3-12: Land-take by artificial development in 24 European countries (1990–2000). Source: EEA, 2006b.

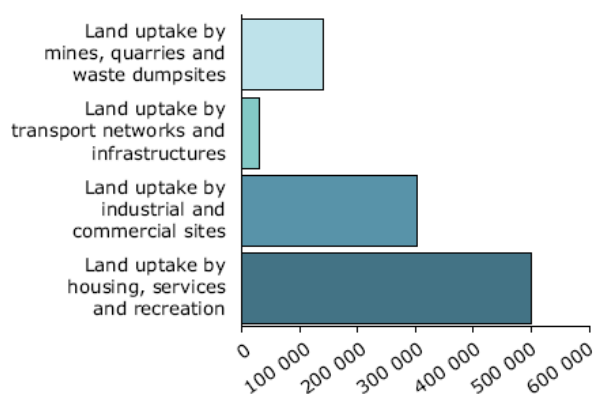


Figure 3.3-13: Flows to urban land uses (ha) according to their final use in 24 European countries (1990–2000). Source: EEA, 2006b.

A wealth of data concerning Portugal, much of it from the Corine Land Cover, is available as well. A valuable graph prepared by Caetano, Carrão, & Painho (2005) illustrates the land use flows that occurred between 1985 and 2000 (Figure 3.3-14). The transition of forests to artificial surfaces (21 thousand ha) and the transition of agricultural areas to artificial surfaces (33 thousand ha) are among the most important changes.

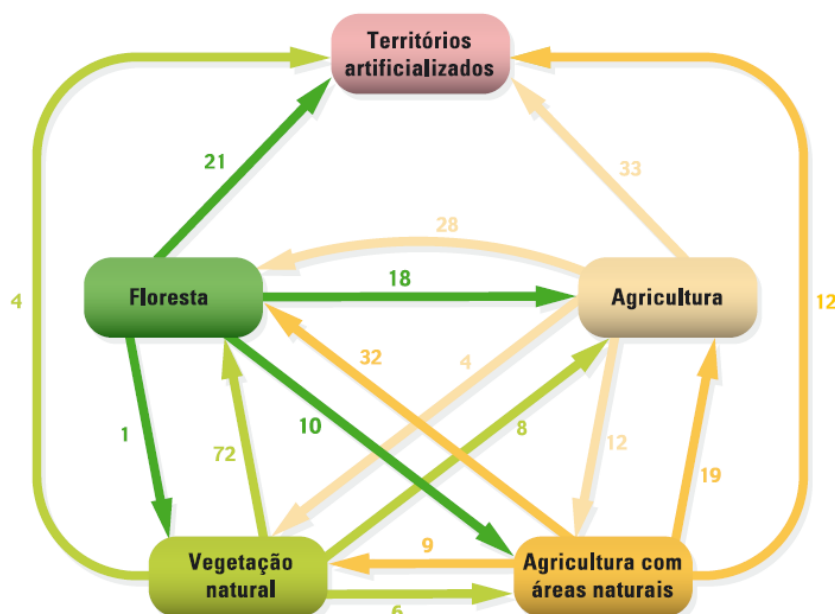


Figure 3.3-14: Flows between land uses (thousand ha) in Portugal (1985–2000). Source: Caetano, et al., 2005.

☐ Empirical data about urban cycles, urban growth and sprawl > Trends and patterns of urban sprawl in the United States

The study of sprawl across the United States metropolitan regions carried out by Fulton, et al. (2001) showed that urbanized land grew at a much faster rate than population. The country's urbanized land increased by 47%, from approximately 21 million ha in 1982 to 31 million ha in

1997. During this period, population grew by only 17 percent, which led to decreased densities in 264 out of the 281 metropolitan areas studied. These trends diverged across the country. The South accommodated a great share of population growth at the expense of a large amount of previously nonurban land. In the Northeast and Midwest, slow-growing metropolitan areas have consumed extremely large amounts of land for urbanization in order to accommodate a very small population growth. The map proposed by Theobald (2005) depicts these sprawling trends (Figure 3.3-15).

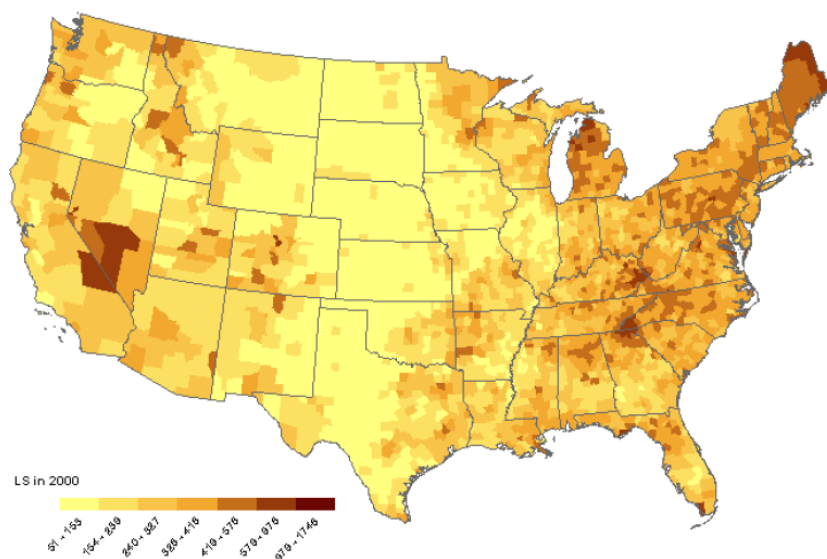


Figure 3.3-15: Landscape sprawl metric values for the United States in 2000 and averaged by county. A darker color indicates more sprawl or greater effect on the landscape. Source: Theobald, 2005.

In another landmark report, the Transportation Research Board (2002) carried out a projection of population growth and sprawl in the United States for the period 2000–2025. They concluded that a large share of the fastest population growing areas will be found in a relatively small number of geographic units (three out of 50 states and 40 out of nearly 3100 counties contained one third of the all household growth), and that sprawl and population growth will take place to a much greater degree in the South and West than in the Northeast and Midwest.

New methodologies are being used to study the patterns of sprawl and population growth. Using selected landscape metrics such as patch density, mean patch size, perimeter-to-area ratio and contrasting edge, Irwin & Bockstael (2007) demonstrated a significant increase in the fragmentation of developed and undeveloped land between 1973 and 2000 in the fast-growing state of Maryland. Tsai (2005), in turn, used the Moran's Index and the Gini coefficient to investigate the distribution of population and employment in the 219 United States metropolitan areas with less than 3 million people. The empirical data revealed that population

and employment are concentrated in certain sub-areas of the metropolitan area (as given by the Gini coefficient), and that two-thirds of the metropolitan areas have populations that are spatially clustered (as given by the Moran coefficient). It is difficult to compare the results of the various studies because reliable standards are lacking and because authors employed differing methodologies and definitions of sprawl.

Sprawl is also evident from city level data. In the last 25 years, the population of New York grew by 5% and its urban surface by 61%. Phoenix, Arizona, occupy an area three times as big as Los Angeles despite accommodating a smaller population (Girardet, 1999/2007). In Greater

Chicago, population grew by 38% between 1950 and 1990 and spread over 124% more land; in metropolitan Cleveland, population increased by 21% during the same period while the city extended through 112% more land (O'Meara, 1999).

Empirical data about urban cycles, urban growth and sprawl > Trends and patterns of urban sprawl in Europe

The scale of urban sprawl in Europe is not as great as in the United States, but a recent report published by EEA has called attention to this problem. The subtitle, “the ignored challenge,” is instructive. Ireland, Portugal, Spain, Netherlands and Greece were the countries whose artificial surfaces grew faster between 1990 and 2000 (Figure 3.3-14). Annual growth rates of around 3% were observed, much higher than the average rate of 0,6% obtained for the 23 countries studied. Ireland, Portugal and Spain

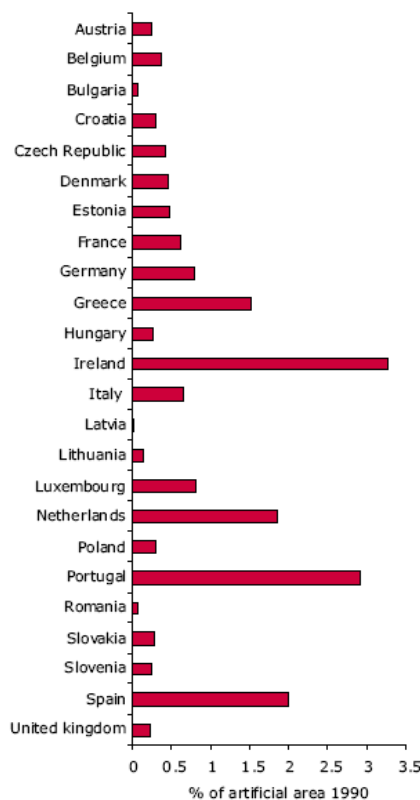


Figure 3.3-16: Mean annual artificial surface land-take by country (1990–2000). Source: EEA, 2006a.

had a very low share of built-up surfaces in the reference period (around 1,1–1,4% in 2000), which may have exaggerated the perceived amplitude of land use change. Besides these trends, in 2000 the countries with a higher share of urbanized land were still Belgium, Denmark and the Netherlands (EEA, 2006a).

Urban sprawl has been particularly intensive along the coastal regions of Europe, particularly the Mediterranean. During the period 1990–2000, urbanization in the coast grew approximately 30% faster than urbanization in inland areas, with the highest rates of increase (20–35%) again in the coastal zones of Portugal, Ireland and Spain (EEA, 2006b). In the

Barcelona Metropolitan Region, Catalán, et al. (2008) found that urban expansion between 1993 and 2000 was six times as large as population growth. The largest increases were observed in the medium-sized cities of the region and in the municipalities of the external part of the first metropolitan ring. Istanbul is another good example of a fast growing city: in the past 50 years, the growth the built-up area has expanded by 600% and the population grew

Table 3.3-4: Estimates of population density gradients. Source: Clark, 1967, as cited in Anas, Arnott, & Small, 1998.

City	Year	Density Gradient (per mile)
London	1801	1.26
	1841	0.93
	1901	0.37
	1931	0.27
	1939	0.23
	1961	0.14
Paris	1817	2.35
	1856	0.95
	1896	0.80
	1931	0.76
	1946	0.34
Frankfurt	1890	1.87
	1933	0.92
Birmingham, UK	1921	0.80
	1938	0.47
Rangoon	1931	1.16
	1951	0.55
New York	1900	0.32
	1940	0.21
	1950	0.18
Chicago	1880	0.77
	1900	0.40
	1940	0.21
	1956	0.18
Los Angeles	1940	0.27
Boston	1900	0.85
	1940	0.31
Sydney	1911	0.48
	1954	0.26
Christchurch	1911	1.61
	1951	1.34

from approximately one million to 10 million (EEA, 2006b). Other examples of sprawl in coastal territories can be found in Porto, Madrid, Marseilles and the nearby Rhône valley, Milan, Bologna, Venice and the Veneto region, and Athens (Catalán, et al., 2008). Most European cities have become over the years much less compact. In half of the urban areas studied by the Moland project, for instance, more than 90% of all residential areas built after the mid-fifties were considered low density (EEA, 2006b). One consequence of sprawl is the blur of boundaries between urban and rural land uses. As a result, population becomes more uniformly distributed and the density gradients from the center to the periphery tend to decrease (Table 3.3-4).

Although urban expansion has been persistent, it reached the peak in fifties–sixties with an annual average of 3,3% increase in built-up

surfaces (EEA, 2006b). Turok & Mykhnenko (2007) argued that the decline of population growth rates in cities since the sixties was the result of falling rates of urbanization rather than the slowdown in the birth rate. The diminishing agricultural population or the weaker urban economies (less attractive for migrants) may help explaining those trends.

Besides the overall sprawling trend observed in most cities, they do show diverse patterns and trajectories of change. As proposed by the theory of urban cycles, cities and countries may be in different stages of their development. The work of Couch, et al. (2007) is suggestive of this. They divided European conurbations into four groups (Table 3.3-5):

- the largest group is experiencing population growth and sprawl at the same time. Cities in this group exist in all zones except Northern Europe, with Western and Central Europe

Turok & Mykhnenko (2007) carried out a more detailed examination of population trends, but did not analyze land use changes. They classified the trajectories of 310 European cities over the period from the sixties until 2005 into nine classes (here grouped for synthesis purposes):

- the most common profile (30% of the cities) was continuous growth (mostly in France, Spain and Germany);
- 37% of the cities experienced medium-term or recent decline. These cities were mainly found in Russia, Ukraine, Poland and Romania;
- 42 cities (14%) experienced a positive turnaround since 1980 (mostly in the United Kingdom, former West Germany, Belgium and Italy);
- 26 cities (8,4%), mostly in Eastern Europe, followed a discontinuous path. They grew in the eighties, temporarily declined in the nineties, and then returned to growth in the early noughties¹⁰;
- only 13 cities (4,2%) experienced continuous or long-term decline. Three of them are located in the United Kingdom and seven in Germany.

Turok & Mykhnenko (2007) found that, since the late nineties, large cities recovered their rates of growth faster than smaller cities – in spite of the diseconomies of scale associated with big cities. Moreover, national economic conditions, settlement structures and governance arrangements seemed to influence the trajectories followed by cities. French and Spanish cities, for instance, were the most likely to experience long-term growth. On the contrary, cities in Russia, Poland, Ukraine and Romania were the most likely to have a downturn since 1990; cities in Belgium and in the United Kingdom were the most likely to experience a positive turnaround. The discrepancy found in city's trajectories led the researcher to caution against the existence of a broadly similar urban life cycle: "City resurgence is a multidimensional phenomenon requiring a basket of indicators to capture fully" (Turok & Mykhnenko, 2007, p. 175). Further research is needed to uncover the more difficult to grasp sociocultural and institutional factors that may help explaining the different urban trajectories, and why reurbanization is happening in some cities and not in others.

❑ Empirical data about urban cycles, urban growth and sprawl > Trends and patterns of urban sprawl in Portugal

Artificial surfaces have increased 42% (70 thousand ha) between 1985 and 2000, and represented around 3% of the Portuguese terrestrial surface in 2000 (Caetano, et al., 2005). This growth has been particularly significant around the metropolitan areas of Lisbon and Porto, along the coastline Lisbon-Setubal and Porto-Viana do Castelo, and more recently along

¹⁰ The current decade.

the Algarve coast (Figure 3.3-17). The pressure on the coastal regions is becoming so intensive that, in 2000, half of continental urban areas were located within 13 km of the coastline (EEA, 2006b). In the area between Lisbon and Porto urban expansion has mainly occurred near highways and only to a lesser extent near the coast (Caetano, et al., 2005). As would be expected, the maps of urban growth and population dynamics are similar, which again demonstrates the importance of urbanization processes in driving the expansion of artificial surfaces (Figure 3.3-18).

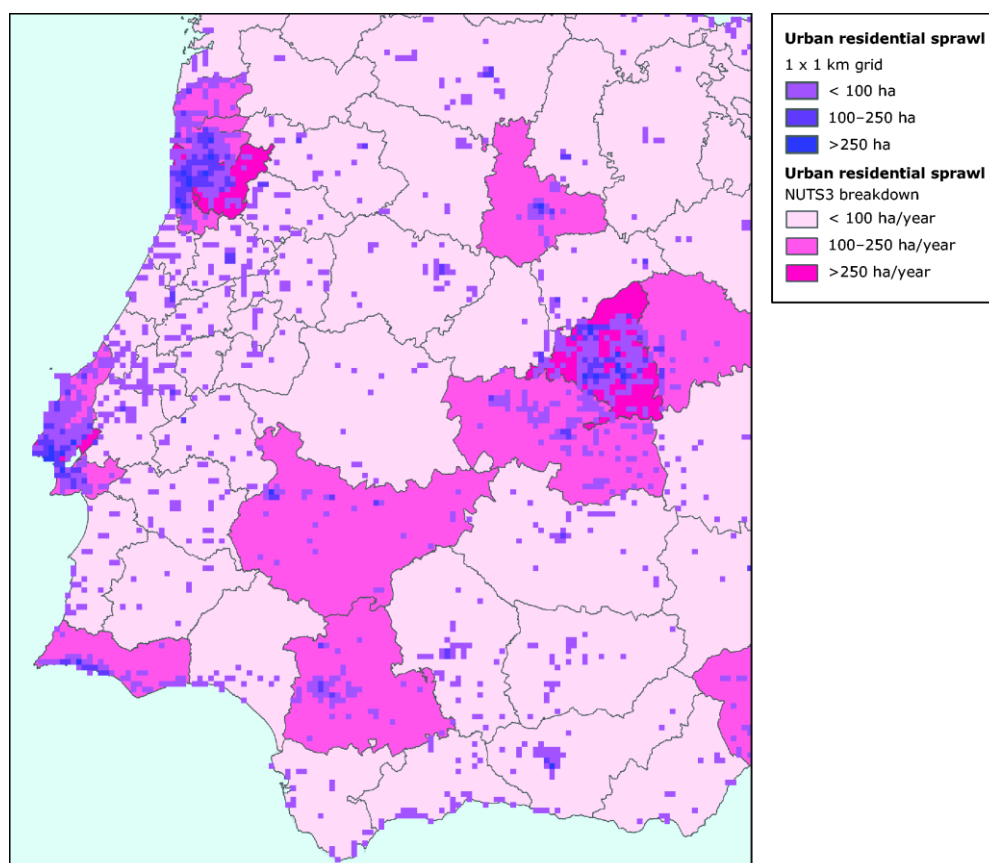


Figure 3.3-17: Spatial distribution of urban expansion (by NUTS 3 regions and by grid-cells). Source: EEA, 2006a.

Discontinuous urban fabric and industrial or commercial units were the most rapidly growing classes of artificial surfaces (Caetano, et al., 2005). Corine Land Cover was the source of the land use statistics provided. Although Corine Land Cover does not provide population densities, the fact that discontinuous urban fabric (and not continuous urban fabric) was the urban class showing the highest growth is a clear indicator that most of the urban development should be classified as sprawl.

Urban growth is generally happening around cities, but naturbanization may help explaining sprawl in remote territories. I have collaborated in the investigation of land use trends in the

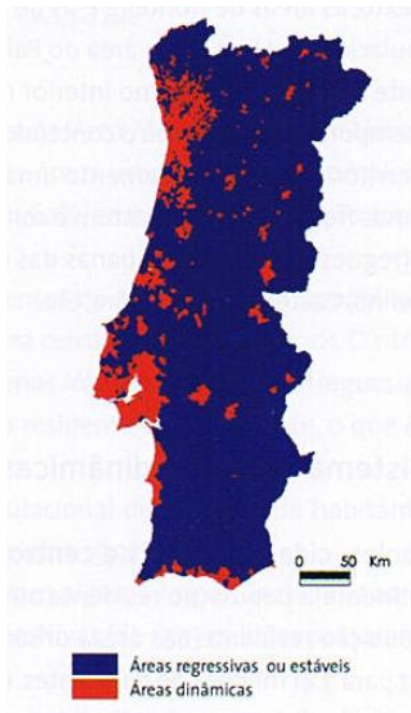


Figure 3.3-18: Population dynamics in Portugal since the fifties. Source: Marques, 2004.

National Park of Peneda-Gerês, in the Northeast. This work (Lourenço, Quental, & Barros, 2009) found evidence of both urbanization and naturbanization processes since the eighties: a relatively large number of people had moved from rural boroughs to towns, and a smaller flow of persons had decided to abandon urban areas and search for other ways of living. Cartographic analysis showed that most urban growth took place in towns, near the major road corridors and near water reservoirs. I have also participated in a strategic plan for the municipality of Ponte da Barca, part of which is also inside the National Park of Peneda-Gerês, finding similar evidence of the concentration of people near towns (Quental, 2006b).

3.4 The impacts of different urban forms

The high concentration of people and businesses in cities lead to numerous impacts on people and on the ecosystems. On the sixties, due to anti-urban ideals, cities were seen as unnatural and unsuitable for humans, as it was thought that excessive densities were at the root of social problems (Newman, 2006). This vision is not supported anymore, since no causal relationship between average city densities and social problems has been shown. Still, cities are associated with numerous impacts, either positive or negative, and at different scales (Figure 3.4-1). At a local scale, problems such as unpleasant living neighborhoods, traffic congestion, noise and impoverished air quality are the most relevant. Some tend to be partially solved as the city develops (the environmental Kuznet's curve seems to explain this kind of problems; McGranahan & Marcotullio, 2005). Regional problems include changes in the hydrological regime of rivers, water pollution and ecosystem degradation. The influence of cities is also extended to larger scales through different routes. One is through the accumulation of city's greenhouse gas emissions in the atmosphere, where they contribute to the disruption of the climate system. Likewise similar emission related impacts, this is a truly global impact. Another impact route is through the appropriation of foreign carrying capacity, for cities are voracious consumers of resources (Folke, Jansson, Larsson, & Costanza, 1997). This impact occurs at the

specific places where resources are harvested. However, as it occurs simultaneously at several locations, it should be considered global as well.

Problem and Characteristics	Intra-Urban (Urban Systems as Human Habitats)	Urban-Region (Urban Systems and Their Biospheres)	Urban-Globe (Urban Systems and Global Ecosystems)
Priority problem identified	unhealthy and unpleasant living environments	deteriorating relations with adjoining ecosystems	excessive "ecological footprints"
Urban areas most closely associated with problems	low-income cities and neighborhoods	large, middle-income, industrial cities	affluent cities and suburbs
Indirect driving forces	demographic change, inequality; trade and development that ignores ecology of infectious diseases and urban ecosystem services	industrialization, motorization; trade and development that ignores impacts on adjoining ecosystems	material affluence, waste generation; trade and development that ignores global ecosystem impacts
Direct driving forces	inadequate household access to safe water, sanitation, clean fuels, land for housing	ambient air pollution, groundwater degradation, river pollution, resource plundering, land use pressures	greenhouse gas emissions, import of resource and waste intensive goods (linear vs. circular flows)
Negative impacts associated with problem	spread of infectious diseases, loss of human welfare and dignity	loss of natural ecosystem services, "modern" diseases, declining agroecosystem productivity	global climate change, loss of biodiversity, depletion of globally scarce natural resources
Temporal characterization of key processes	rapid	varied	slow
Example of historically relevant response	sanitary reform	pollution controls	sustainable cities?

Figure 3.4-1: Problems in urban systems and ecosystem services at three different spatial scales. Source: McGranahan & Marcotullio, 2005.

Ecological footprint assessments have been providing data about the aggregated impact of cities (see also section 2.7). Despite methodological differences, such studies invariably show that the footprints of cities are two to three orders of magnitude larger than the geographic or political areas they occupy (Doughty & Hammond, 2004; Folke, et al., 1997; Girardet, 1999/2007; McGranahan & Marcotullio, 2005; Rees & Wackernagel, 1996; Wackernagel, et al., 2006). Studies concerning the metabolism of cities show in addition that their material and energetic intensity is increasing, even if decoupling from wealth (Kennedy, et al., 2007).

Many authors are caution when they refer to *sustainable cities*, as urban areas are still following unsustainable trajectories, particularly due to rising car dependencies and more intensive consumption patterns (e.g., Beatley, 2003). Doughty & Hammond (2004, p. 1225) referred that cities "cannot be viewed as sustainable in the limited sense of being self-sufficient, reliant on their own carrying capacity as a resource base"; similarly, Lee (2006, p. 10) argued that "the functional question of sustainability has become both nonlocal and local, as distant ecosystems are drawn into the consumption, investment and income-transfer choices made by the residents of cities." At the same time, cities are also associated with positive impacts, particularly on human capabilities. Cities are also among societies' most precious cultural achievements: in most cities there are buildings, streets, and neighborhoods that form a central part of the history and culture of that society (United Nations Centre for Human Settlements, 1996). Cities are the places where citizens can develop their capabilities and profit from

opportunities to a larger extent. These capabilities may be used as a source of democratic reinvigoration and creative energy from where solutions to the challenges of sustainability may emerge (Giddings, et al., 2005). Cities also represent significant economies of scale in various domains. The concentration of people in limited territories reduces the consumption of land, lowers *per capita* infrastructure costs and, most importantly, allows the cost-effective provision of public services such as public transports, health care, cultural activities, green areas, and curbside collection for waste recycling (e.g., Anas, et al., 1998; Haughton & Hunter, 1994; Lee, 2007; McGranahan & Marcotullio, 2005; Roseland, 2005). Rees & Wackernagel (1996) have called to this leverage effect the *urban sustainability multiplier*. Another major and often disregarded influence of cities in contributing to sustainable development is through their role in precipitating demographic transition (Bright, 2003; Daly, 1996; Hibbard, et al., 2007; McNeill, 2007; Sen, 1999/2003), as population growth is one of the most important threats to sustainability (Dasgupta, 2007; Parris & Kates, 2003a).

3.4.1 Influence on several sustainability domains

Different urban forms contribute differently to the aggregated impact of an urban area. Figure 3.4-2 depicts the relationships between the built environment, mobility and travel decisions, and environmental quality.

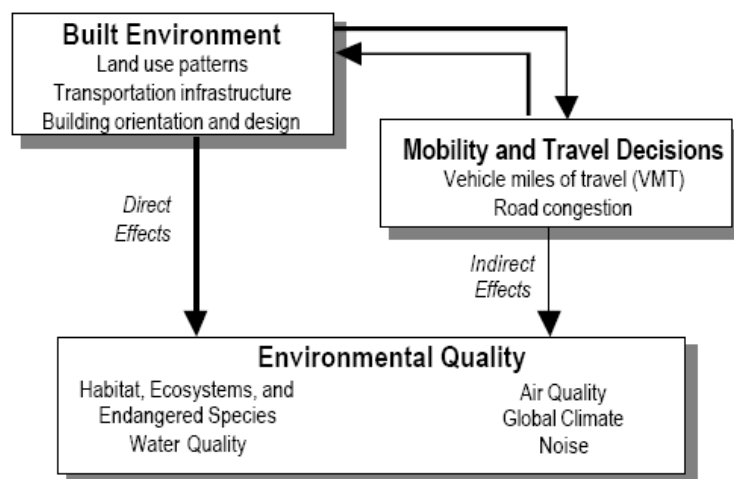


Figure 3.4-2: Direct and indirect effects of the built environment. Source: Environmental Protection Agency, 2001.

One of the often emphasized characteristics of low-density “sprawling” neighborhoods is the monotony of their urban and human environment. Concerning this issue, Manuel Castells mentioned:

“These endless, endless suburbs, absolutely undifferentiated, which unfortunately is not any more just an American feature, areas of the central city which all look alike, such as the mass generation of post-modern buildings. It is an idea of an agglomeration of activities and population which doesn’t have beginning or end, which doesn’t have internal structures, a juxtaposition of a number of urban nuclei which are destructured from the inside, that are unstructured in their relationships” (Castells, 2000, p. 120).

Diffuse urban forms, as opposed to concentrated patterns of human settlements, are also associated with the degradation of the urban center, higher disruption of regional ecosystems due to habitat fragmentation and conversion to urban uses, higher operational energy consumption, lower air quality at the regional scale, and higher social costs, particularly on infrastructure and equipments (Table 3.4-I). Only in what concerns to water quality does sprawl seem to have an advantage over compact land uses.

Table 3.4-I: Effects of higher densities on different sustainability domains.

Domain	Higher density or lower sprawl
Human capabilities	.Associated with higher social capital and lower population uniformity (Haughton & Hunter, 1994; Newman & Kenworthy, 1999)
Dynamism of the city center	.Contributes to the city center dynamism, vitality and renewal (Beatley, 2003; Cappellin, 2007; Newman, 1999; Sheehan & Peterson, 2001)
Ecosystem services and land consumption	.Reduces ecosystem fragmentation and destruction (Alberti & Marzluff, 2004; Deal & Schunk, 2004; Marcotullio & Boyle, 2003; McGranahan & Marcotullio, 2005; Næss, 2001) .Reduces land consumption (Camagni, et al., 2002; EEA, 2006b; Pauleit, Ennos, & Golding, 2005; Transportation Research Board, 2002)
Air quality and climate	.Provide better urban air quality compared to disperse and network cities (Borrego, et al., 2006; Ewing, et al., 2002) .Contributes to the urban heat island (Almeida, 2006)
Water quality	.Increase in the share of built-up areas reduce the water infiltration rate and significantly increase water run-off (Pauleit & Duhme, 2000), causing characteristically altered and often extreme hydrological conditions in rivers (Alberti & Marzluff, 2004; Monteiro, 2009)
Noise	.Lower noise levels in residential and natural environments (Geurs & van Wee, 2006)

Domain	Higher density or lower sprawl
Residential and office energy consumption	.Operational energy consumption <i>per capita</i> in detached houses is 35–50% higher than in attached dwellings except for high-rise buildings (Ewing & Rong, 2008; Holden & Norland, 2005; Rickwood, Glazebrook, & Searle, 2007). Differences between detached and attached houses have been decreasing (Holden & Norland, 2005) . Relatively high housing densities can be achieved before a negative impact on the energy demand becomes significant (Steemers, 2003) . The embodied energy of detached houses per m² is similar to that of low rise buildings, but lower than high rise buildings (Rickwood, et al., 2007) .Specific appliances and design measures may represent significant energy savings (Rickwood, et al., 2007) .Comparisons are difficult and depend on several assumptions (Rickwood, et al., 2007)
Social costs	.Reduces social costs related with infrastructures and equipments (Deal, 2001; Newman & Kenworthy, 1999; O'Meara, 1999; Roseland, 2005; Transportation Research Board, 2002) .Commuting costs are smaller (EEA, 2006b; Newman & Kenworthy, 1999; United Nations Center for Human Settlements, 2001a)

3.4.2 Influence on mobility patterns

Conceptualizing mobility

Travel is regarded, from a utilitarian point of view, as a derived demand (van Wee, 2002). This means that most of the times people travel because they need to reach a destination and not because they enjoy travelling, *i.e.*, the demand for travel does not derive its utility from the trip itself. Travel behavior (which includes a characterization of the transport modes chosen, reasons for traveling, frequency of trips, routes, destinations, etc.) is explained theoretically as the result of people's needs and desires (the reason to travel), by the location of activities and by transport resistances (Handy, 2006; Nunes da Silva, 2005; van Wee, 2002; cf. Figure 3.4-3). Resistances refer to aggregate travel costs, including monetary costs, travel times, effort necessary to reach destination, etc.

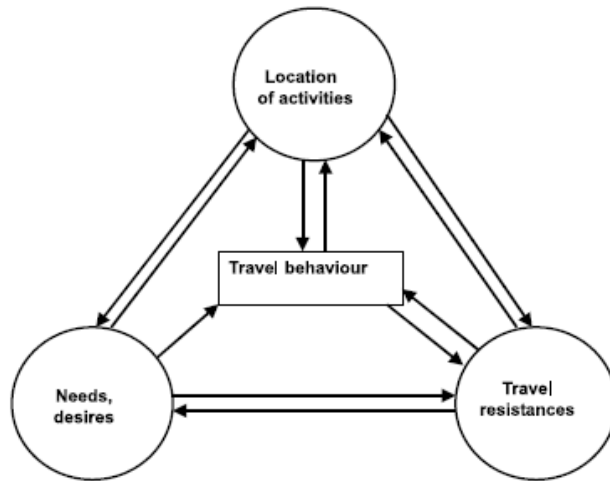


Figure 3.4-3: Relationships between activity locations, needs and desires, transport resistances and travel behavior. Source: van Wee, 2002.

Urban form influences travel behavior through several – often contradictory – complex ways. For the sake of illustration, and resorting to van Wee’s framework, let me focus on dense and compact forms:

- they tend to increase the level of *accessibility* to human activities by reducing travel distances. In addition, they stimulate the existence activities in larger quantities and more attractive (a good example are pop stars, who perform only in selected cities);
- *travel resistances* are in principle reduced because distances are shorter, but they can increase as well as if higher congestion is observed. At the same time, density allows the provision of highly efficient public transports, thereby reducing travel resistances for transit users. Road investments also reduce resistances for car users and encourage dispersed land use patterns, which are especially troubling for mass transit (Cervero, 1998);
- with time, changes in the urban form and travel resistances may also influence citizens’ deep attitudes towards mode choice, as well as the personal valuation of costs (distances are less and less valued as a resistance factor because long-distance travel times have been decreasing).

The picture is this quite complex, which probably explains why little “definite” conclusions have emerged from travel behavior research (Frank, Bradley, Kavage, Chapman, & Lawton, 2008). Figure 3.4-4 details the links between urban form, human conditions, rationales for activity participation, and travelling distances. Socioeconomic conditions (e.g., employment situation, income), demographic aspects (e.g., size and composition of households), and car ownership (driving license holders) play a central role in understanding travel behavior (Meurs & Haaijer, 2001).

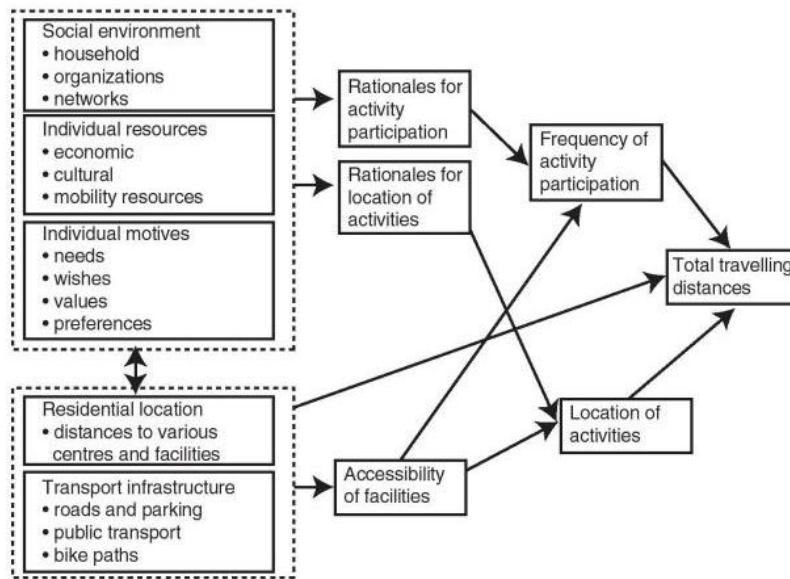


Figure 3.4-4: Behavioral model showing the assumed links between urban, human and social conditions, rationales for activity participation and location of activities, and travelling distances. Source: Næss, 2006.

It is interesting to note that the importance of urban form dimensions on travel behavior are scale dependent. At the neighborhood scale, researchers often concentrate on three main urban form dimensions (the so-called *three Ds*): density, diversity, and design (Cervero & Kockelman, 1997). At the metropolitan level, Tsai (2005) referred to size, density, degree of equal distribution, and degree of clustering as the fundamental dimensions of urban form (see also section 3.3). Figure 3.4-5 presents these dimensions at the various scales.

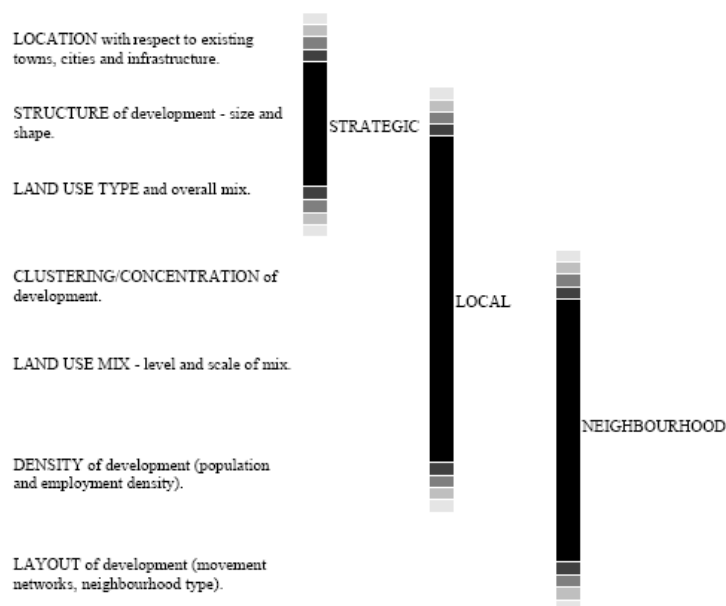


Figure 3.4-5: Urban form characteristics that can affect travel behavior at different scales. Source: Stead & Marshall, 2001.

The role of individual attitudes

One of the issues that research concerning travel behavior has to face deals with the difficulty in disentangling the influences of socioeconomic characteristics and those of urban form. Van Wee's triangle explicitly represents the relationship between activity location and the needs and desires as reciprocal. One issue, commonly known as *residential self-selection* or as *self-selection bias*, explains a part of the credit attributed to urban form for its influence on travel behavior (Schwanen & Mokhtarian, 2005). Self-selection arises when residential location choice is not independent of commute mode choice, as citizens with a predisposition towards a certain type of travel are also more inclined to live in a neighborhood enabling them to realize their preferences. While this effect does not diminish the importance of having transit oriented development neighborhoods – after all, people who are naturally inclined to use public transports need to live in places enabling that preference – it may however change the way researchers and politicians perceive the role of urban form in affecting travel behavior. From being one direct cause of certain mobility patterns, urban form would be regarded as an enabler – or disabler – of predetermined individual preferences. This leaves unanswered, however, the question of how do people construct their attitudes. My feeling is that researchers are being excessively conservative in their reasoning about the importance of urban form, but I fully support the improvement of research designs so that all relevant causal chains can be understood.

The theory of planned behavior provides a useful epistemological framework to better understand the role of personal attitudes and beliefs in shaping behavior (and, as a consequence, travel behavior) – see Figure 3.4-6. By focusing on beliefs, this theory does not posit a significant role for the built environment in explaining travel behavior (Handy, 2006). Urban form might come into play through its influence on the beliefs an individual holds about the likelihood of possible factors that facilitate or constrain a behavior. For cycling, such factors might include the presence or absence of cycle lanes, or a general sense of safety. The theory also emphasizes attitudes and social norms, factors that are absent from the utilitarian framework commonly used in travel behavior research (Handy, 2006).

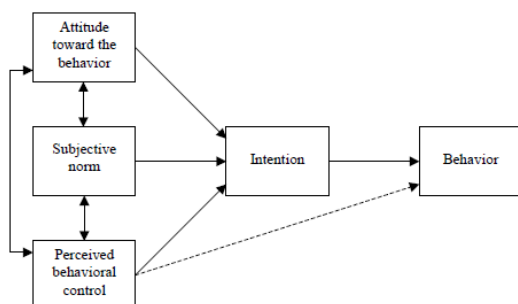


Figure 3.4-6: Theory of planned behavior. Source: adapted from Azjen, 1991, as published in Handy, 2006.

3.4.3 Empirical evidence concerning the influence on mobility patterns

A number of papers providing empirical evidence concerning traveling patterns were examined (a brief description of each, including the main conclusions, is provided in the annex A.2). Being a stimulating research topic, a large amount of studies is published regularly. As a result, the review does not attempt to be exhaustive. Instead, my aim is to provide sufficient evidence about the issues being investigated, to cover the most common modeling approaches, and to cover recent and promising methods. My review also mentions other, more detailed, literature reviews.

Modeling approaches

A number of approaches have been used to address empirically the question of how urban form influences travel behavior. One important question deals with scale that best represents the object of research. As travel behavior is an individual decision, it should, in principle, be better captured by approaches based on the individual. On the contrary, there would make no sense to develop climate models, for instance, for small territories, as climate is intrinsically larger in scale. However, the researcher has to make compromises. Official surveys usually lack questions deemed as essential, and carrying out a specific questionnaire is highly expensive. Aggregate data is, sometimes, a good alternative, as a number of different data providers can be requested to help and participate in the research. In addition, if the research deals with the effects of urban form on mobility patterns, then one would expect that relationships would be present at aggregate levels, for urban form can only be defined at some level of territorial aggregation.

The basic distinction in travel behavior models has to do with the scale of analysis. Aggregate studies (of which this thesis is an example) use averaged values from territorial units such as cities or smaller zones (boroughs, neighborhoods, census tracks, etc.). It is expected that averaging does not eliminate existing relationships under investigation. For disaggregate designs, the unit under investigation is the individual or the household. In addition to the aggregate effects of urban form, these studies are able to capture subtle effects related to personal characteristics. Disaggregate studies offer tremendous opportunities to test complex research questions dealing with human behavior. No wonder, then, that most of the attention is devoted to them. Discrete choice models and activity-based models represent two of such approaches. Travel choice models predict the probability of an individual choosing a particular alternative based on the utility of that alternative relative to others (Handy, 1996). The activity-based approach is more complex and recognizes that a person's daily trips are made as part of a chain of activities. This chain affects the choices that each traveler must make: when a

trip should be made, by what mode, by what route, the sequence of trips, etc. (Miller, Kriger, & Hunt, 1999). Modeling approaches have become increasingly sophisticated, either in terms of the statistical techniques employed or in terms of the rationales underneath, although both are related. The focus has been to move from simple correlations and empirical relationships to building causal models, understanding the complexity of individual choices regarding travel behavior, and acknowledging uncertainty (Handy, 2006; Miller, et al., 1999 – see also Figure 3.4-7).

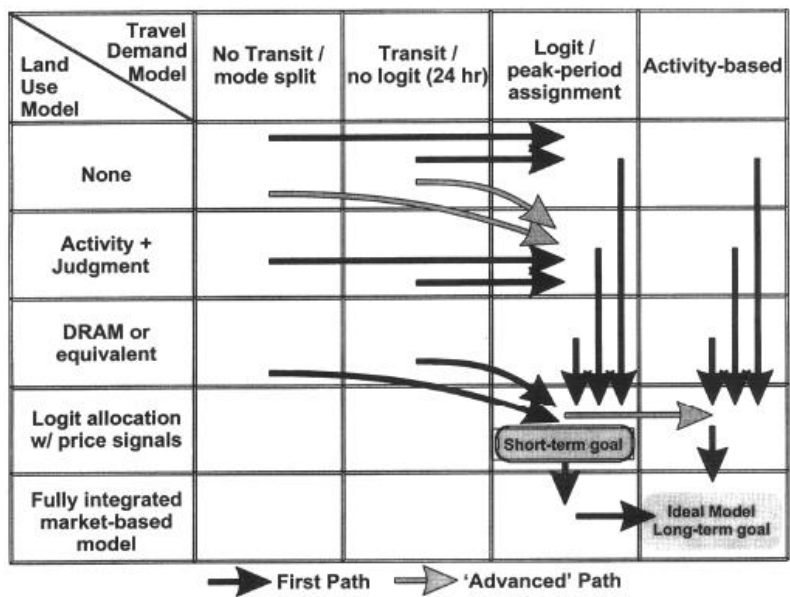


Figure 3.4-7: A taxonomy of transportation-land use modeling capabilities. Source: Miller, et al., 1999.

Statistically speaking, most of the studies analyzed involve multiple or logistic regressions. Most models controlled for basic socioeconomic characteristics such as education and income. As a result, estimates about the influence of urban form indicators are in principle reliable. It would be tempting to compare the coefficients obtained by each author, but it would be naive and erroneous to do so because those methods are highly dependent on the variables included or omitted. Just as other authors have made in their literature reviews (Abreu e Silva, 2007; Arrington & Cervero, 2008; Handy, 2006; Rickwood, et al., 2007) I preferred to rely on general conclusions about the relative importance of groups of variables (each group of variables could be considered a sustainability domain) on mobility patterns. In the next subsections, I will describe important empirical findings in this area, drawing from the list of literature presented in the annex A.2.

Comprehensive measures of impact or behavior

Most of the literature analyzed focused on specific measures of travel behavior. A few studies, however, calculated comprehensive measures of impact (such as the ecological footprint or the total energy use) or comprehensive measures of travel behavior (such as the total physical activity). Some of the most relevant are briefly reviewed here.

A meta-review conducted by Handy (2006) showed that accessibility emerged as a strong correlate of total physical activity (which includes active travel and other physical activity). However, individual factors were often more important in explaining it. Urban design factors appeared to be more important for recreational physical activity. Similarly, Forsyth, Oakes, Schmitz, & Hearst (2007) concluded that higher-density environments promoted active travel while lower density environments promoted leisure walking. They added, however, that overall physical activity was similar in both settings.

In studying possible compensatory mechanisms, Holden & Norland (2005) found that residents having access to a private garden traveled less for recreation purposes than did residents without a garden. Total energy use decreased as density reached a certain level, beyond which it started to increase. In Norway, Holden (2004) reported higher *per capita* ecological footprints with decreasing household size, and with increasing car ownership rates and income. Detached houses and low-density areas were also associated with higher footprints. In the United Kingdom, the ecological footprint of BedZED neighborhood (an environmental friendly housing development) was 30% lower than the average United Kingdom footprint (Newman & Jennings, 2008). These two latter studies, however, were not based on formal statistical tests.

Aggregate measures travel behavior impacts

In this category I include studies involving dependent variables which attempt to aggregate into a single value the impact of travel behavior. Unlike the previous section, however, these studies exclude the impacts caused by other dimensions. This is usually accomplished by estimating greenhouse gas emissions from transportation or by estimating the ecological footprint of travel behavior.

Geurs & van Wee (2006) simulated alternative land use development scenarios for the Netherlands and concluded that, without compact urban development policies between 1970 and 2000, carbon emissions would have been higher. Nicolas, Pochet, & Poinboeuf (2003) reported 2,5 times higher carbon emissions for suburban residents in the Lyons conurbation than city center residents. Newman & Kenworth (1999), in a widely cited research, concluded that total *per capita* transportation energy decreased with density and with city size, and that urban form explained at least half of the observed differences (Figure 3.4-8). Their sample included 46 cities from all continents. Measures of density and accessibility in the Barcelona Metropolitan Region were also found of greater importance than income or job ratio in

explaining transportation ecological footprint (Muñiz & Galindo, 2005). Banister, Watson, & Wood (1997) found significant relationships between energy use in transports and population density in a selection of six cities in the United Kingdom and the Netherlands. At the borough scale, in Milan, net density and housing age had a strong negative influence on mobility impact (Camagni, et al., 2002).

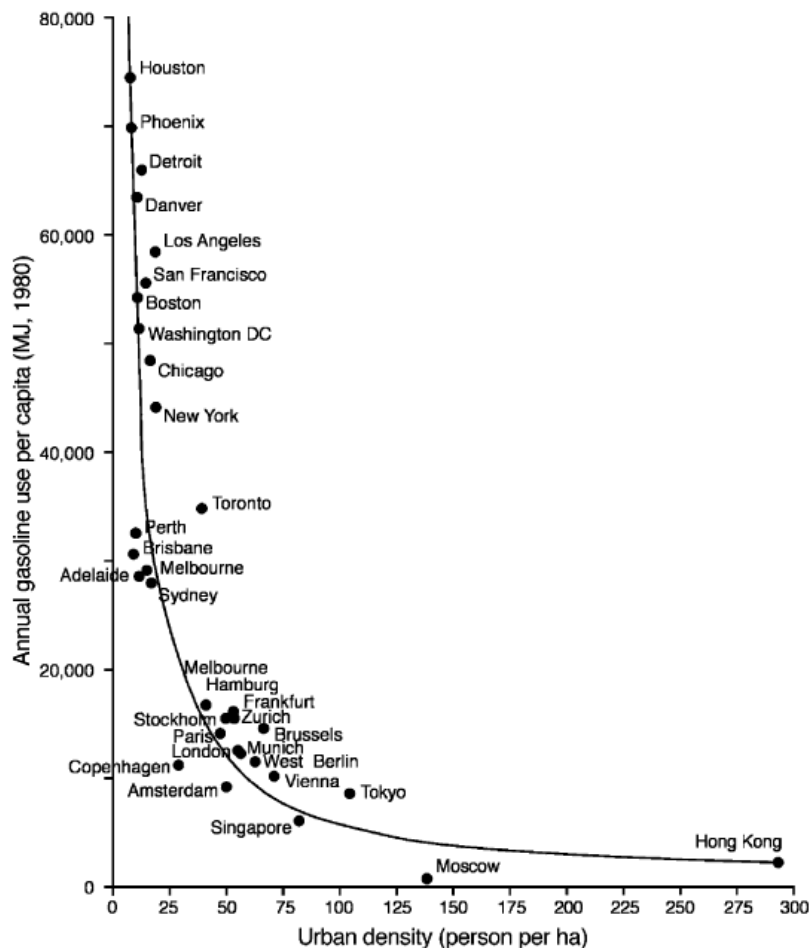


Figure 3.4-8: Gasoline use *per capita* versus urban density (1980). Source: Newman and Kenworthy, 1989, as cited in Newman & Kenworthy, 1999.

Specific measures of impact or behavior

This subsection provides the best evidence to understand the causal mechanisms between different independent variables and measure of travel behavior.

□ Specific measures of impact or behavior > Aggregated models

At the metropolitan scale, in the United States, Ewing, Pendall, & Chen (2002) found that traveling distances and car ownership rates were higher in sprawling areas than in less sprawling regions. Moreover, transit usage and walking were more intensive in less sprawling areas. At the city level, and between 1960 and 1990, Cameron, Kenworthy, & Lyons (2003) explained about 90% of the variance in private motorized share and travel distance with an

equation containing only population density and a traffic saturation factor. These researchers updated and expanded the database used by Newman & Kenworthy (1999), which contained a sample of 46 cities in all continents. Newman & Kenworthy suggested the existence of a critical point around 20 to 30 persons/ha below which car-dependent mobility patterns were an inherent characteristic of the city. In addition, car dependency varied considerably but it was not related to wealth (Figure 3.4-9). Van de Coevering & Schwanen (2006) studied 31 cities in Europe, Canada and United States. Again, urban form measures were found significant, although the influence of specific variables differed between Europe and United States cities. Similar conclusions were reached by Bento, Cropper, Mobarak, & Vinha (2003), who found, in a sample of 114 cities in the United States, job ratio, population centrality and rail service significant predictors of public transport shares.

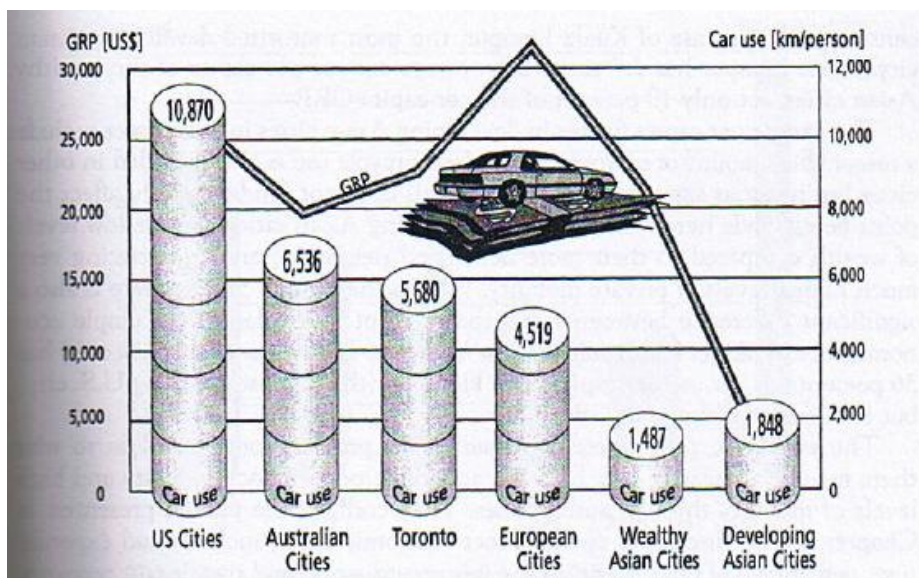


Figure 3.4-9: Travel distance *per capita* by car and wealth (1990). Source: Newman & Kenworthy (1999).

Some researchers also analyzed smaller territorial units. In a recent study employing SEM at the level of traffic analysis zone, Lin & Yang (2009) found that density encouraged trip generation and discouraged car use; land use mix also reduced the number of trips but was associated with higher car shares; and pedestrian-friendly road design had a negative effect on car use. Bhat & Guo (2007), working at the same scale, concluded that demographic characteristics and income had a more prominent effect on car ownership rates than the built environment. Holtzclaw, Clear, Dittmar, Goldstein, & Haas (2002) studied neighborhoods in Chicago, Los Angeles and San Francisco, and concluded that travel distances by car were a strong function of density, income, household size and availability of public transports. Urban design features turned out less relevant. Studying the boroughs of Sydney and Melbourne, Rickwood, et al. (2007) found a clear and nonlinear positive relationship between density and

public transport use. The largest effects took place at up to 70 people/ha. In their literature review, these authors collected evidence across countries, cities, and neighborhoods that density reduced vehicle travel. In another literature review about the performance of transit oriented development areas in the United States, Arrington & Cervero (2008) concluded that, between 1970 and 2000, public transport ridership for work trips increased in those areas despite a marked decline in the surrounding (not transit-oriented) areas.

❑ Specific measures of impact or behavior > Disaggregated models

In Germany, and using longitudinal data from 1996–2003, Vance & Hedel (2007) concluded that urban form significantly influenced car use. The finding was robust to alternative econometric specifications. Van Acker, Witlox, & Van Wee (2007) employed SEM and found that travel behavior in Flanders, Belgium, was mainly influenced by the respondent's social status: longer distances were associated with higher social status. In the Metropolitan Area of Lisbon, and again using structural equations, Abreu e Silva (2007) has shown that residents in dense, central and compact areas with a reasonable land use mix were more likely to use public transports, cycle or walk, and less likely to own a car. Employment location had a significant influence on mode choice as well. Similar conclusions were reached by Næss (2006) for Copenhagen. In detailed qualitative interviews carried out by Næss, it should be underlined that respondents said they preferred, for most travel purposes, the possibility of choosing among facilities rather than proximity. Frank, Bradley, Kavage, Chapman, & Lawton (2008) concluded that travel time (particularly wait time) was a very important predictor of public transport use in Seattle. The positive role of density, land use mix, and street connectivity (at the residence and employment locations) on walking, cycling and use of public transports was confirmed. Again in the United States, Washington, Lawrence Frank & Co. (2005) showed that higher accessibility to institutional and recreational equipments increased the likelihood that someone travelled by foot. With respect to the likelihood of choosing public transports, it declined as the distance to transportation routes increased, as travel distances from home to work were longer, and with car ownership. In Maryland, Cervero (2002) found that density and diversity of land uses exerted the strongest influence on the mode chosen by individuals, whereas urban design factors played a weaker role. Meurs & Haaijer (2001) compared the influence of socioeconomic and environmental characteristics on distinct travel modes and reasons in the Netherlands. The largest effect of urban form was related to walking and shopping trips. Commuter traffic was essentially related to personal characteristics. The importance of socioeconomic characteristics was also stressed by Stead (2001), who concluded that land-use characteristics explained only up to one third of the variation in travel distance per person.

❑ Specific measures of impact or behavior > Attitudes and residential self-selection

The most rigorous models control for the effect of personal attitudes and residential self-selection on travel behavior – whose absence could, otherwise, inflate the importance of urban form. Cao, Mokhtarian, & Handy (2007) used an innovative research design: they inquired 547 residents who moved to another house in four traditional and four suburban neighborhoods in Northern California. As such, the effect of residential self-selection was explicitly controlled. They concluded that self-selection had a significant direct and indirect impact on travel behavior, but the role of urban form remained significant as well. Schwanen & Mokhtarian (2005) carried out an even more detailed research. Respondents of a questionnaire were considered consonant when they lived in a neighborhood that corresponded to their stated preferences, and dissonant in the remainder cases. In a traditional neighborhood, dissonant residents were far more likely to commute by car than consonant residents, but they were still less car dependent than residents of suburban neighborhoods. Their results suggested that residential self-selection processes played a significant role in explaining travel patterns, but they also confirmed that territorial structure had an autonomous influence. Næss (2006) confirmed the existence and relevance of residential self-selection phenomena. He performed, in addition to almost two thousand questionnaires, several in-depth qualitative interviews with 17 households. This information was useful to understand the deep motivations of some persons when choosing where to live and how everyday travel decisions were taken.

Another interesting line of research is the comparison of mobility patterns among homogeneous groups of individuals or territorial units, thereby providing for a more precise control of some variables of interest. Hibbers et al. (1999), as cited in van Wee (2002), did not find significant differences in travel behavior between several types of residential areas built near the city limits, suggesting that preexistent attitudes of movers prevailed.

❑ Specific measures of impact or behavior > Longitudinal changes in travel behavior

Explicit testing for the influence on travelling behavior originating from longitudinal changes in urban form has only been carried out occasionally. A remarkable exception is the already cited research performed by Cao, Mokhtarian, & Handy (2007), which can be considered a quasi-longitudinal design. Researchers found that accessibility was the most important factor reducing car use and that, overall, the effect of the urban form on travel behavior was similar to or larger than that of sociodemographic characteristics. Urban design factors were found to stimulate walking but played a secondary role. The main weakness of this research was that changes in travel behavior were obtained *ex post* from the perception of respondents, and not as observational data.

3.5 Synthesis

3.5.1 Urban sustainability goals

It was visible from section 3.2 that policy declarations and scientific literature mention a very large diversity of urban sustainability goals. Often, the specific goals privileged by an author reflect her background or the scope of the paper, which may explain why urban planning or governance considerations were sometimes neglected. The overall picture – portrayed in Table 3.5-1 – is quite ambitious and does not aid much in rationalizing about urban sustainability. Based on the Campbell (1996), who concentrated on the roles and goals of planners, on Fainstein (2000), who expounded the stereotyped planning approaches, and also on insights from the literature review presented in chapter 2, I organized urban sustainability goals into categories. This classification is especially helpful to understand the different characteristics and roles of each category in fostering sustainable urban development. The urban sustainability goals identified comprise issues of very different nature, although all of them play a role in supporting cities. *Instruments* are social constructs such as institutions and methodologies that provide enabling and supportive functions for urban sustainability policies. They include strategic planning, LA21 processes, monitoring mechanisms, and management systems. These instruments set the conditions for *resource* mobilization. Urban form and natural capital are two kinds of resources available to the planner to contribute to sustainability. Most authors recommend measures aiming at achieving certain levels of population density, land use mix, and accessibility to different urban functions. Human capabilities could also be understood as resources, but they comprise and end in themselves. Two types of goals can be distinguished as intermediate means. One is economic development, which is widely accepted as necessary to create employment and wealth; the other is sufficiency and efficiency, which is concerned with the minimizing the scale and impact of the economy. Another domain of central importance to sustainability is human behavior, which is, *inter alia*, affected by human capabilities, urban form, and rules. All these issues are important for sustainability but they lack an intrinsic value. They are relevant insofar as they contribute to the fulfillment of the *ultimate ends*, i.e., intermediate ends play mainly an instrumental function. Ultimate ends comprise justice, human well-being, and environmental sustainability. Justice should be understood in a broad sense that includes equity between individuals, between generations, and between regions. It is necessary that the development of a community is not achieved at the expense of other places' sustainability, and that all resources imports are fair. There has been a tendency to overemphasize intermediate ends such as economic development (or the “money fetishism” thoroughly characterized by Daly, 1996) to the detriment of valuing appropriately the ultimate ends of society.

Table 3.5-1: Urban sustainability goals as expressed in policy documents and scientific literature.

	Instruments	Resources		Intermediate means		Behavior	Ends		
	Governance	Urban form	Natural capital	Economic development	Sufficiency and efficiency	Ecological citizen	Justice	Human well-being	Environmental sustainability
Slow	.Planning (including LA21 processes) .Assessment of alternatives .Cooperation	.Density and polycentrism .Accessibility .Infrastructure .Transportation system	.Clean environment .Risk minimization	.Economic development .Improvement of town and countryside relationships	.Dematerialization .Resource use efficiency .Cleaner vehicles .Environmental friendly production .Product longevity	.Preference for walking, cycling and public transports .Less intensive consumption patterns .Environmental friendly lifestyle	.Equity (in the present, in relation to the future, and in relation with other places) .Transparency .Participation	.Social capital .Diversity .Identity	.Ecosystem health .Biodiversity
Faster	.Monitoring and reporting .Fund-raising .Green taxes and incentives .Management systems	.Urban containment .Land use mix .Urban renewal .High-quality public spaces .Bioclimatic architecture .Green areas .Walkability and cyclability .Heritage preservation	.Reduce greenhouse gas emissions .Air quality	.City and street vitality	.Green procurement .Closed material flows .Preference for local resources and food			.Basic needs .Safety .Health .Housing .Employment .Education .Integration	

3.5.2 Urban growth and sprawl

The review presented in section 3.3 resulted not only in a list of the most important drivers of urban sprawl, but also suggested that each variable acts at a given scale where it plays a specific role. There are so many relevant variables that one could be tempted to think of sprawl as something very unlikely to happen. An accident occurs when a combination of undesirable circumstances takes place at the same time and perhaps at the same location. But the process of sprawl is much different. A better analogy is evolution: key variables have adapted continuously to become almost perfect tuned. Sprawl could represent the fine tuning of several explanatory factors. However, as society is nowadays more aware of the detrimental effects of sprawl, policies are needed to stimulate the reoccupation of urban centers, as postulated by the theory of urban cycles.

The root causes of sprawl lie in the slow and large-scale processes that are usually the most powerful drivers (Holling, 2001; Meadows, 1999; see also Figure 3.5-1). They are in the first place constituted by the self-reinforcing and synergistic triangle constituted by economic growth, globalization, and urbanization (migration to cities). Families are in addition increasingly small, which implies that more dwellings are needed to accommodate the same population. These factors explain why cities have been growing, but not necessarily where urban growth occurs. The fact is that many families prefer the ideal of living in a detached house surrounded by a quiet and beautiful environment, creating a demand for housing in the periphery, where such conditions can be met. Still, these conditions are necessary but not sufficient to start sprawl. A number of enabling and stimulating factors are essential for the process of suburbanization to happen:

- a fiscal system allowing landowners to retain the surplus value when their land is urbanized, which inflates the land prices in the center and motivates the retention of land for speculation, while promoting the urban use of lower value land in the periphery;
- a banking system that facilitates the access to credit, thus augmenting enormously the number of families capable of buying a new house;
- since land is more expensive in the center than in the periphery, house prices follow the same pattern, and families have a great monetary incentive to move out of the central town; this also explains why incomers tend to settle in the suburbs;
- lack of coordination and competition among neighboring municipalities to attract inhabitants and to obtain a higher tax base tend to relax the application of existing rules and the zoning of excessive amounts of land for urban purposes in municipal and regional plans.

	Resource scarcity causing pressure of production on resources	Changing opportunities created by markets	Outside policy intervention	Loss of adaptive capacity and increased vulnerability	Changes in social organization, in resource access, and in attitudes
Slow	Natural population growth and division of land parcels Domestic life cycles that lead to changes in labour availability Loss of land productivity on sensitive areas following excessive or inappropriate use Failure to restore or to maintain protective works of environmental resources Heavy surplus extraction away from the land manager	Increase in commercialization and agro-industrialization Improvement in accessibility through road construction Changes in market prices for inputs or outputs (e.g., erosion of prices of primary production, unfavourable global or urban-rural terms of trade) Off-farm wages and employment opportunities	Economic development programs Perverse subsidies, policy-induced price distortions and fiscal incentives Frontier development (e.g., for geopolitical reasons or to promote interest groups) Poor governance and corruption Insecurity in land tenure	Impoverishment (e.g., creeping household debts, no access to credit, lack of alternative income sources, and weak buffering capacity) Breakdown of informal social security networks Dependence on external resources or on assistance Social discrimination (ethnic minorities, women, lower class people, or caste members)	Changes in institutions governing access to resources by different land managers (e.g., shift from communal to private rights, tenure, holdings, and titles) Growth of urban aspirations Breakdown of extended family Growth of individualism and materialism Lack of public education and poor information flow on the environment
Fast	Spontaneous migration, forced population displacement, refugees Decrease in land availability due to encroachment by other land uses (e.g., natural reserves or the tragedy of enclosure)	Capital investments Changes in national or global macro-economic and trade conditions that lead to changes in prices (e.g., surge in energy prices or global financial crisis) New technologies for intensification of resource use	Rapid policy changes (e.g., devaluation) Government instability War	Internal conflicts Illness (e.g., HIV) Risks associated with natural hazards (e.g., leading to a crop failure, loss of resource, or loss of productive capacity)	Loss of entitlements to environmental resources (e.g., expropriation for large-scale agriculture, large dams, forestry projects, tourism and wildlife conservation), which leads to an ecological marginalization of the poor

Figure 3.5-1: Typology of causes of land use change. Source: Lambin & Geist, 2006.

Sprawl would certainly not be possible without a network of radial transport systems linking city centers with the suburbs. The stunning developments in the transport sector acted as the main factor triggering sprawl in the first place, and as a stimulating factor thereof. Highways and cars allow people to travel greater distances in the same time. Citizens, through their personal choices, find a compromise between travel costs and housing costs.

As highlighted by Deal & Schunk (2004), the driving factors of sprawl function as feedback loops that favor fringe development. Nevertheless, their relative importance depends on the specific context, as several studies have shown (Camagni & Faggian, 2002; Couch, et al., 2007; EEA, 2006b).

3.5.3 Impacts of different urban forms

Virtually every study analyzed found some measure of urban form as relevant in predicting mobility patterns and travel behavior. Evidence comes from different cultures, countries, cities and neighborhoods. Research from the United States is overrepresented, but there is already a wealth of European research, excellent contributions from Australia and some recent papers from Asia.

The literature review clearly suggests that travel behavior is a multilevel process. The importance of each relevant dimension in predicting travel behavior seems to be scale

dependent. According to the theory of panarchy, “it is certainly true that slower and larger levels set the conditions within which faster and smaller ones function” (Holling, 2001, p. 397). At larger scales, such as the metropolitan region or the city – and in line with the conclusion of Newman & Kenworthy, 1999 – mobility patterns are largely related to the territory’s population density: higher densities promote alternatives modes of transport other than the car. Sociodemographic characteristics such as income still play a significant role. The overall structure of a region conditions the performance of processes occurring at lower levels. Mobility patterns in boroughs and neighborhoods thus need to be understood in the context of the wider region. Friedman et al. (1994), as cited in Kennedy, Miller, Shalaby, MaClean, & Coleman (2005), and Cervero (1998), both refer to the limited effect that a neo-traditional neighborhood can have on travel behavior if placed as an island in a “sea of freeway-oriented suburbs”. Hibbers et al. (1999), as cited in van Wee (2002), gave empirical credit to such claims. Furthermore, the relationship between urban form and mobility patterns may be characterized by thresholds. Newman & Kenworthy (1999, p. 100), for instance, refer that “there appears to be a critical point (about 20 to 30 persons per ha) below which automobile-dependent land use patterns appear to be an inherent characteristic of the city.”

As we move down in the scale of analysis, the effect higher-level variables may change in magnitude, and more variables become statistically significant. At the borough or neighborhood scales, sociodemographic characteristics (particularly income, car ownership and household size) seem to outpace urban form in explaining mobility patterns. Density, accessibility, land use mix, and level of public transport service, retain however a prominent role. The influence of urban design features seems to be of minor importance, although significant relationships have been found with walking and cycling, especially for recreation purposes. The truly importance of building and maintaining high quality public spaces is probably not well captured by regression-based statistical models.

The individual level is the scale at which more specific causal mechanisms can be tested. Handy (2006), for instance, questioned the use of density as a cause of travel behavior, suggesting that the relationship is spurious and the true underlying causal mechanism is related to accessibility, availability of public transports and alike. However, the fact is that density remained significant even after those variables were entered in models. It could suggest the existence of nonlinear relationships or nonaccounted dimensions. Still, I dare to suggest that density plays a distinct influence on travel behavior, which is perhaps related to a sort of “contagious effect” that emerges as interactions between people become frequent enough.

At the household or individual levels, other research questions can be tested. Attitudes and residential preferences, for instance, were found to significantly influence travel behavior. The effect of urban form remained significant, though. Overall, the role of personal characteristics

seems to be even larger than urban form in explaining travel behavior. To complicate things further, the effect magnitude of each variable is dependent on the travel reason and mode, although the global conclusions remain valid. Walking behavior, for instance, is especially difficult to predict.

Another issue to take into consideration is that of compensatory mechanisms, *i.e.*, the possibility that individuals or households perform better in some indicators but worse on others, so that their aggregate impact becomes difficult to predict and might assume unexpected outcomes. Evidence is still quite ambiguous, but exists: Holden & Norland (2005) found that suburban residents with access to a private garden whose daily travel distances are higher seem to travel less for recreation purposes than urbanites living in dense areas; and Forsyth, et al. (2007) found that walking was related to residential density but total physical activity was not. At a first glance, this could introduce an unacceptable relativism to all the aforementioned conclusions. However, studies about the influence of urban form and sociodemographic conditions on the overall environmental impact of people have reached similar conclusions (e.g., Holden, 2004), suggesting that the magnitude of compensatory mechanisms is smaller than the “main effects” caused by urban form and sociodemographic conditions. Hopefully, it is expected that specific causal models representing known pieces about human behavior may be joined together to provide clearer answers to the sustainability challenge.

Even if the specific causal mechanism linking urban form and travel behavior is not fully scientifically understood yet, most of the requisites for such causation are already met. Urban form is known to influence travel behavior. Having said that, I would cite the question raised by Anderson, Kanaroglou, & Miller (1996) concerning energy consumption: “it is one thing, however, to say that cities with different urban forms have different rates of energy consumption; it is quite another to say that a significant improvement can be achieved through realistic changes to the form of a particular city”. This question raises the problem of which changes are feasible from a practical or political point of view, but has also a scientific implication: do changes in existing urban fabric bring about the expected results as obtained from cross-sectional studies? Cross-sectional studies test equilibrium states, whereas longitudinal designs account in addition to the marginal effect of predictors on the dependent variables. Unfortunately, even the authors having panel data available usually end up with a series of cross-sectional studies. This is probably due to the increased difficulty in modeling panel data, although a number of different approaches are established (e.g., Hedeker & Gibbons, 2006). The work of Cao, Mokhtarian, & Handy (2007) is a remarkable exception. They found that longitudinal changes in urban form precipitated changes in travel behavior after controlling for personal characteristics and attitudes. Their work represents a further

step into the ambitious goal of establishing definitive causation between urban form and travel behavior.

When estimating the effect of urban form on travel behavior, researchers should take into account the contribution of the different urban form dimensions. Because urban issues are intrinsically complex, current empirical models represent simplified versions of reality. In the real life, density and accessibility are not independent from each other. On the contrary, they are linked by a causal mechanism. It is therefore incorrect to estimate, for instance, the effect of density on travel behavior ignoring the indirect effects stemming from the path linking density with other urban form dimensions having a distinct influence on travel behavior. In this sense, urban form dimensions act in a synergistic way and should be analyzed accordingly (Environmental Protection Agency, 2001; van Wee, 2002).

Rees & Wackernagel (1996) have called to this leverage effect the *urban sustainability multiplier*. A similar idea was conveyed by Neff (1996), as cited in Newman & Kenworthy (1999), regarding the effect of public transports. In the United States, and According to Neff, when public transports replace car travel, one km of transit may replace as much as 8,6 to 12,0 km of car travel.

4. Modeling territorial structure at the borough scale

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4. Modeling territorial structure at the borough scale

4.1 Introduction

Chapters 2 and 3 reviewed a broad range of literature concerning sustainable development in different contexts. This chapter translates the knowledge acquired into a methodology capable of modeling relevant sustainability processes at the borough level. Variables, indicators, model specifications, and methods are referred through a logical progression of analytical steps. Figure 4.1-1 displays the methodological steps explained in detail in this chapter. They can be grouped into three main parts:

- the built of a conceptual framework to be used as a reference for data analysis;
- the computation of meaningful indicators and factors to be used as explanatory or dependent variables in the statistical modeling;
- the effective use of data to model relevant urban sustainability processes and achieve the objectives of this thesis.

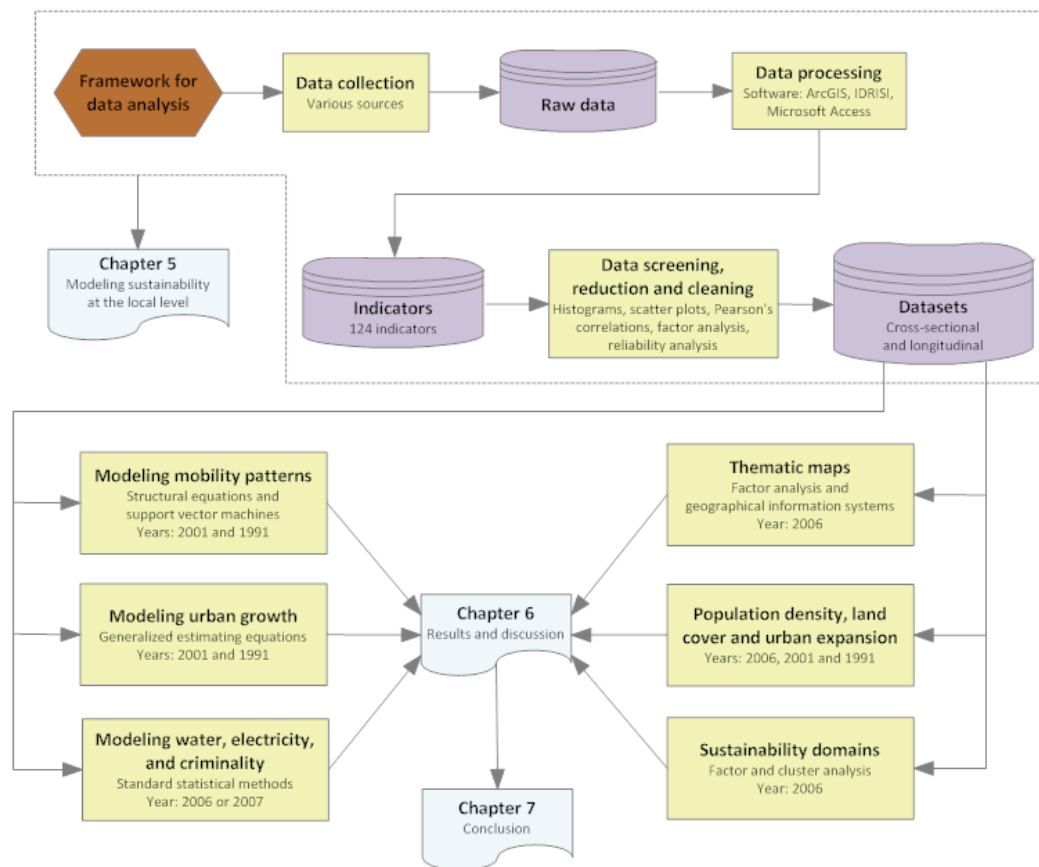


Figure 4.1-1: Methodological steps followed.

The processing of data from raw datasets to indicators and factors was complex. Some indicators were readily calculated from statistics, while others required extensive computing and the connection of different kinds of input (e.g., statistics with cartography). Figure 4.1-2 details Figure 4.1-1 and aids in understanding the steps followed from raw sources to the final results.

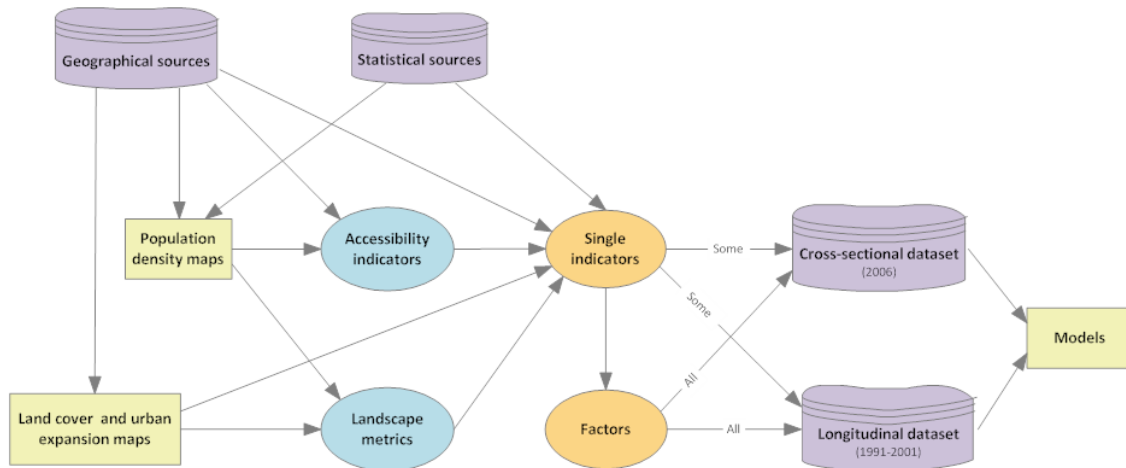


Figure 4.1-2: Raw sources, intermediate results, datasets and final results. Results are shown in rectangles, variables in ellipses, and the remainder figures are datasets.

4.2 The human ecosystem framework

Theoretical constructs of sustainability presented throughout section 2.4 were worked, integrated, and adapted to the scale and issues of the urban phenomena. The resulting conceptual framework – the human ecosystem framework (after Machlis & Force, 1997) – represents the rationale for urban sustainability developed in this thesis and used as the theoretical basis for data analysis. This practical dimension resides in the capacity of the framework to aid in model building, functioning as a source to derive indicators while ensuring the theoretical consistency of the task.

The framework is rooted in several inspirational contributions. The hierarchical sustainability pyramid proposed by Daly (1973) and Meadows (1998) is of central importance. It is based on the capital approach to sustainability and connects the *ultimate means* (natural resources) to society's *ultimate ends* (happiness, enlightenment, etc.). The pyramid evidences the complementary importance of the different types of capital and reminds people that the economy is not itself an end but a way to achieve something more important. Moreover, the fact that the natural resources rest at the base of the pyramid stresses the fundamental supportive role of nature for the Earth ecosystem. The work of Amartya Sen (1999/2003) played an essential role in the conceptualization of human capabilities. Likewise, the notions of *human needs*, *human values* and *political options* (Alkire, 2002) have been incorporated, which

act in a complex way as forces directing societal evolution. It is presumed that, individually, people behave so as to maximize the satisfaction of their needs in the context of a large set of values; collectively, societies manifest preferences through political options. Bossel's (2000) theory of system orientators may be considered an extension of the theory of human needs since it is, in principle, applicable to any given system. *Institutions*, understood as the conventions, norms and formally sanctioned rules of a society, were considered as resources because of their role in providing expectations, stability and meaning essential to human existence and coordination (e.g., Bromley, 2006; Vatn, 2005). The framework addresses the concepts of *ecosystem services* and *processes* globally disseminated by MEA (2005). They acknowledge the flow of intangible benefits to human beings and other species beyond the physical resources *stricto sensu*. Recognizing the multiple service flows coming from nature is an essential step in their proper valuation, which in turn is a condition for the conservation of ecosystems. A related and more tangible concept is that of the metabolism of society, which refers to the flow of materials and energy between society and nature (Fischer-Kowalski & Weisz, 1999). These flows, in turn, originate impacts on the quality of life of individuals and on the ecosystems. The DPSIR framework, which provides an interpretative structure to such causal chains (Stanners, et al., 2007; cf. section 2.7), is embedded in the human ecosystem model. However, the perspective endorsed here is different: while DPSIR presumes that all dynamics are detrimental to sustainability, the human ecosystem framework assumes a neutral point of view by describing all the relevant sustainability domains and their interactions, regardless of being beneficial or detrimental to sustainable development. The result is shown in Figure 4.2-1.

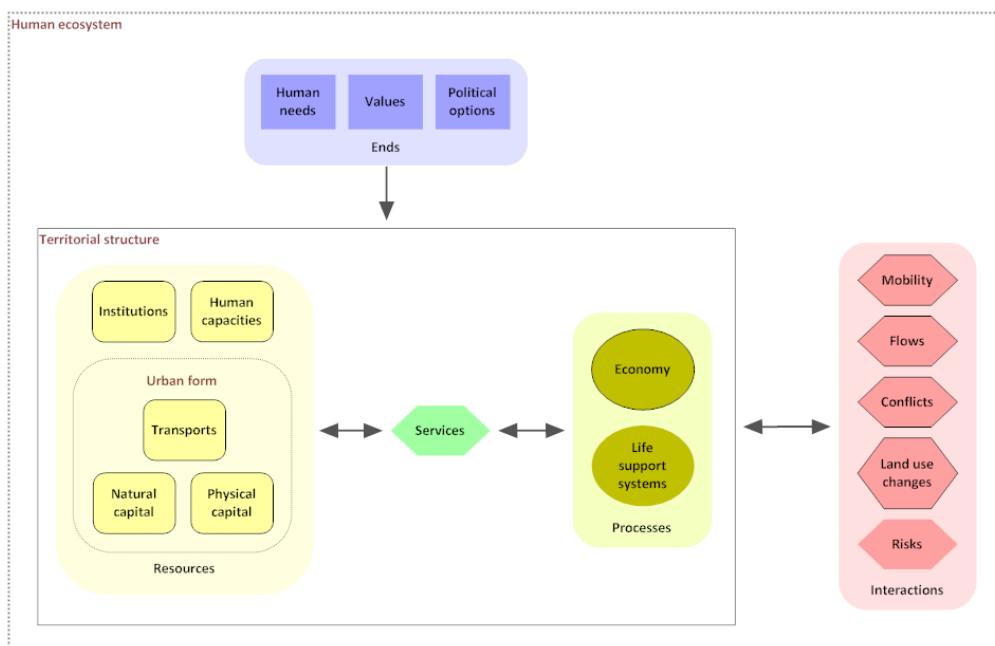


Figure 4.2-1: The human ecosystem framework used for data analysis in this thesis.

The framework has both a theoretical and practical dimension. As theory, it provides a conceptual structure that accounts (a) for human-nature interactions; (b) for the societal evolution towards biological and cultural ends; (c) for the metabolism of human ecosystem; and (d) for some cause-effect relationships between driving forces and impacts. The framework explicitly recognizes the main urban sustainability dimensions and the relationships and dependencies between them. *Resources* represent the basic assets for system functioning. *Processes* use or transform those resources and generate *services* that capitalize or consume them (for instance, research builds on existing knowledge, which tends to accumulate; education increases human capabilities; on the contrary, many firms require the direct input of natural resources, which are consumed and transformed by the manufacturing processes). *Interactions* represent observable consequences of system's metabolism. They usually have a deteriorating impact on resources (e.g., pollution, criminality), but their influence can also be ambiguous (land conversion for new housing has a negative impact on the environment, but may have a positive impact on the incomer's quality of life). *Ends* translate the preferences of societies and the needs of both human and natural systems. Ends incorporate a portion of variable desires and options (striving for equality among humans, for instance) and a portion of inevitable constraints imposed by the laws of nature (e.g., complex life can subsist only under very restrictive conditions that must be continuously maintained).

4.3 Study area, scale of analysis and temporal dimension

The study area is the *Metropolitan Area of Porto*¹¹. Located in Northern Portugal and extending over 814 km², the metropolitan area comprises nine municipalities and was inhabited in 2006 by an estimated 1,28 million people, which makes it the second largest in Portugal. It is also a highly industrialized region, where the headquarters of many important companies are located in sectors like textiles, shoes, furniture, auto parts, jewellery, chemical and steel, etc. In the scientific arena, the region is home to several universities, including the University of Porto and the Catholic University. The University of Porto is the largest university in Portugal, with over 27000 students, 60 undergraduate degrees, 120 MSc's and over 100 PhD programs. At the center of the metropolis lies the city of Porto, which is also the capital city of the North region. Porto concentrates a great share of the metropolis population (almost 20%) and a disproportionate part of administrative and cultural services.

¹¹ *Metropolitan Area of Porto*, in the sense used in this thesis, corresponds to the geographical territory of the metropolis before its enlargement in 2005 and 2008. It also corresponds to the NUTS3 subregion *Metropolitan Area of Porto*.

The scale of analysis of this thesis is the *borough*¹². Boroughs are small territories ruled by local authorities directly elected by the people, although with rather limited powers. Each municipality is subdivided into one, and usually more, boroughs. There are a total of 130 boroughs in the Metropolitan Area of Porto (cf. annex A.5 for the name and location of each borough). All results and conclusions of this thesis are valid only at the borough level, complementing other research designs carried out at scales such as the national, regional, or individual.

Study area: Metropolitan Area of Porto

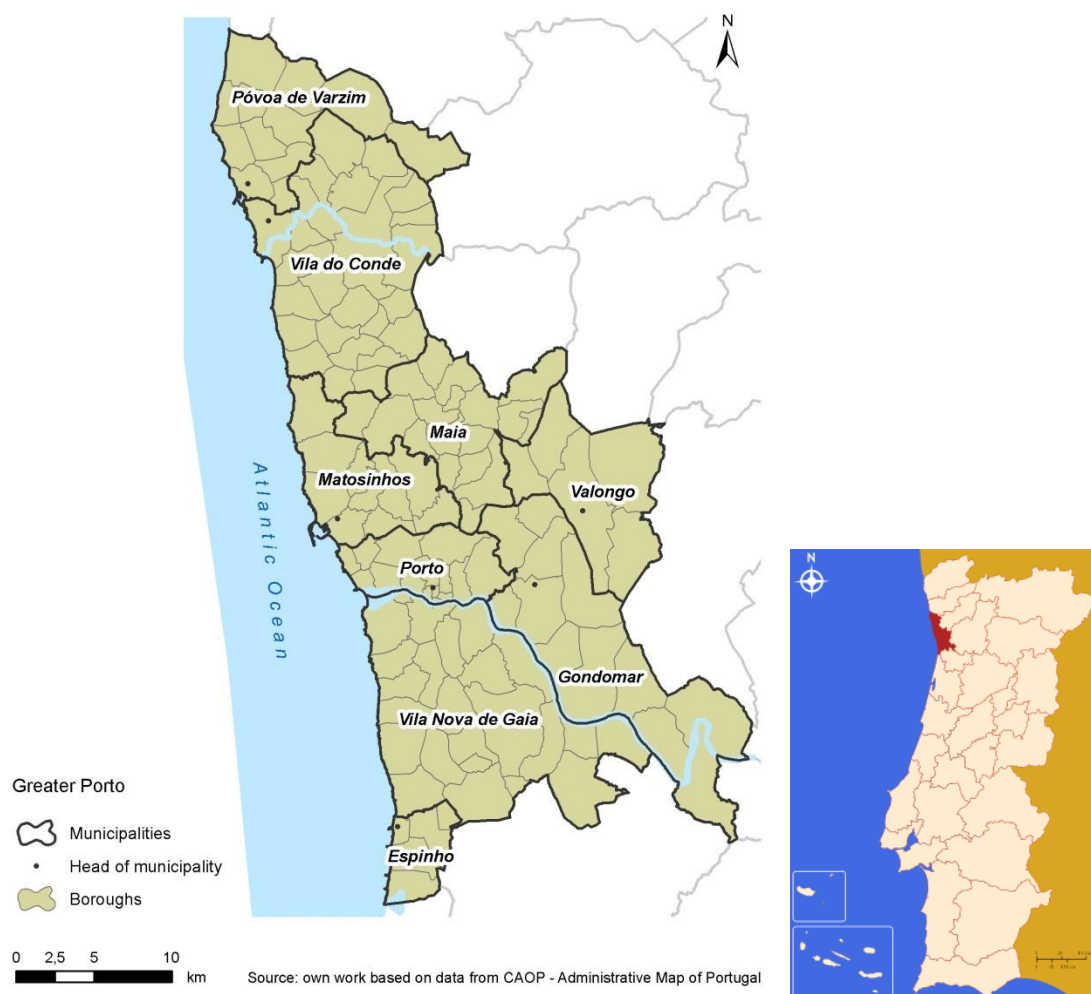


Figure 4.3-1: Location of the Metropolitan Area of Porto in Portugal. Source of the right image: Wikipedia.

¹² Borough was used as a translation for *freguesia* (in Portuguese) was *borough*. Other possibility would be *civil parish*.

Regarding the temporal dimension, this thesis aims at strengthening existing research by adding a longitudinal dimension. Panel data models are more effective than their cross-sectional counterparts in identifying causal relationships. Hence, and taking as a basis the decennial population census from where a large amount of data is readily available, data were gathered for the years 1991 and 2001. The year 2007, though not corresponding to any census, was added to provide for a more recent picture of the region. During the development of this work, different time spans were used depending on the data available for each particular analysis. Given the ambition, lack of data were inevitable and in some cases required the mixture of different years (e.g., using a variable from 2008 on a study involving the 2001 time period) in order to avoid missing important information. However, this was made to a limited extent and only when there were reasons to believe that results would still be accurate (for instance, when the variance and covariance structure of a set of variables was maintained).

4.4 Data collection (raw data)

The research design used in this thesis required data for each of the 130 boroughs (times the number of indicators and times the number of periods, limited by availability). A great effort was put in collecting ignored explanatory or confounding variables, thus setting the conditions for more accurate statistical models.

Raw data were used in a variety of computations to derive indicators. Some variables, such as population counts and urban fabric area, were often used to calculate normalized indicators. Instead of describing all the raw variables used, I preferred to avoid inevitable duplications and concentrate on the resulting indicators as described in the section 4.5. A table with the data sources from where raw variables were directly queried or calculated can be consulted in the annex A.4.

4.4.1 Cartographic datasets

Given the importance of cartographic datasets for this thesis, essential information about each of them is provided in Table 4.4-I.

Table 4.4-1: Additional information about the cartographic datasets.

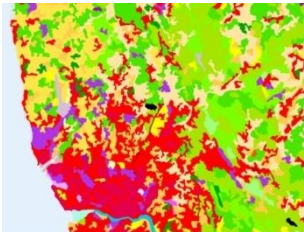
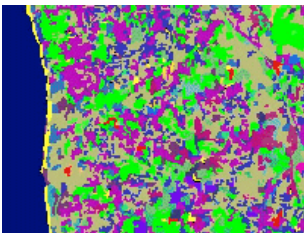
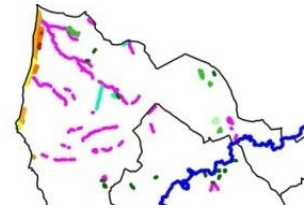
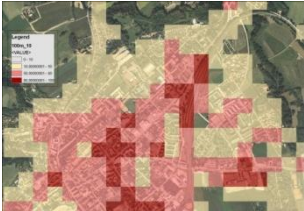
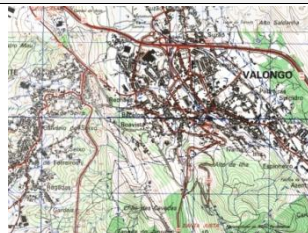
Dataset	Description	Characteristics	Image example
Corine Land Cover	Land use and land cover data comparable across the European Union and some Central and Eastern Europe countries	1:100000 Vector or raster Minimum mapping unit = 25 ha (or 5 ha for land cover changes) 44 classes	
COS – Land use map	Land use and land cover data for Portugal	1:25000 Vector or printed Minimum mapping unit = 1 ha Complex but very detailed classification	
Metropolitan Area of Porto ecological structure	Ecological land cover, including native vegetation and areas with ecological (REN) or agricultural protection status (RAN)	1:25000 Vector	
Orthophotographs	Orthophotographs	1:5000 Raster	
Orthophotographs	Orthophotographs (from Google Maps)	High resolution Raster	
Soil sealing	Map of built-up areas and the degree of soil sealing	Raster Pixel = 20 m Average soil sealing in%	
Satellite images	(See below for detailed information)		

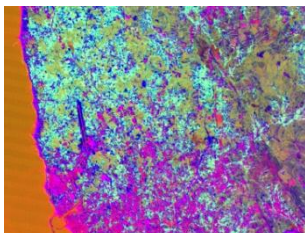
Table 4.4-1 (continued)

Dataset	Description	Characteristics	Image example
Topographic maps – series M888	Topographic map of Portugal and the most detailed covering the whole country.	1:25000 Vector, raster or printed	

4.4.2 Satellite images

The absence of detailed land cover data (appropriate for studies at the borough level) led me to develop specific land use maps of the region based on several data sources. For instance, some boroughs in the Metropolitan Area of Porto are just a few km wide, rendering the 1:100000 scale and minimum mapping unit of 25 ha of the Corine Land Cover useless; and the medium scale COS – Land use map – is available only for 1990. Seventeen years later, efforts are underway to complete the 2007 update, a considerable interval given the huge need for up-to-date cartographic information by a variety of public and private institutions. As this thesis concentrates on urban issues, a new map that could overcome the problems of other datasets was therefore needed. Several satellite images freely available from the Image 2000 and Image 2006 projects (affiliated to Corine Land Cover) fulfilled all the requirements. Detailed characteristics about the satellites and their images are provided in Table 4.4-2 and Table 4.4-3.

Table 4.4-2: Characteristics of the satellite images used.

Satellite	Landsat 5	Landsat 7	IRS-P6
Date*	~1987	2000	2006
Sensor	TM	ETM	LISS III
Bands	6 + 1	7 + 1	4
Pixel resolution	50 m	25 m	23 m
Example image			

* Refers to the specific dates used in this thesis.

Table 4.4-3: Data sources from where raw variables were queried or calculated.

Band no.	Region	Wavelength	Landsat TM resolution	Landsat ETM+ resolution	IRS-P6 LISS III resolution
1	Blue	0,45–0,515 μm	30 m	30 m	
2	Green	0,525–0,605 μm	30 m	30 m	23 m
3	Red	0,63–0,69 μm	30 m	30 m	23 m
4	NIR	0,75–0,90 μm	30 m	30 m	23 m
5	MIR	1,55–1,75 μm	30 m	30 m	23 m
6	TIR	10,4–12,5 μm	120 m	60 m	
7	MIR	2,09–2,35 μm	30 m	30 m	
8	Pancromatic band	0,52–0,9 μm		15 m	

Processing of satellite images to obtain land cover maps is explained in the next section.

4.5 Data processing (indicators)

Taking the human ecosystem framework as a basis and the knowledge acquired from section 2.7 (“Sustainability indicators”), a number of variables was assembled that were important to understand urban sustainability and explain specific dimensions such as mobility patterns, consumption of water and electricity, urban growth, and criminality. Raw variables were processed to derive indicators, which were organized according to the Table 4.5-1 (cf. Figure 4.2-1 as well). Table 4.5-2 presents all indicators used and provides details about their designations, formulas, scales, dates and correspondence to data sources. Additional explanations are given thereafter for those indicators whose computation required a more laborious calculus.

Table 4.5-1: Hierarchical organization of the indicators.

Resources	Resources
Human capabilities	Urban form
Population dynamics	Natural capital
Equity	Density and sprawl
Wealth	Infrastructure
Employment	Equipments and buildings
Health	Transports
Education	
Social capital	
Processes	Interactions
Economy	Flows
Economic activity	Water
Trade and services	Electricity
Manufacturing and construction	
Agriculture	Conflicts
Economic diversity	Crimes against people
Real estate market	Pedestrian crashes
	Mobility
	Air quality
	Modal share
	Travel time and distance
	Land use changes
	Urban expansion

Table 4.5-2: Set of indicators calculated.

Indicator ¹	Formula ²	Scale, units and remarks ³	Date ⁴	Data source ⁵
Resources				
Human capabilities				
<u>Population dynamics</u>				
Aging	Inhabitants > 65 yo ÷ inhabitants < 14 yo × 100	Ratio	2001, 1991	Census
Birth rate	Births ÷ inhabitants × 1000	Ratio; Per year	Av. 2001–2006, av. 1995–2000	Census
Dwelling occupancy	Population ÷ occupied dwellings	Ratio	2001, 1991	Census
Family size	Population ÷ families	Ratio	2001, 1991	Census
Lone person households	Lone person families ÷ families × 100	Ratio	2001, 1991	Census
Old age dependency	Inhabitants > 65 yo ÷ inhabitants 15 < yo < 64 × 100	Ratio	2001, 1991	Census
Young age dependency	Inhabitants < 14 yo ÷ inhabitants 15 < yo < 64 × 100	Ratio	2001, 1991	Census
<u>Equity and diversity</u>				
Female-male illiteracy ratio	Female illiteracy rate ÷ male illiteracy rate	Ratio	2001, 1991	Census
Female-male unemployment ratio	Female unemployment rate ÷ male unemployment rate	Ratio	2006, 2001, 1991	SS (2006); Census (2001, 1991)
Resident's job diversity	See entry below "Diversity indices"	Ratio	2001, 1991	Census
<u>Wealth</u>				
Home acquisition costs		Ratio – Euros; Per month	2001	Census

Table 4.5-2 (continued)

Indicator ¹	Formula ²	Scale, units and remarks ³	Date ⁴	Data source ⁵
Income support	Beneficiaries of means-tested income support ÷ families × 100	Ratio –%; 2007: proportion of families 2001: proportion of inhabitants	2007, 2001, 1991	SS (2007); Census (2001, 1991)
Wage		Ratio – Euros	2008	SS
<u>Employment</u>				
Unemployment rate	Unemployed inhabitants ÷ labour force × 100	Ratio –%	2008, 2001, 1991	SS (2008); Census (2001, 1991)
<u>Health</u>				
Child mortality	Deaths < 1 yo ÷ live births × 1000	Ratio	Av. 2001–1995, av. 1996–2000	Census
Medical leaves	Medical leave days ÷ labour force	Ratio; Per year	2007	SS
<u>Education</u>				
Higher education	Inhabitants with higher education ÷ population × 100	Ratio –%	2001, 1991	Census
Illiteracy	Illiterate inhabitants ÷ population × 100	Ratio –%	2001, 1991	Census
School desistance	Inhabitants 10 < yo < 15 that haven't completed the 9 th educational year and are not attending school ÷ Inhabitants 10 < yo < 15 × 100	Ratio –%	2001, 1991	Census
Secondary education	Inhabitants with secondary education ÷ population × 100	Ratio –%	2001, 1991	Census
Students	Inhabitants attending school ÷ population × 100	Ratio –%	2001, 1991	Census
<u>Social capital</u>				
Abstention	Eligible voters that do not go to vote ÷ eligible voters × 100	Ratio –%	2005, 2001, 1997	CNE

Table 4.5-2 (continued)

Indicator ¹	Formula ²	Scale, units and remarks ³	Date ⁴	Data source ⁵
Volunteering	Registered volunteers ÷ population × 1000	Ratio; Not used	2008	Entrajuda
Youth NGOs	Youth NGOs ÷ inhabitants 5 < yo < 19 × 10000	Ratio	2008	IPJ
Urban form				
<u>Natural capital</u>				
Ecological status	Area under ecological protection (REN) ÷ nonurban fabric area × 100	Ratio –%	2007, 2000	CIBIO
Forest area	See below entry "Land cover classification"	Ratio – ha	2006, 2000, 1990	Satellite
Forest proportion	Forest area ÷ terrestrial area × 100	Ratio –%	2006, 2000, 1990	Satellite
Forest proportion – non urbanized	Forest area ÷ nonurban fabric area × 100	Ratio –%	2006, 2000, 1990	Satellite
Native forest proportion	Native forests ÷ forest area × 100	Ratio –%	2004	CIBIO
<u>Density and sprawl</u>				
Building net density	Buildings ÷ urban fabric area	Ratio – No. / ha	2006, 2001, 1991	Census
Compactness	See below entry "Landscape metrics"	Ratio	2006, 2001, 1991	Satellite
Dwellings per building	Dwellings ÷ buildings	Ratio	2007, 2001, 1991	Census
Gini index	See below entry "Landscape metrics"	Ratio	2006, 2001, 1991	Satellite
Moran's I	See below entry "Landscape metrics"	Ratio	2006, 2001, 1991	Satellite
New buildings	(Buildings in t ₂ – buildings in t ₁) ÷ terrestrial area × 100	Ratio – No. / ha	2002–2007, 1995–2001	Census
New dwellings	(Dwellings in t ₂ – dwellings in t ₁) ÷ terrestrial area × 100	Ratio – No. / ha	2002–2006, 1991–2001	Census

Table 4.5-2 (continued)

Indicator ¹	Formula ²	Scale, units and remarks ³	Date ⁴	Data source ⁵
Population	See below entry "Population estimates" for the estimate of population in 2006	Ratio	2006, 2001, 1991	Census
Population density	Population ÷ terrestrial area	Ratio – No. / ha	2001, 1991	Census
Population net density	Population ÷ urban fabric area	Ratio – No. / ha	2006, 2001, 1991	Census
Standard distance ratio	See below entry "Landscape metrics"	Ratio	2006, 2001, 1991	Satellite
Urban fabric area	See below entry "Land cover classification"	Ratio – ha	2006, 2000, 1990	Satellite
Urban fabric proportion	Urban fabric area ÷ terrestrial area × 100	Ratio –%	2006, 2000, 1990	Satellite
Urban patches	See below entry "Landscape metrics"	Ratio	2006, 2000, 1990	Satellite
Urban patch average area	Urban fabric area ÷ urban patches	Ratio – ha	2006, 2000, 1990	Satellite
Urban patch density	Urban patches ÷ terrestrial area	Ratio – No. / km ²	2006, 2000, 1990	Satellite
<u>Infrastructure</u>				
Waste collection provision	Buildings with waste collection ÷ buildings × 100	Ratio –%	2001	Census
Bus lane density	Length of bus lanes ÷ urban fabric area	Ratio – m / ha	2008	STCP
Drinking water provision	Dwellings with drinking water ÷ dwellings × 100	Ratio –%	2001, 1991	Census
Sewerage system provision	Dwellings with sewerage system ÷ dwellings × 100	Ratio –%	2001, 1991	Census
Highway node distance	See below entry "Accessibility indicators"	Ratio – m	2007, 2001, 1991	Google, IFAP
Road density	Length of the road network ÷ urban fabric area	Ratio – m / ha	1997	IGeoE
<u>Equipments and housing</u>				
Building age		Ratio – years	2001, 1991	Census

Table 4.5-2 (continued)

Indicator ¹	Formula ²	Scale, units and remarks ³	Date ⁴	Data source ⁵
Damaged buildings	Damaged buildings ÷ buildings × 100	Ratio –%	2001, 1991	Census
Green space area	Green space area ÷ population	Ratio – m ² ; Green spaces > 1500 m ²	2007, 2001, 1991	Google, IFAP
Green space density	Green space area ÷ urban fabric area	Ratio – m ² / ha; Green spaces > 1500 m ²	2007, 2001, 1991	Google, IFAP
Green space distance	See below entry “Accessibility indicators”	Ratio – m; Green spaces > 1500 m ²	2007, 2001, 1991	Google, IFAP
Healthcare distance	See below entry “Accessibility indicators”	Ratio – m	2007	ARS
Junior school distance	See below entry “Accessibility indicators”	Ratio – m; Only public schools	2007	GEPE
Kindergarten distance	See below entry “Accessibility indicators”	Ratio – m; Only public schools	2007	GEPE
Nonconventional dwellings proportion	Nonconventional dwellings ÷ dwellings × 100	Ratio –%	2001, 1991	Census
Pedestrian routes density	Length of pedestrian routes ÷ urban fabric area	Ratio – m / ha; Not used	2007	ESB
Primary school distance	See below entry “Accessibility indicators”	Ratio – m; Only public schools	2007	GEPE
Secondary school distance	See below entry “Accessibility indicators”	Ratio – m; Only public schools	2007	GEPE
Sports facilities	Sports facilities ÷ population × 10000	Ratio; Only public facilities	2002	Inventories
<u>Transportation</u>				
Bus net density	Length of bus routes ÷ urban fabric area	Ratio – m / ha	2008, 2001	STCP, Bus
Bus stop distance	See below entry “Accessibility indicators”	Ratio – m	2008, 2001	STCP
Car ownership		Ordinal – %; Not used	2000	Mobility
Metro stop distance	See below entry “Accessibility indicators”	Ratio – m	2007	Metro
STCP stop distance	See below entry “Accessibility indicators”	Ratio – m	2008, 2001	STCP

Table 4.5-2 (continued)

Indicator ¹	Formula ²	Scale, units and remarks ³	Date ⁴	Data source ⁵
Train stop distance	See below entry “Accessibility indicators”	Ratio – m	2007, 2001, 1991	Google, IFAP
Processes				
Economy⁶				
<u>Economic activity</u>				
Companies		Ratio	2003	FUE
Companies net density	Companies ÷ urban fabric area	Ratio – No. / ha	2003	FUE
Job net density	Jobs ÷ urban fabric area	Ratio – No. / ha Public sector jobs are excluded	2005	FUE
Jobs		Ratio; Public sector jobs are excluded	2005	FUE
Jobs to labour force ratio	Jobs ÷ labour force	Ratio; Public sector jobs are excluded	2005	FUE
<u>Trade and services</u>				
H & R establishments		Ratio; Includes companies and individual enterprises	2006	FUE
H & R establishments net density	H & R ÷ urban fabric area	Ratio – No. / ha; Includes companies and individual enterprises	2006	FUE
Street trade establishments		Ratio; Includes companies and individual enterprises	2005	FUE
Street trade establishments net density	Street trade ÷ urban fabric area	Ratio – No. / ha; Includes companies and individual enterprises	2005	FUE
T & S companies		Ratio	2003	FUE

Table 4.5-2 (continued)

Indicator ¹	Formula ²	Scale, units and remarks ³	Date ⁴	Data source ⁵
T & S companies net density	T & S companies ÷ urban fabric area	Ratio – No. / ha	2003	FUE
T & S job net density	T & S jobs ÷ urban fabric area	Ratio – No. / ha	2005	FUE
T & S jobs		Ratio	2005	FUE
T & S location quotient	See below entry "Economic indicators"	Ratio; 2003: societies; 2005: jobs	2005, 2003	FUE
<u>Manufacturing and construction</u>				
Construction location quotient	See below entry "Economic indicators"	Ratio; 2003: societies; 2005: jobs	2005, 2003	FUE
M & C companies		Ratio	2003	FUE
M & C companies net density	M & C companies ÷ urban fabric area	Ratio – No. / ha	2003	FUE
M & C jobs		Ratio	2005	FUE
M & C jobs net density	M & C jobs ÷ urban fabric area	Ratio – No. / ha	2005	FUE
Manufacturing location quotient	See below entry "Economic indicators"	Ratio; 2003: societies; 2005: jobs	2005, 2003	FUE
<u>Agriculture and fisheries</u>				
A & F job density	A & F jobs ÷ terrestrial area × 1000	Ratio – No. / ha	2001, 1991	Census
A & F jobs		Ratio	2001, 1991	Census
A & F labour force		Ratio	1999, 1989	AC
A & F labour force density	A & F labour force ÷ terrestrial area × 1000	Ratio – No. / ha	1999, 1989	AC
Kitchen gardens	Kitchen gardens ÷ utilised agricultural area × 1000	Ratio – No. / ha; Not used	1999, 1989	AC
Utilised agricultural area		Ratio – ha	1999, 1989	AC
UAA proportion	Utilised agricultural area ÷ terrestrial area × 100	Ratio –%	1999, 1989	AC

Table 4.5-2 (continued)

Indicator ¹	Formula ²	Scale, units and remarks ³	Date ⁴	Data source ⁵
<u>Economic diversity</u>				
Economic diversity	See entry below "Diversity indices"	Ratio; 2003: societies; 2005: jobs	2005, 2003	FUE
Office and residential buildings proportion	Office and residential buildings ÷ buildings × 100	Ratio –%	2001, 1991	Census
<u>Real estate market</u>				
Occupied dwellings proportion	Occupied dwellings ÷ dwellings × 100	Ratio –%	2001, 1991	Census
Restored buildings proportion	Restored buildings ÷ dwellings × 100	Ratio –%	Av, 2002–2007, av. 1995–2001	Census
Seasonally vacant dwellings proportion	Seasonally vacant dwellings ÷ dwellings × 100	Ratio –%	2001, 1991	Census
Urban expansion area available proportion	Urban expansion area available ÷ terrestrial area × 100	Ratio –%	2000	SNIT
Vacant dwellings proportion	Vacant dwellings ÷ dwellings × 100	Ratio –%	2001, 1991	Census
Interactions				
Flows				
Electricity consumption <i>per capita</i>	Electricity consumption ÷ corrected consumers × dwelling occupancy Corrected consumers = families × (Occupied dwellings proportion + Seasonally vacant dwellings proportion ÷ 2 + Vacant dwellings proportion ÷ 6)	Ratio – kWh; Per year; Unavailable for the municipality of Porto	2008	EDP

Table 4.5-2 (continued)

Indicator ¹	Formula ²	Scale, units and remarks ³	Date ⁴	Data source ⁵
Water consumption <i>per capita</i>	Water consumption ÷ corrected consumers × dwelling occupancy Corrected consumers = Consumers × (Occupied dwellings proportion + Seasonally vacant dwellings proportion ÷ 2 + Vacant dwellings proportion ÷ 6)	Ratio – m ³ ; Per year; Available only for the municipalities of Espinho, Maia, Matosinhos and Porto	2007	Water
Conflicts				
Crimes against people <i>per capita</i>	Crimes against people	Ratio; Per year; Unavailable for Espinho	2007	PSP, GNR
Pedestrian crashes <i>per capita</i>	Pedestrian crashes ÷ population × 10000	Ratio; Per year; Only pedestrian crashes with deaths or serious injuries	Av. 2001–2006	ANSR
Mobility				
<u>Air quality</u>				
Air quality index		Interval; 1 = Very good; 2 = Good; 3 = Fair; 4 = Weak; 5 = Bad; Not used Data results from an air quality model	2006	UFP
<u>Modal share</u>				
Modal share: PT		Ratio –%; Only home-work trips	2001, 1991	Census
Modal share: Car		Ratio –%; Only home-work trips	2001, 1991	Census
Modal share: 2 wheels		Ratio –%; Only home-work trips	2001, 1991	Census
Modal share: Foot		Ratio –%; Only home-work trips	2001, 1991	Census
Pass	Inhabitants with a transport pass ÷ population × 100	Ratio –%; Not used	2001	STCP

Travel time and distance

Trip time	Ratio – min; Only home-work trips	2001, 1991	Census

Land use changes

Urban expansion	(Urban fabric area in t_2 – Urban fabric area in t_1) ÷ terrestrial area × 100	Ratio –%	2000–2006, 1990–2000	Satellite

Other variables**Geographic positioning**

Distance to the head of municipality	See below entry “Accessibility indicators”	Ratio – m	(Constant)	CAOP
Distance to the head of Porto	See below entry “Accessibility indicators”	Ratio – m	(Constant)	CAOP
Distance to the river Douro	See below entry “Accessibility indicators”	Ratio – m	(Constant)	CAOP
Distance to the sea	See below entry “Accessibility indicators”	Ratio – m	(Constant)	CAOP

A & F: agriculture and fisheries; H & R: hotels and restaurants; T & S: trade and services; UAA: utilized agricultural area; PT: public transports.

¹ Indicator names may differ slightly from the names used in graphs, but their correspondence is unambiguous.

² Variables are evaluated for each borough; some formulas or further explanations are placed elsewhere because of space constraints; blanks were left when the indicator coincides with the raw variable and therefore no computations were made.

³ Scale: ratio, interval, ordinal or categorical; Units: counts are not mentioned.

⁴ Av.: average between all the years in the interval.

⁵ Refer to annex A.4 for data source codes; only primary data sources are mentioned; data sources used as denominators in normalizations are not referred.

⁶ More information about the economic indicators is provided below and in Table 4.5-3.

Information provided in Table 4.5-2 is sufficient to understand how most of the indicators were obtained. However, some of them required more extensive computing. The following sub-sections provide additional explanations about these cases.

4.5.1 Land cover classification

Producing land cover maps

The main goal of processing satellite images was to obtain basic land cover maps for each of the time periods under analysis (1990, 2000 and 2006), i.e., maps containing a broad classification of land cover types. A more detailed classification scheme would require a much more sophisticated procedure than the one employed and additional resources, including fieldwork to choose training sites and to assess classification accuracy. Still, the task was laborious and demanding – some steps requiring a trial and error approach until a satisfactory result was obtained – but it was essential to calculate all land cover indicators shown in Table 4.5-2. Image processing and classification was conducted with the software Idrisi Andes, an increasingly popular and powerful program to work with raster.

Figure 4.5-1 synthesizes the whole procedure. The first step was the concatenation of images coming from different path rows and the reduction of noise through principal components analysis. Visual inspection of the principal components determined the retention of the first four components, the remainder being discardable noise. Then, as is common practice in image classification (see, e.g., Gibson & Power, 2000), unsupervised classification was carried out first to identify the main clusters of values present in the images, and which could in principle be distinguished from each other. Usually the first 10 clusters account for about two-thirds of all pixels and contain all major land cover types. Training sites were defined for most of them in a total of around 20. A maximum likelihood classification was applied thereafter yielding preliminary classified images. Land cover types were then generalized into four broad classes allowing a higher classification accuracy: urban, forests, other pervious surfaces and water. The careful analysis of results and their systematic comparison with orthophotos was very important to understand the behavior of the algorithm and to spot classification problems. The main error was the misclassification of clay barrel tiles and other urban fabric areas as bare soil (nonirrigated arable land) and, in a smaller extent, the opposite. If not corrected, this problem would inflate the urban fabric area especially in rural places. The correction was made resorting to external cartography, which was accepted as reference. Whenever urban areas were misclassified as soil, or vice-versa, pixel classification was changed. Although this procedure introduced some errors because of scale differences (if external cartography was appropriate for the intended use in this thesis then image classification would have been unnecessary at the first place), it is still a definite worthwhile compromise. In addition, pixels

classified as urban in a time period were always considered as such in subsequent periods. Final classified images were obtained after resampling to a pixel of 30 m so that comparisons between different time periods could be performed. The results are shown in the annex A.II.

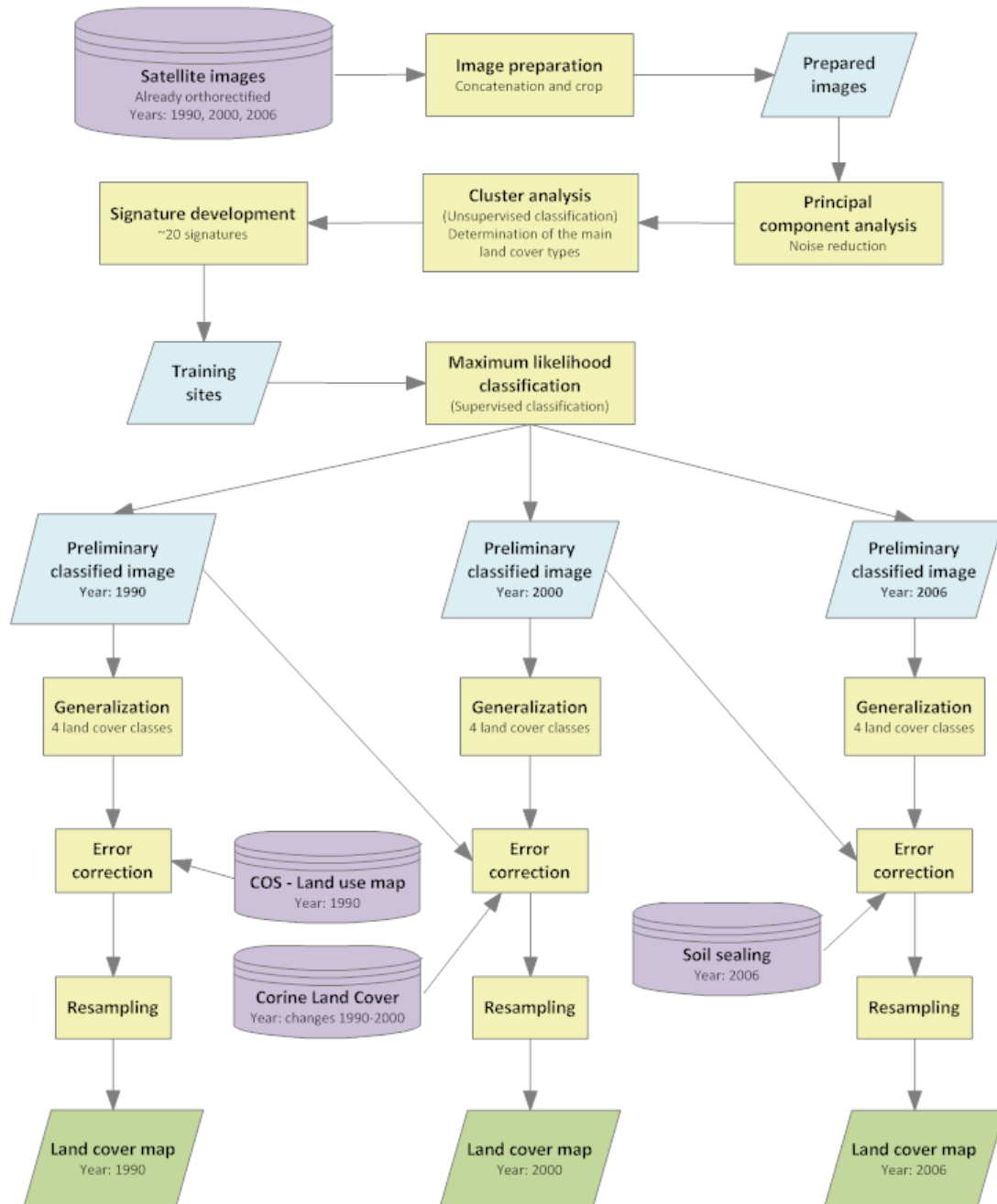


Figure 4.5-I: Processing of satellite images to obtain classified land cover maps.

Producing population density maps

The calculation of area-based indicators at the borough level from thematic land cover maps was straightforward, but a lengthy procedure was necessary to derive an urban fabric map with a very detailed distribution of population that could be used as a source to compute

accessibility indicators. This type of dasymetric maps attempts to circumvent the modifiable areal unit problem and to avoid the so-called ecological fallacy, whereby the use of averaged statistical values mask the diversity inside each unit (Móia, 2006; cf. the work of Silva, 2009b, who developed a fine-grained population density map for the regions West and Tagus valley, in Portugal).

This time ArcGIS 9.3 was preferred given its excellent capabilities to perform a great variety of calculations. ArcGIS' ModelBuilder was particularly useful to automate tasks permitting the fine-tuning of tools' parameters. The first step was the conversion of raster images to thematic vectors (one map for each land cover class). The procedure is represented in Figure 4.5-2 using ModelBuilder's symbology.

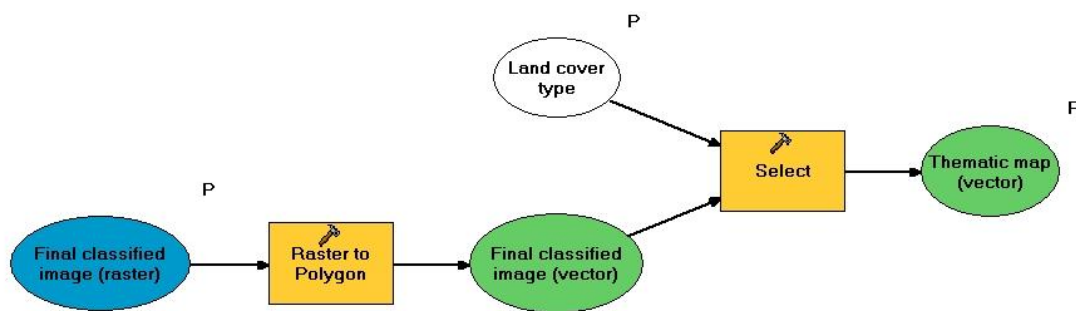


Figure 4.5-2: Conversion of a raster image to a thematic land cover map.

Polygons obtained from the conversion were simplified (radius = 30 m) and aggregated (distance = 50). In addition, small polygons (area < 2400 m²) were discarded and holes were retained only when their size was significant (area > 2400 m²). This procedure, even though altering the results, allowed for smoother and more continuous polygons, avoiding peculiar boundaries and their artificial separation, and eliminated insignificant isolated polygons. The bottom line is that the processed urban fabric is probably a more faithful picture of reality. Lastly, urban fabric polygons were intersected with the distribution of population at the statistical subsection level. See Figure 4.5-3 for the complete procedure.

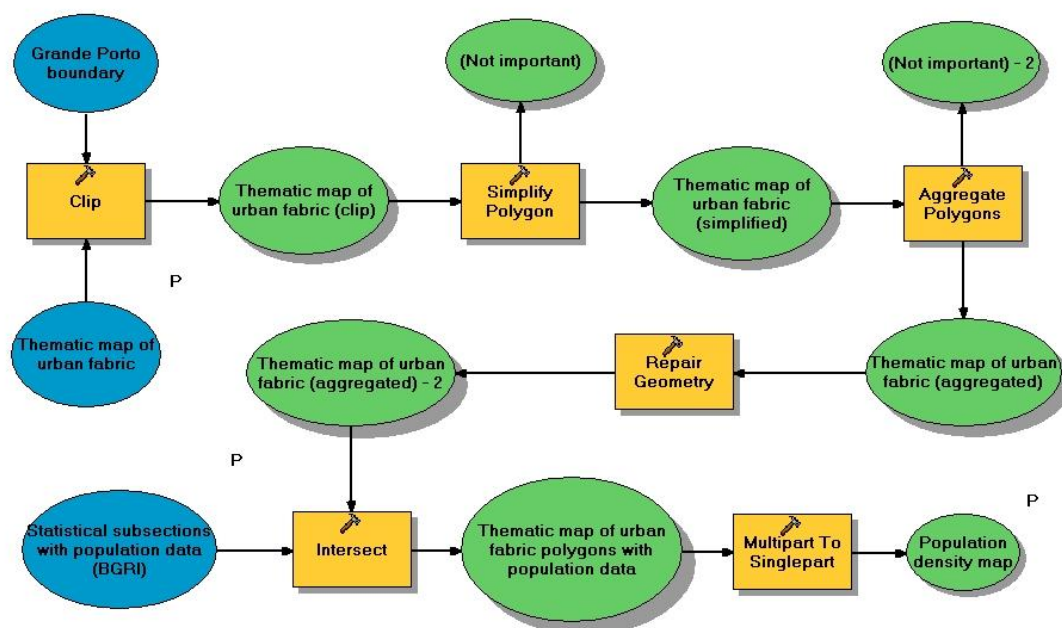


Figure 4.5-3: Generation of a fine grained population density map.

The intersection of both layers (urban fabric polygons and statistical subsections) generated an enormous amount of polygons (Metropolitan Area of Porto is currently subdivided into 11424 subsections; with the intersection, 18545 polygons were created). The population of each subsection was then distributed by the smaller urban polygons resulting from the intersection described above proportionally to their area. The population sum at each subsection therefore remained the same as found in the original dataset (BGRI). A very detailed map of population distribution was obtained at the end.

4.5.2 Accessibility indicators

ESPON Monitoring Committee (2004) and Silva (2009a) were used as theoretical foundations in the selection of accessibility indicators. Accessibility can be defined as “the amount and the diversity of places of activity that can be reached within a given travel time and/or cost” (Bertolini, le Clercq, & Kapoen, 2005, p. 209). All accessibility indicators involving distances were computed with the *Generate near table* toolbox in ArcGIS. As inputs, the population density map and the reference points from where distances ought to be calculated were used. The computer determined the distance from each urban polygon to the nearest point and generated a table with all of them. A weighted mean of distances was subsequently performed to obtain a value for each borough (the weighting factor was the population of each polygon). This procedure allowed for a very precise estimation of the average distance of each borough’s population to public equipments, for instance.

4.5.3 Landscape metrics

The main theoretical sources of landscape metrics were Leitão, Miller, Ahern, & McGarigal (2006), Magalhães, Abreu, Loousã, & Cortez (2007), Mitchell (2005) and Tsai (2005). These indicators were computed using as source the population density maps. A distinction between polygons and patches is necessary for the sake of rigor. A *patch* is a relatively homogeneous nonlinear area that differs from its surroundings (Forman, 1995, as cited in Leitão, et al., 2006). *Polygon* is used in its known geometric sense. Because of intersections between urban fabric areas and population data at the statistical subsection level (cf. above entry “Land cover classification”), an urban mosaic may consist of a large number of polygons. Figure 4.5-4 clarifies the distinction.

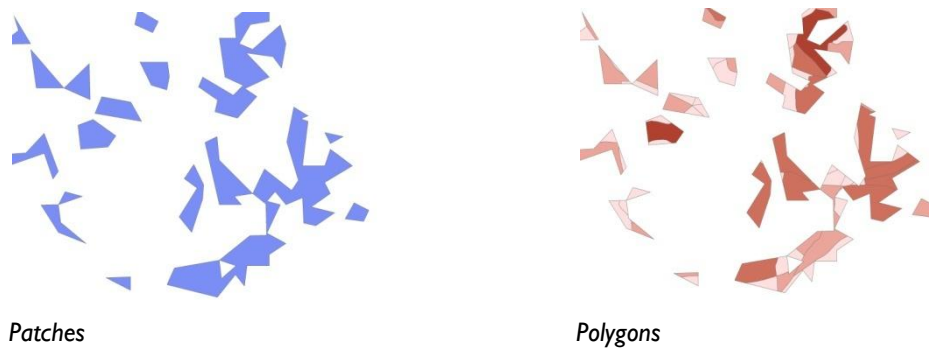


Figure 4.5-4: Each unit on the left figure is an urban patch; the corresponding polygons on the right are colored according to their resident population.

Compactness

Compactness represents the degree of approximation of the actual urban form to the reference form of a circle. It is calculated by dividing the perimeter of a circle whose area is equivalent to the real urban fabric area by the total perimeter of the urban fabric patches:

$$\text{Compactness} = \frac{2 \times \sqrt{\pi \times A}}{P}$$

where A is the urban fabric area in a given borough and P the sum of perimeters of all urban fabric patches. As compactness approaches 1 the urban form becomes increasingly similar to a circle.

Gini index

The Gini index, although more commonly applied to income inequalities, can be applied in other contexts to measure the degree of inequality of a distribution between the subjects under analysis. It is given by the following formula:

$$\text{Gini index} = 0,5 \sum_{i=1}^N X_i - Y_i$$

where N is the number of all polygons, X_i is the proportion of urban area in patch i and Y_i is the proportion of population in patch i (Tsai, 2005). In this sense, the Gini index can be interpreted as measuring the degree to which development is concentrated in a few parts of a borough, regardless of high-density sub-areas being clustered or sparsely scattered (Tsai, 2005). To better understand the index, it is useful to keep in mind that it would maintain its value in the event that the existing urban polygons (and their population) were randomly assorted throughout the territory (i.e., a random pattern of the original territorial structure). In practice, the Gini index approaches 0 for homogeneous distributions of the population across the territory, and approaches 1 as the gradient of population densities increase between urban polygons.

Moran's I

Moran's I was directly calculated by ArcGIS' spatial statistics toolbox and for this reason its computational formula is not presented here¹³. Moran's I measures spatial autocorrelation based on both feature locations and feature values simultaneously. Given a set of urban polygons and the population of each, a high positive value indicates that high-density sub-areas are closely clustered, a value close to zero means random scattering and a negative value represents a "chessboard" pattern of development (Tsai, 2005; see also Figure 4.5-5). However, negative values are seldom encountered.

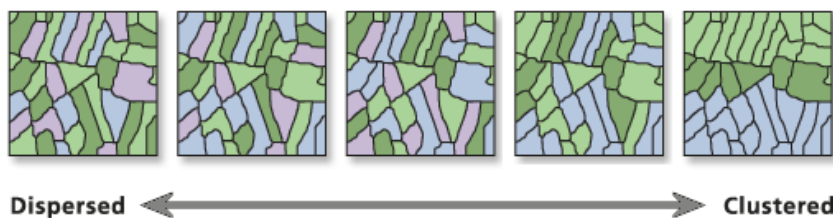


Figure 4.5-5: Moran's I values range from -1,0 (dispersed pattern, on the left) to +1,0 (clustered pattern, on the right). Source: ArcGIS 9.3 support.

¹³ Refer to Mitchell (2005, pp. 121-126) for detailed information.

Besides the Moran's I value, the ArcGIS tool computes a Z score and a p-value evaluating the significance of the index. This is because without looking at statistical significance it is not possible to know if the observed pattern is just one of many possible versions of random. To ensure consistency and accuracy, the Moran's I values used in this thesis were always their respective Z scores.

Standard distance ratio

Another spatial statistic offered by ArcGIS is the *standard distance*. Likewise its standard deviation counterpart, the standard distance provides a single value representing the dispersion of features around their geometrical center (in this thesis, the geometrical center was determined as a weighted mean according to the population of each polygon) (Mitchell, 2005, pp. 39-44). Because it is expected that larger boroughs will have larger standard distances, the values were normalized so that comparisons across different boroughs were meaningful:

$$\text{Standard distance ratio} = \frac{\text{Standard distance}}{\frac{2}{3} \times \frac{A}{\pi}}$$

where A is the total urban fabric area in a given borough. The denominator represents the theoretical radius of a circle whose area is equivalent to the observed urban fabric area. Hence, as the ratio approaches 1, the sprawl of urban polygons is reduced.

4.5.4 Population estimates

Official population counts are carried out every 10 years. In the meantime, INE – Statistics Portugal – releases yearly population estimates at the municipal level based on diverse sources such as the civil and SEF – Aliens and Borders Service – registries. Population estimates at the borough level were computed from the population counts in 2001 assuming that growth trends observed between 1991 and 2001 persisted, and these results were then corrected so that the official estimates for each municipality would be accurate:

$$\text{Population estimate}_{i, 2006} = \text{Biased pop. est.}_{i, 2006} \times \frac{\text{Official population estimate}_{m, 2006}}{\text{Biased phop. est.}_{m, 2006}}$$

where the subscript i denotes the borough and the subscript m refers to the municipality. The *biased population estimate* _{$i, 2006$} is the expected population in 2006 assuming that

population follows an exponential function whose growth rate is given by the growth rate observed in the decade 1991–2001:

$$\text{Biased population estimate}_{i,2006} = \text{Population}_{i,2001} \times \text{growth rate}_{i,1991-2001}^5$$

$$\text{Growth rate}_{i,1991-2001} = \frac{\text{Population}_{i,2001}^{\frac{1}{10}}}{\text{Population}_{i,1991}}$$

These formulas allow more precise population estimates than simply assuming that the proportion of inhabitants in each borough relative to the respective municipality remained unchanged since 2001 (the date of the last census).

4.5.5 Economic indicators

Data concerning economy was obtained from a very large database managed by INE – Statistics Portugal – called FUE – Statistical Units Database. It compiles a variety of information about each statistical unit (companies, organizations, municipalities, public institutes, etc.) including, for the private sector, the number of employees and the annual turnover. Unfortunately, these data is not available for the public sector. The interpretation of indicators must therefore be aware of this limitation. Doubts can be overcome with the aid of Table 4.5-3.

Table 4.5-3: Correspondence between the Classification of Economic Activities and the indicators.

Indicator	Corresponding CAE 2.I codes
Companies (all)	A+B+C+D+E+F+G+H+I+J+K
Jobs (all)	A+B+C+D+E+F+G+H+I+J+K
Construction	F
Manufacturing	C+D+E
Services	J+K
Trade	G+H+I
Hotels and restaurants	No. 551+553+554+555I
Street trade	No. 521+522+523+524+525+527+633+725

Location quotient

Location quotient indicators compare the local economy (the borough, in this thesis) to a reference economy (the Metropolitan Area of Porto region) in order to identify specializations in the local economy. It is computed according to the following formula:

$$\text{Location quotient of sector } i \text{ in borough } j = \frac{a_{i,j} \div a_j}{A_i \div A}$$

where $a_{i,j}$ is the employment in the economic sector i in the borough j , a_j is the total employment in borough j (which corresponds to the variable *Jobs* used in the calculation of the economy factor), A_i is the employment in the economic sector i in Metropolitan Area of Porto, and A is the total employment in the Metropolitan Area of Porto. The results are readily interpretable: a location quotients lower than 1 signifies that the economic sector being analyzed is less concentrated in the local economy than in the region, while location quotients higher than 1 mean that the economic sector being analyzed is more concentrated in the local economy than in the region. A large location quotient indicates local economic specialization. It is noteworthy that the location quotient does not inform about the level of the economic activity. In fact, smaller economies are probably more prone to disparate values of specialization because of the small numbers in the equation above.

4.5.6 Diversity indices

Diversity measures are usually computed by adapting the so-called Shannon's entropy:

$$\text{Shannon's entropy} = - \sum_{i=1}^N (p_i \times \ln p_i)$$

where N is the number of categories and p_i is the proportion of category i members relative to the sum of all members. Details are provided in Table 4.5-4.

A value of 0 indicates maximum specialization. Economic diversity increases with the index value and achieves a maximum when all classes share equal proportions given by $\ln \text{number of classes}$.

Table 4.5-4: Categories used for the determination of diversity indices.

Resident's job professions (<i>i</i>)	Economic sectors (<i>i</i>)
Three classes	Four classes (based on the number of jobs in each economic activity)
Agriculture and fisheries	CAE 2.1 C+D+E: manufacturing
Manufacturing and construction	CAE 2.1 F: construction
Services	CAE 2.1 G+H+I: trade
	CAE 2.1 J+K: services

4.6 Unused and unavailable data

Some of the indicators mentioned in Table 4.5-2 have a remark stating that they were not utilized. They were not entirely removed from this thesis' proposed framework, because, in some cases, data were kindly provided by colleagues, and it would not be ethical to ignore their prompt help. More importantly, those data were discarded because there were good reasons to do so:

- a dependent variable could not be adequately explained by available independent variables (pedestrian crashes);
- data didn't bring relevant additional information (pedestrian routes and kitchen gardens) given other indicators available;
- data were restricted to one time period (car ownership);
- data could not be compared to other existing indicators (modal shares for 2006);
- data did not cover the entire study area (use of transportation pass);
- data were unreliable (registry of volunteers and volunteering activities).

Besides the vast amount of data gathered, some important indicators could not be obtained: car ownership for 1991 and 2006; modal shares for 2006 comparable to the census-derived values for 2001 and 1991; travel times and distances by transportation mode; average wage for 1991 and 2001; economic indicators for 1991, and water consumption for the municipalities whose values are lacking.

4.7 Data screening, reduction and cleaning

The stage of data preparation involved several steps in order to derive, from the large set of original indicators, a smaller number of relevant variables already cleaned from univariate outliers and ready to be used in modeling. Procedures generally follow the recommendations

of statistical textbooks such as Quinn & Keough (2002), Cohen, Cohen, West, & Aiken (2003) and StatSoft (2007). All analyses were performed with the software *Statistica 8*.

4.7.1 Data screening

Screening was performed through a variety of methods, including two- and three-dimensional scatter plots, histograms and correlation matrices. This was a very important step because it promoted acquaintance with data.

4.7.2 Data reduction: factor and reliability analyses

The large number of indicators available surely conveyed redundant information. Aggravated by the curse of dimensionality, an excessive number of input variables in models would most certainly create unnecessary problems. The *curse of dimensionality* generally refers to the exponential increase in computation and the difficulty involved in fitting models, estimating parameters, or optimizing a function when the dimensionality of input is increased (Kohonen Kohonen, 2001).

Factor analysis with principal axis factoring was performed as a way to synthesize data and to determine the number of existing dimensions. Unlike ordinary factor analysis, the aim was to obtain a small number of new variables synthesizing existing indicators. The statistical procedure was carried out in Statistica 8 and followed the recommendations of Costello & Osborne (2005), StatSoft (2007) and Garson (2009). To guarantee theoretical consistency, input indicators were chosen according to the structure of Table 4.5-1 (indicators belonging to human capabilities, territorial structure, and economy were entered separately in different factor analysis). The number of factors was determined through parallel analysis: only those factors with higher than random eigenvalues were retained (Garson, 2009). Hierarchical factors were chosen so that a more realistic structure could be achieved (also, there was no need for orthogonality between factors).

Factors were then separated from this initial structure containing all input variables: each factor became a composite of the variables loading strongly on it. In addition, each factor had to be a construct of a meaningful set of indicators conveying information about a relevant process. To maximize the consistency of the indicators selected for each factor, Cronbach's alpha was calculated (on standardized indicator values). An iterative process readily available in Statistica led to the removal of indicators until excellent ($\alpha > 0,90$) or very good ($\alpha > 0,80$) reliabilities were achieved. The combined use of theory, factor analysis, and Cronbach's alpha ensured both uni-dimensionality and high consistency of the chosen indicators (Garson, 2009; StatSoft, 2007; Yu, 2001).

In order to obtain the values of the new variables, factor analysis was again conducted but a factor at a time and having as inputs the selected subset of indicators belonging to that factor (*i.e.*, the indicators resulting from the procedure described above). Factor loadings are presented in annex A.6. The resulting scores are new variables representing the common variance of constituent indicators, which can be understood as a synthesis of the information they convey. Factor scores were then standardized to facilitate comparability between them. Correspondence between factor scores and the original units of constituent variables is provided in annex A.7. Correspondence between the z scores of single indicators and their real units is given by the standard deviation (see annex A.8).

4.7.3 Final datasets

The final datasets used as inputs in models are:

- a longitudinal dataset covering the years of 1991 and 2001 to study mobility patterns and urban growth (Table 4.7-1);
- a longitudinal geographical dataset covering the years of 1991, 2001 and 2006 to map land cover and land cover changes;
- and a cross-sectional dataset covering the year of 2006 to describe the region and to study water consumption, electricity consumption, crimes against people, pedestrian crashes, air (Table 4.7-2).

Each dataset combines both the factors and single-indicators, which were added whenever they represented important issues not adequately represented in any of the calculated factors.

Table 4.7-1: Factor structure and single indicators used in the longitudinal dataset (2001–1991).

Human capabilities		Urban form		Transports	Economy	Interactions
Education	Aging/Lone househ.	Density	Accessibility	Bus net density*	Economy	Modal share: PT
Higher education	Aging	Building age	Healthcare distance*	Train stop distance*	Companies net density*	Modal share: Car
Illiteracy	Dwelling occupancy	Dwellings per building	Highway distance*		Job net density*	Modal share: Foot
Resident's job diversity	Family size	Moran's I	Junior school distance*		H & R net density*	Trip time
Secondary education	Lone person households	Population density	Secondary school dist*	Economy	Street trade net density*	
School desistance		Population net density	Sports facilities*	Agriculture	T & S companies net dens*	
		Urban patch av. area		A & F jobs	T & S job net density*	
		Urban patch density		A & F job density	Occup. regularity	Urban growth
Income support				A & F labour force	Occupied dwell. prop.*	New dwellings
Students				A & F labour force density	Seasonally vac. dwell.*	New buildings
Unemployment		Dispersion¹⁴	Green space distance	UAA		Urban expansion
Wage*		Gini index		UAA proportion	Economic diversity*	
		Standard distance			Urban expans. area prop.	
		Urban fabric proportion				

Note: variables in the dataset (factors and single-indicators) are shaded; factor names are **shaded and bolded**, and constituent variables appear as regular text.

A & F: agriculture and fisheries; H & R: hotels and restaurants; T & S: trade and services; UAA: utilized agricultural area

* Because of lacking data, these variables are assumed to be constant with time.

¹⁴ The name *dispersion* was preferred instead of *sprawl* because there was no possibility, at this point, to check whether this factor was a good measure of urban sprawl or not.

Table 4.7-2: Factor structure and single indicators used in the cross-sectional dataset (2006).

Human capabilities		Urban form		Transports	Economy		Interactions
Education	Aging/Lone hh.	Density	Accessibility	Bus net dens.	Economy	Agriculture	Air quality
Higher educ.*	Aging*	Building net density	Healthcare distance	Metro stop dist.	Jobs	A & F jobs*	Crimes against people
Illiteracy*	Dwell. occupancy*	Compactness	Highway distance	Train stop dist.	Job net density	A & F job density*	Electricity cons.
Sec. education*	Family size*	Dwell. per building	Junior school dist.		Office resid. build.	A & F lab. force*	Pedestrian crashes
Students*	Lone person hous.*	Moran's I	Kindergarten dist.		H & R	A & F lab. force dens.*	Water cons.
		Population density	Primary school dist.		Street trade	UAA*	
		Pop. net density	Sec. school distance		T & S jobs	UAA proportion*	Urban growth
Abstention	Birth rate	Urban patch av. area	Sports facilities*		T & S. job net dens.		New dwellings
Child mortality	Resid. job divers.*	Dispersion	Basic services		T & S loc. quot.	Occup. regularity	New buildings
Inc. support	Unemployment	Gini index	Drinking water prov.*			Occupied dwell. prop.*	Urban expansion
Wage	Youth NGOs	Standard distance	Sewerage provision*		Economic diversity	Seasonally vac. dwell.*	
		Urban fabric prop.			Urban exp. area		
		Natural capital	Green space distance				
		Forest proportion	Damaged buildings*				
		Forest prop. non urb.	Native forests				

Note: variables in the dataset (factors and single-indicators) are **shaded**; factor names are **shaded and bolded**, and constituent variables appear as regular text.

A & F: agriculture and fisheries; H & R: hotels and restaurants; T & S: trade and services; UAA: utilized agricultural area

* Because of lacking data, the most recent values from 2001 or 2002 were used.

4.8 Data analysis

The last methodological step involved the analysis of data resulting from processing, screening, reduction and cleaning. The analysis was carried out through multiple complementary procedures described in the following topics. The most important results are displayed in chapter 5 whereas supplementary material is provided as annex.

4.8.1 Descriptive statistics

A number of basic descriptive statistics (mean, median, standard deviation, quantiles, percentiles, minimum, and maximum values, skewness, kurtosis) and graphs (histograms, normal probability plots) were computed for each variable. In addition, correlation matrices for all variables in each dataset are provided in annex A.8.

4.8.2 Thematic maps

A number of thematic maps portray the values of the most relevant factors and single-indicators for each borough. ArcGIS 9.3 was used for this purpose. Since factors are z scored, I decided to present all maps in standard deviation units, which also emphasize relative differences across the territorial units.

4.8.3 Population density, land cover, and urban expansion

Maps with four land cover classes resulted from the process described in section 4.5, “Land cover classification.” The same section explains the preparation of detailed population density maps.

A map showing urban expansion areas for the periods 1990–2000 and 2000–2006 was obtained using the *symetrical difference* toolbox of ArcGIS 9.3. For instance, urban expansion between 1990 and 2000 was the spatial difference between the urban land cover in 2000 and in 1990. The resulting layer was cleaned by deleting all small polygons (area < 2400 m²).

4.8.4 Modeling mobility patterns with structural equations

SEM represents a general and flexible technique capable of testing complex causal models, latent constructs and access the resulting model fit (Kline, 2005; Tomarken & Waller, 2004). Unlike multiple regression, whose models are necessarily straightforward and use up all degrees of freedom in the calculation of parameter estimates, in SEM the researcher usually presumes that several parameters are constrained and explicitly models error terms, allowing the test of specific hypothesis and the estimation of model fit. SEM is therefore regarded as a

confirmatory methodology rather than exploratory. Parameter estimation is done comparing the actual covariance matrices representing the relationships between variables and the model-implied covariance matrices (Schumacker & Lomax, 2004; Shipley, 2004).

Although SEM is often referred as *causal modeling*, causal relationships can only be determined when a demanding set of criteria are met (Twisk, 2003). Observational studies such as the one put forth by this thesis do not usually fulfill all of those criteria and, therefore, the issue of causation must be regarded with caution. Still, this work represents an important step towards the establishment of causal relationships because a longitudinal dataset consisting of two time periods was used. The versatility of SEM makes it an increasingly popular method to test longitudinal data, as the interest for latent growth and other longitudinal data models among the SEM community demonstrates (Bollen & Brand, 2008; Tomarken & Waller, 2004).

The potential of SEM is offered at the cost of stricter data and sample size assumptions: in addition to the common multiple regression assumptions, maximum likelihood estimation requires data to be multivariate normal. Moreover, SEM is regarded as a large sample technique, especially when the number of parameters to be estimated is large (Kline, 2005). Methods less sensitive to the normality assumption, such as the *generalized least squares*, usually require very large sample sizes (Shipley, 2004) and are not therefore of practical interest for this thesis. Recently, robust methods of estimation have been developed that correct for the effects of skewness and kurtosis on the maximum likelihood results. These methods provide accurate estimates of standard errors for the parameters and for the model chi-square (Shipley, 2004; Tomarken & Waller, 2004). The most relevant limitation of SEM is the difficulty in modeling nonlinear effects. Although it is possible to add interaction effects similarly to what is done in multiple regression, several problems may arise. Until computer programs start to incorporate easier to use techniques, most research papers involving SEM probably will continue to skip testing for interactions (Tomarken & Waller, 2004). Estimation difficulties and goodness of fit problems obliged me to ignore interactions as well.

Partial least squares was considered as an alternative to SEM, but the often proclaimed advantages in terms of relaxed assumptions about data do not seem to hold in Monte Carlo simulations. In one such study, Goodhue, Lewis, & Thompson (2006) showed that there was no evidence that partial least squares had an advantage in terms of power at small sample size when compared with SEM. Moreover, parameter estimates obtained by SEM were closer to the true values than the estimates obtained by partial least squares.

Procedure and parameters

SEM was performed using the software *EQS 6.1* according to the recommendations of Garson (2009), Kline (2005) and Schumacker & Lomax (2004). Strictly speaking, this thesis employed a hybrid methodology between structural equations and path analysis because the latent

variables used were previously obtained as scores resulting from exploratory factor analysis (cf. section 4.7). As a result, confirmatory factor analysis was not necessary. Maximum likelihood was employed to estimate models. Covariance matrices were analyzed.

The following steps were followed:

1. the distribution of the variables was checked. The only variable significantly kurtotic was economy;
2. the first model was built considering the knowledge in the field and the availability of data. Statistically, the model proposed follows the basic rationale behind the *latent difference score dynamic model* developed by Ferrer & McArdle (2003). This model explicitly addresses the levels of variables at a given period and their change in subsequent periods;
3. the normalized estimate of Mardia's coefficient indicated a significant departure from multivariate normality. EQS output indentified the cases with the largest contribution to multivariate kurtosis, which were considered outliers and removed;
4. goodness of fit statistics indicated that the original structural model was a poor representation of reality;
5. the achievement of a good model required testing for several alternative possibilities. As models with numerous variables become very complex, different configurations – all of them respecting theory – are possible. This stage relied mainly on the chi-square test and on the standardized root mean-square residual as indicators of model fit;
6. after a good theoretical model was developed, modification indices (the Wald test for dropping parameters and the Lagrange test for adding parameters) were analyzed to improve model fit. Literature, however, cautions against ad-hoc modifications not backed up by compelling theory (Garson, 2009; Kline, 2005; Schumacker & Lomax, 2004);
7. a final model was attained when both theory and indices indicated a good fit. Model chi-square, which should not be significant at the 5% level, was particularly relevant (Shipley, 2004, for instance, questioned the scientific foundations of other fit indices; and recently, Chen, Curran, Bollen, Kirby, & Paxton, 2008, has shown that there is no empirical support for the 0,05 cutoff value associated with the root mean square error of approximation).

Variables and cases

The longitudinal dataset in the wide format¹⁵ was used but the variables *education* and *density*, for which both 1991 and 2001 values were available, were changed so that one of their

¹⁵ In the wide format, each row represents one subject, and different observations for the same subject appear in different columns.

observations represented the value in 1991 and the other observation represented the change from 1991 to 2001. The number of cases ($n = 127$) comply with the recommendations of Hoogland and Boomstra (1998), as cited in Shipley (2004). When data is severely nonnormal, they suggest a minimum sample size of five to 10 times the degrees of freedom ($df = 13$). Three models were developed, each having one main dependent variable:

- modal share: car (2001 and 1991);
- modal share: public transports (2001 and 1991);
- modal share: foot (2001 and 1991).

The following variables were also included in the models: education (1991), education change (1991–2001¹⁶), wage (2008), density (1991), density change (1991–2001), economy (2005), accessibility (2001) and bus net density (2008). Other variables were not used because they did not improve significantly the explanatory capacity of models and because their inclusion would create exceedingly complex models requiring very large sample sizes.

Final model

The final basic structural equation model proposed is displayed in Figure 4.8-1 (see also equations below). It is a longitudinal model where different periods are being modeled simultaneously. The rationale behind the model is as follows:

- modal shares in 1991 were explained by a set of variables from that period, while modal shares in 2001 were explained by those same variables and additionally by variables indicating the change from 1991 to 2001. Because of data shortcomings, some variables had to be considered timeless;
- density, accessibility and bus net density (variables concerning the territorial and transportation structure; cf. Figure 4.2-1) at one period were assumed to be a consequence of education so that residential self-selection phenomena could be accounted for. This probably conservative approach is routinely employed in SEM (Abreu e Silva, 2007; Mokhtarian & Cao, 2008; Van Acker, et al., 2007);
- economy, accessibility and bus net density in one period were considered a consequence of density since they adapt or profit from increased human concentrations;
- changes in education (from 1991 to 2001) were understood as a consequence of prior educational, density and accessibility levels, thus accounting for the expected time-related changes and for the changes due to the migration of the young educated persons from the denser boroughs towards accessible and cheaper places in the urban fringe (Instituto

¹⁶ This represents the value in 2001 minus the value in 1991.

Nacional de Estatística - Direcção Regional do Norte, 2004). Changes in density were in addition explained by changes in the educational level, again to account for the self-selection bias;

- residuals from fitting the equations involving modal shares were assumed to covary. This technique was employed to account for the effect of unavailable explanatory variables that were a common cause of the variables being modeled. Specifically, the effect of variables such as car ownership, the ratio of travel time by car to the travel time by public transport, or even historical reasons that help explain modal shares but were unavailable, was controlled so that parameter estimated could be as reliable as possible.

The following equations correspond to the structural model presented in Figure 4.8-I (Note: * indicates a free parameter to be estimated; variances and covariances are not indicated; main dependent variables are the modal shares of car, public transports, and foot):

$$\text{Wage} = *Education (1991) + E4$$

$$\text{Education change (1991–2001)} = *Wage + *Education (1991) + *Density (1991) + *Accessibility + E8$$

$$\text{Economy} = *Education (1991) + *Density (1991) + E11$$

$$\text{Bus net density} = *Education (1991) + *Economy + *Density (1991) + *Accessibility + E12$$

$$\text{Density (1991)} = *Education (1991) + E13$$

$$\text{Density change (1991–2001)} = *Educ. (1991) + *Educ. (1991–2001) + *Density (1991) + *Access. + E14$$

$$\text{Accessibility} = *Education (1991) + *Density (1991) + E15$$

$$\text{DV1 (1991)} = *Wage + *Educ. (1991) + *Economy + *Bus net dens. + *Density (1991) + *Access. + E20$$

$$\text{DV2 (2001)} = *Wage + *Education (1991) + *Education (1991–2001) + *Economy + *Bus net density + *Density (1991) + *Density (1991–2001) + *Accessibility + E21$$

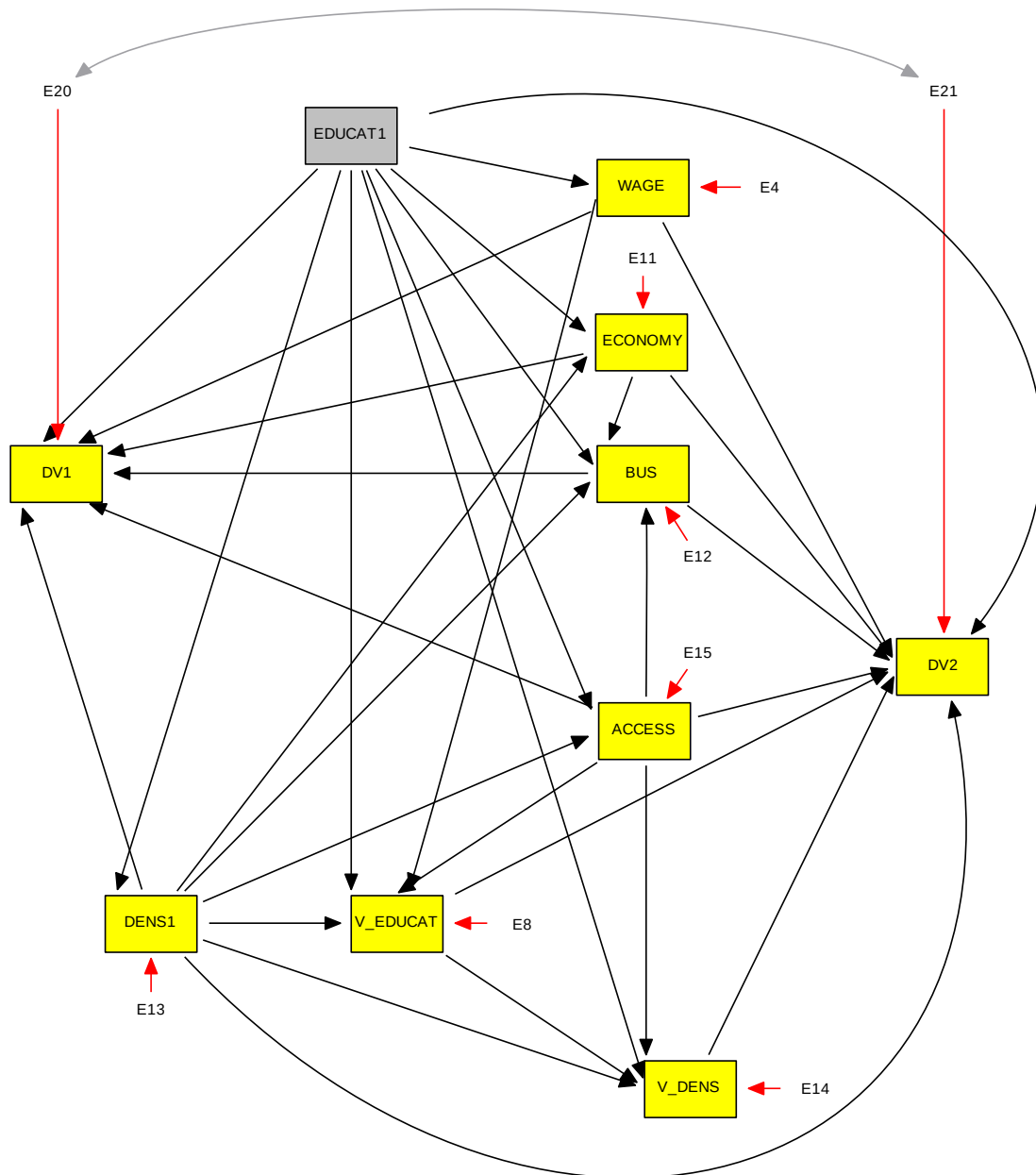


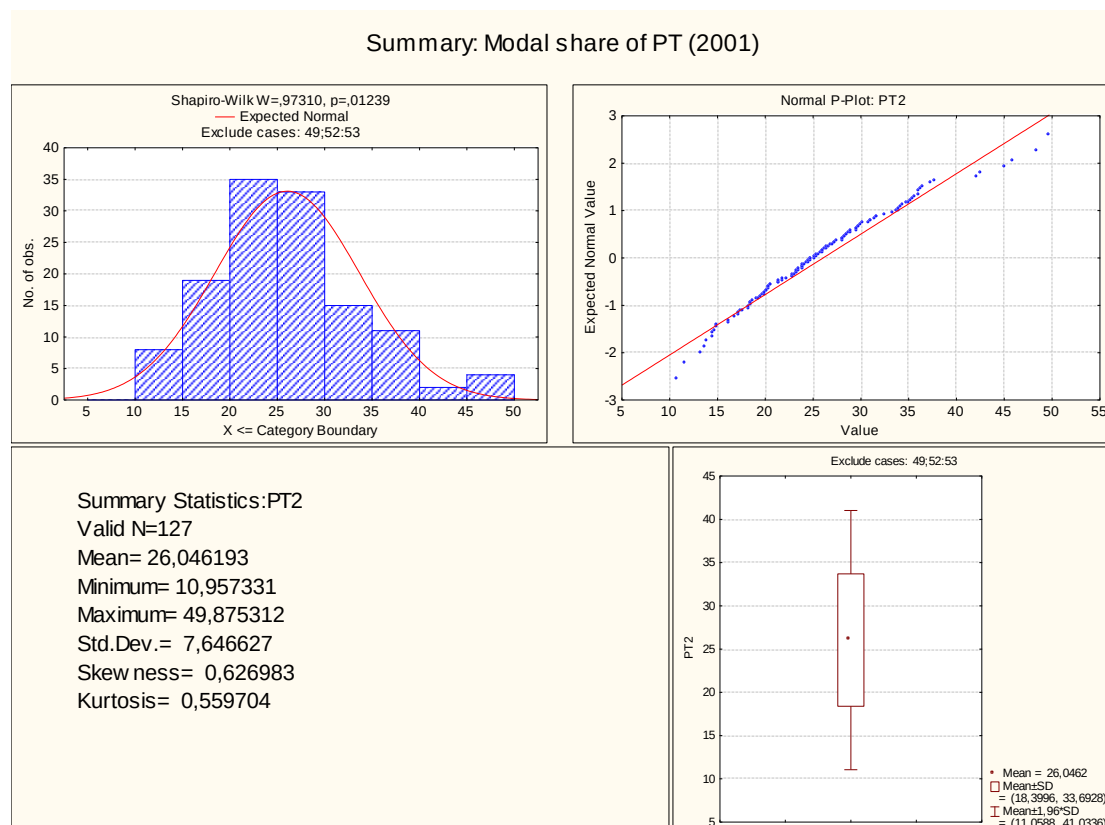
Figure 4.8-1: Final structural equation model. DV1 and DV2 were substituted respectively by the modal shares of car (1991 and 2001), by the modal shares of public transports (1991 and 2001), or by the modal shares of foot (1991 and 2001). EDUCAT1: education (1991); V_EDUCAT: education change (1991–2001); DENS1: density (1991); V_DENS: density change (1991–2001); BUS: bus net density (2008).

Characteristics of the final models:

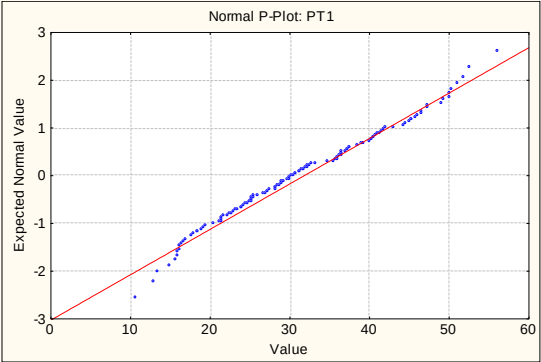
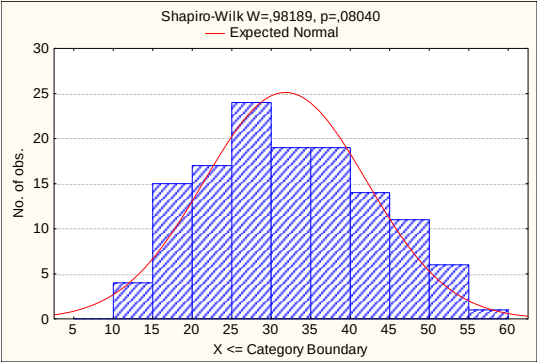
- degrees of freedom = 12;
- number of dependent variables = 9;
- number of independent variables = 10;
- number of free parameters = 43;
- number of fixed nonzero parameters = 9.

Testing of assumptions

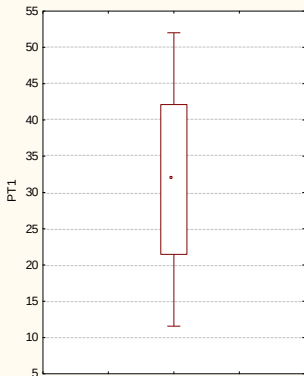
The Mardia's test for multivariate normality revealed significant departures from normality in the three models: a normalized coefficient of 11,28 was obtained (values higher than 1,96 indicate significant nonnormality at the 95% level). Histograms for some of the dependent variables are provided in Figure 4.8-2. All graphics reported were obtained after the elimination of outliers. Because data were not multivariate normal, the estimation of standard errors and the chi-square test were performed resorting to robust methods available in EQS as recommended by Shipley (2004) and Tomarken & Waller (2004).



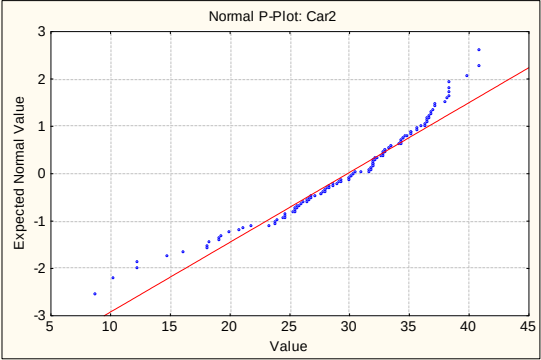
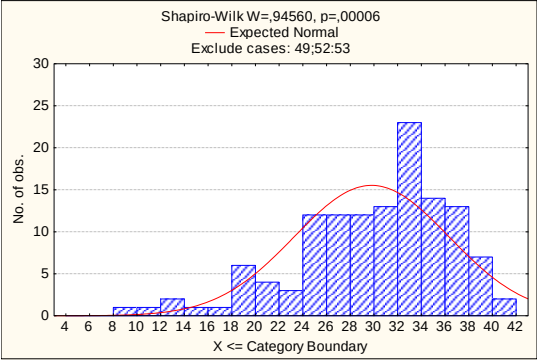
Summary: Modal share of PT (1991)



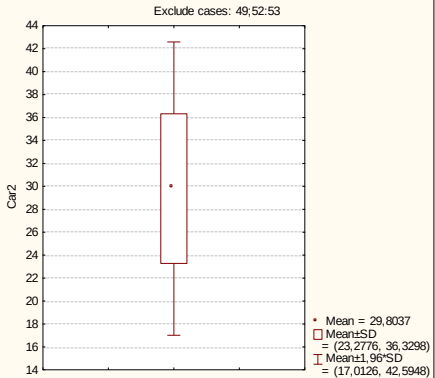
Summary Statistics:PT1
Valid N=130
Mean= 31,794831
Minimum= 10,807018
Maximum= 56,318253
Std.Dev.= 10,321618
Skew ness= 0,196497
Kurtosis= -0,730853



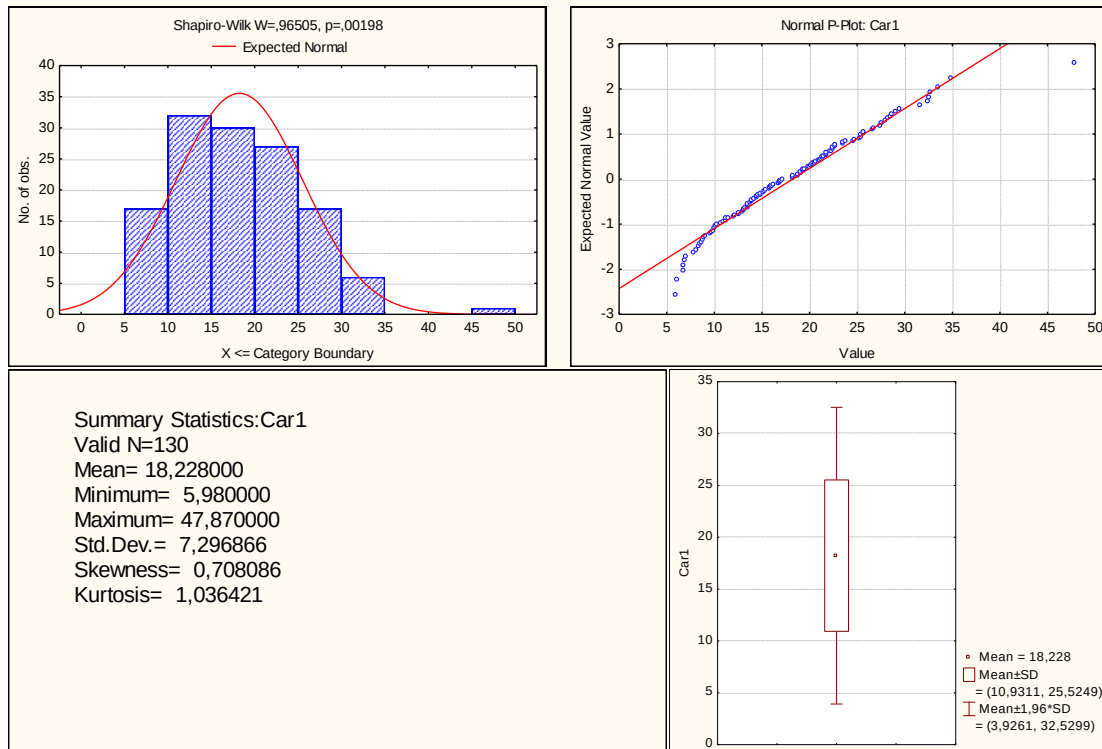
Summary: Modal share of car (2001)



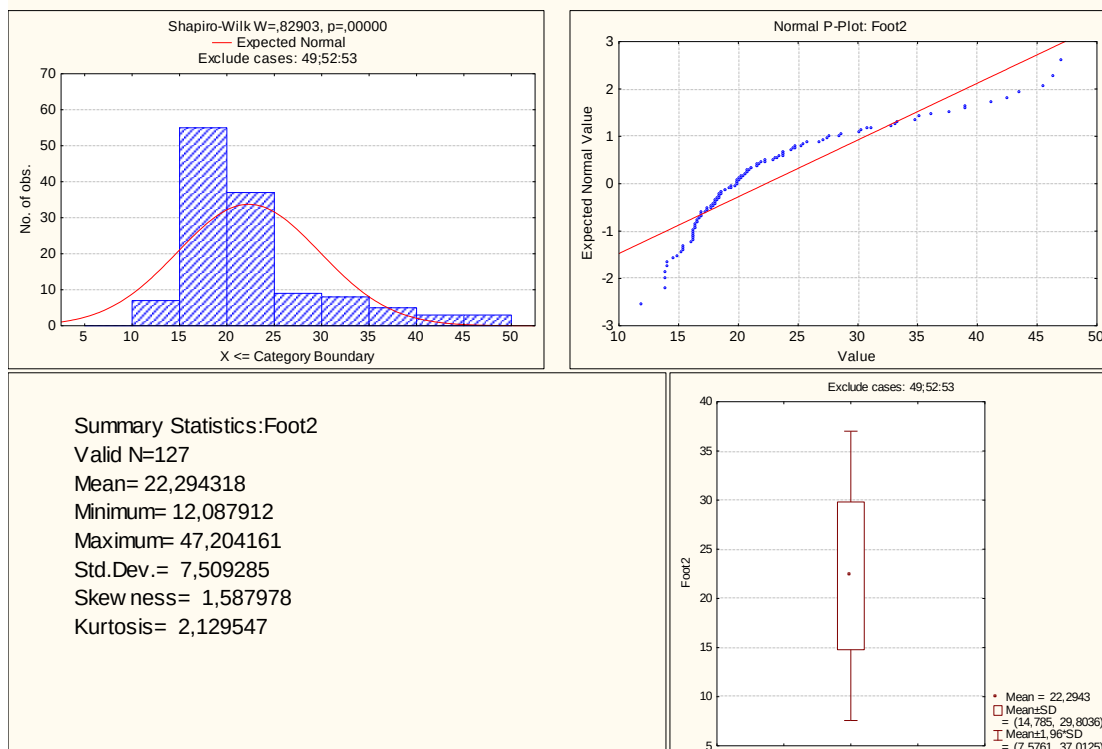
Summary Statistics:Car2
Valid N=127
Mean= 29,803701
Minimum= 8,830000
Maximum= 40,980000
Std.Dev.= 6,526074
Skew ness= -0,908829
Kurtosis= 0,803684



Summary: Modal share of car (1991)



Summary: Modal share of foot (2001)



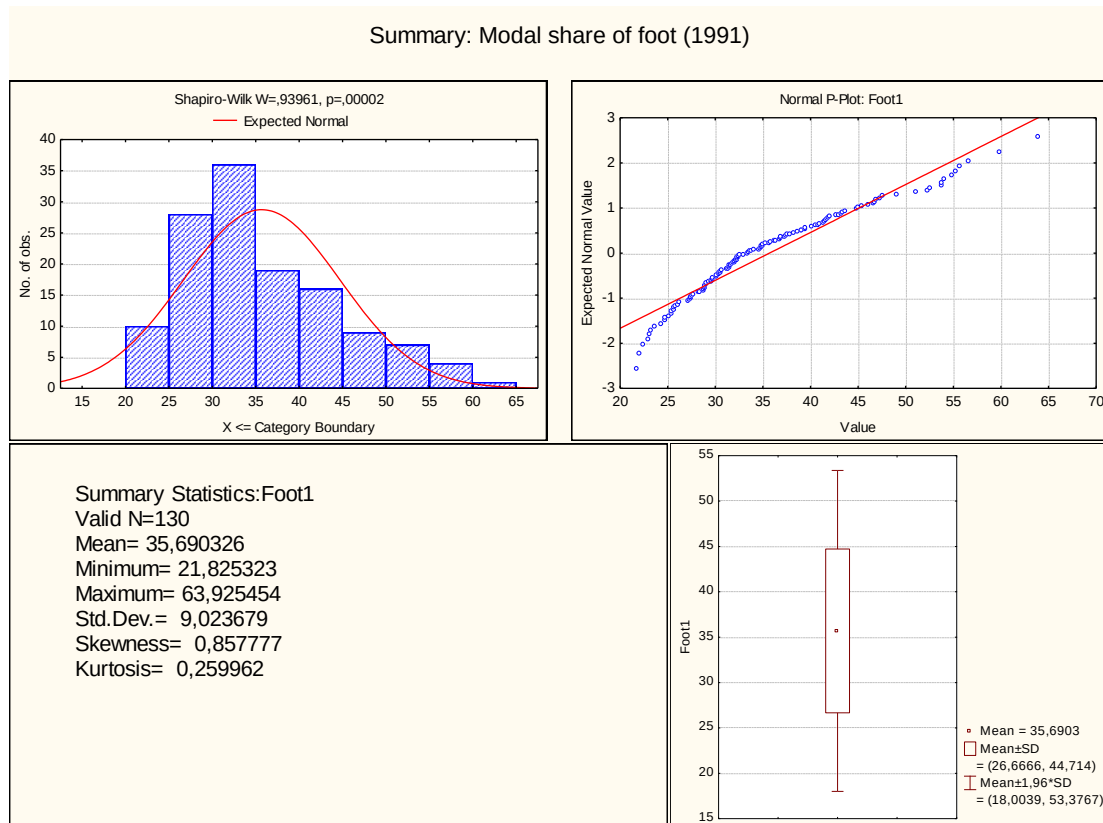


Figure 4.8-2: Histogram, descriptive statistics and normality evaluation for the three main dependent variables.

No serious multicollinearity problems were detected by EQS.

Testing of model fit followed the recommendations of Schermelleh-Engel, Moosbrugger, & Müller (2003) and Shipley (2004). Selected fit indices are presented in Table 4.8-I (for detailed goodness of fit results cf. Table 5.4-I). According to the chi-square test, for the car and foot shares models there were not enough evidence of significant differences between the covariance matrices of those models and the population covariance matrices. For the share of public transport, the differences between the model-implied covariance matrix and the population covariance matrix was significant ($p = 0,02$). However, as Schermelleh-Engel, Moosbrugger, & Müller (2003) remark, the chi-square test is very sensible. Other fit indices suggest that the public transport model is also correctly specified. All goodness of fit statistics are presented in section 5.4.

Table 4.8-1: Selected fit indices and respective rules of thumb.

Fit measure	Good fit	Acceptable fit	Assessment of models ¹		
			Car	PT	Foot
<u>Tests of significance²</u>					
χ^2 (p-value)	0,05 < p ≤ 1,00	0,01 < p ≤ 0,05	Good	Acceptable	Good
χ^2 / df	0 ≤ χ^2 / df ≤ 2	0 ≤ χ^2 / df ≤ 2	Good	Good	Good
<u>Descriptive measures of overall model fit</u>					
RMSEA	0 ≤ RMSEA ≤ 0,05	0,05 ≤ RMSEA ≤ 0,08	Good	Poor	Good
SRMR	0 ≤ SRMR ≤ 0,05	0,05 ≤ SRMR ≤ 0,10	Good	Good	Good
<u>Descriptive measures based on model comparisons</u>					
CFI	0,97 ≤ CFI ≤ 1,00	0,95 ≤ CFI ≤ 0,97	Good	Good	Good
NNFI	0,97 ≤ NNFI ≤ 1,00	0,95 ≤ NNFI ≤ 0,97	Good	Poor	Good
GFI	0,95 ≤ GFI ≤ 1,00	0,90 ≤ GFI ≤ 0,95	Good	Good	Good

¹ Based on robust estimators.² The Yuan-Bentler residual-based statistic was used for significance testing.

Outliers and residual analysis

The following cases contributed significantly to multivariate nonnormality and therefore were considered outliers and removed: Foz do Douro, Miragaia and Nevogilde. Residual analysis did not detect any other outlier (Figure 4.8-3).

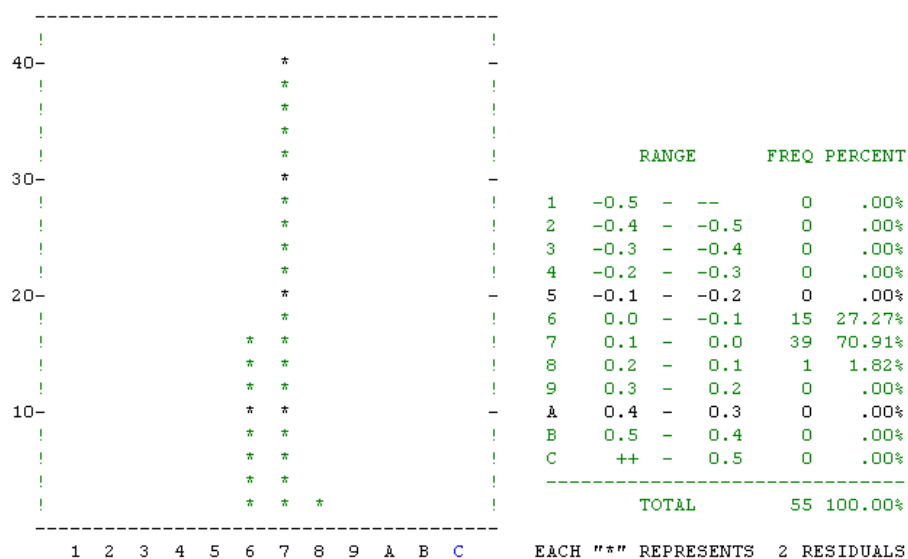


Figure 4.8-3: Distribution of standard residuals in the model concerning the share of car (similar results were obtained for the two other models).

The test for the spatial autocorrelation of residuals was not performed because no conclusions could be drawn from it. Since it was specified that the residuals from the main dependent variables were correlated (a common practice to account for common causes not represented in the model; cf. Figure 4.8-1), autocorrelation may be present because of the effect of omitted variables.

4.8.5 Modeling mobility patterns with support vector machines

Data mining is a new type of exploratory and predictive data analysis whose purpose is to delineate systematic relations between variables when *a priori* expectations as to the nature of those relations are incomplete (Luan, 2002). Data mining and statistics share many techniques, but historically “it might be that statistics have been more concerned with testing hypotheses, whereas data mining has been more concerned with formulating the process of generalization as a search through possible hypotheses” (Witten & Frank, 2005). Data mining is more interesting when used in large datasets in order to uncover hidden trends and patterns in data (Luan, 2002).

In this thesis, the main goal of employing data mining was to compare a statistical method that is based on traditional statistics (structural equations) with a technique whose result is oriented towards prediction accuracy and not with providing explanations or causal relationships. In addition, data mining techniques are usually able to detect nonlinearities in data and are less influenced by outliers than traditional statistical techniques. This is because of the ability to carry out cross-validation during model building, which avoids overfitting and produces relationships between variables that are more generalizable to different datasets (StatSoft, 2007).

Different data mining methods available in Statistica 8 were tried and their goodness-of-fit compared. Support vector machines consistently yielded the best results in terms of prediction error and were therefore chosen as the preferred method. This method performs regression and classification tasks by constructing flexible and nonlinear decision boundaries (StatSoft, 2007).

Procedure and parameters

Procedure followed the recommendations of Hsu, Chang et al. (2003). Data were divided into training (75%) and test (15%) samples according to a yearly-stratified random sampling. Various parameters were determined automatically by the software through v-fold cross-validation so as to achieve a minimal validation error:

- modal share of public transports: regression type I ($C=6,000$, $\epsilon=0,200$); kernel: radial basis function ($\gamma=0,200$); number of support vectors= 75 (56 bounded);
- modal share of car: regression type I ($C=16,000$, $\epsilon=0,100$); kernel: radial basis function ($\gamma=0,200$); number of support vectors= 48 (13 bounded);
- modal share of foot: regression type I ($C=4,000$, $\epsilon=0,200$); kernel: radial basis function ($\gamma=0,200$); number of support vectors= 59 (38 bounded).

Variables and cases

The longitudinal dataset in the long format was used with $n = 260$ and 130 subjects. Three models were developed, each having one main dependent variable:

- modal share: car (2001 and 1991);
- modal share: public transports (2001 and 1991);
- modal share: foot (2001 and 1991).

The following independents were used for each of the dependent variables and retained in the model: year (2001, 1991), education (2001, 1991), unemployment (2001, 1991), income support (2001, 1991), wage (2008), students (2001, 1991), density (2001, 1991), bus net density (2008), economy (2005), and agriculture (1999, 1989).

Model visualization

In order to understand the models generated, fictitious data for the independent variables were assembled and the results predicted. When the influence of one independent variable was being studied, the levels of all the other independents were kept constant. In addition, values did not go beyond the range of observed values in the original dataset.

4.8.6 Modeling urban growth with generalized estimating equations

Longitudinal data from 1991 and 2001 were available to model urban growth. As would be expected, urban growth in these two time periods was highly correlated ($r = 0,79$), rendering the generalized linear models inadequate. These models have been extended to accommodate correlated data either by generalized linear mixed models or by generalized estimating equations (Hardin & Hilbe, 2002; Hedeker & Gibbons, 2006). The latter was preferred because both methods are equally appropriate (Twisk, 2003) and because the use of random effects requires the satisfaction of highly unrealistic assumptions (Bollen & Brand, 2008). When using generalized estimating equations, three parameters must be specified by the researcher: the distribution of the dependent variable, the form of correlation matrix for the repeated measures, and the link function between the dependent and independent variables.

Procedure

The *generalized estimating equations* module of SPSS 17.0 was used to carry out the analysis according to the following procedure:

1. the distribution of the dependent variable was selected after comparing the fit of different distributions through the quasi-likelihood under the independence model criterion. The log-normal distribution proved to be the best option. A normal distribution of urban growth and a log link function were therefore chosen;
2. as recommended by Cui & Qian (2007), the correlation structure minimizing the quasi likelihood under independence model criterion when all input variables were entered in the model was chosen as the most suitable. An independent correlation structure was selected;
3. the terms in the equation were selected as described in modeling crimes against people: nonsignificant effects were removed one at a time based on their p-values (the higher the value the more likely the variable was removed) and on theoretical grounds (variables likely to be related to urban growth were removed later). As the terms were removed, corrected quasi likelihood under independence model criterion was checked to guarantee that model fit improved. Nonlinear effects were tested similarly as an addition to an equation already containing the main effects identified first;
4. residual analysis, although hampered by the lack of statistical outputs (only raw residuals and Pearson residuals are available in SPSS), permitted the deletion of visible outliers. The process was repeated (points 3 and 4) until an acceptable model was achieved.

Variables and cases

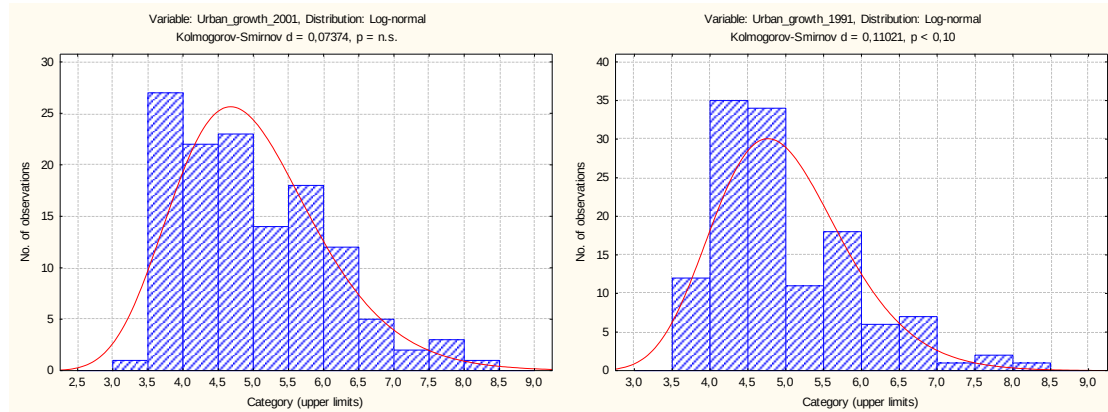
The longitudinal dataset in the long format¹⁷ was used with $n = 252$ and 130 subjects. The dependent variable was urban growth (2000–2006, 1990–2000) modeled with a log link function. As independents the following were initially used (only the underlined variables were retained in the final model): distance to Porto, distance to river Douro, accessibility (2007), agriculture (1999, 1989), distance to the sea, distance to head of municipality, birth rate (av. 2001–2006, av. 1995–2000), density (2001, 1991), natural capital (2001, 1991). Nonlinear terms retained¹⁸: distance to river Douro², accessibility², and distance to Porto $\times$ accessibility.

¹⁷ In the long format, all time periods of the same measure are grouped into the same column. Each row represents one observation.

¹⁸ Superscripts in the variable names represent (squared) exponents.

Testing of assumptions

The distribution for each time period of urban growth showing the best fit was the log-normal (Figure 4.8-4). All graphics reported were obtained after the elimination of outliers.



Variable	Descriptive Statistics				
	Valid N	Mean	Minimum	Maximum	Std.Dev.
Urban_growth_1991	127	4,988317	3,887580	8,111820	0,928550
Urban_growth_2001	125	4,992030	3,421110	8,059040	1,069420

Figure 4.8-4: Histogram and descriptive statistics for urban growth.

No serious multicollinearity problems were found since all correlations were below 0,8 (Table 4.8-2).

Table 4.8-2: Correlation matrix for all variables retained in the final model of urban growth.

Effect	Urban_growth - Estimated correlation matrix of estimates						
	Distribution : NORMAL						
	Link function: LOG						
	Distance_Porto	Distance_Douro	Accessibility	Agriculture	1*3	2^2	3^2
Intercept	0,168781	-0,420546	-0,459812	-0,034153	0,006595	-0,658631	-0,346955
Distancia_Porto	1,000000	-0,677897	0,377557	-0,531840	-0,036297	-0,297723	0,090163
Distancia_Douro	-0,677897	1,000000	0,107685	0,219955	-0,152975	0,400351	0,000299
Accessibility	0,377557	0,107685	1,000000	-0,134793	0,049490	0,026530	0,558714
Agriculture	-0,531840	0,219955	-0,134793	1,000000	0,014161	0,080067	-0,025691
Distancia_Porto*Accessibility	-0,036297	-0,152975	0,049490	0,014161	1,000000	0,099887	0,604540
Distancia_Douro^2	-0,297723	0,400351	0,026530	0,080067	0,099887	1,000000	-0,088082
Accessibility^2	0,090163	0,000299	0,558714	-0,025691	0,604540	-0,088082	1,000000

Outliers and residual analysis

Residual analysis and detection of outliers were conditioned by the availability of only two statistics: raw and Pearson residuals (which, in fact, were almost identical). According to the recommendations of Hardin & Hilbe (2002), observations clearly isolated in the scatter plot

shown in Figure 4.8-5 were considered outliers and removed: São Pedro da Afurada (1991), Vermoim (1991), Aguçadoura (1991), São Pedro da Afurada (2001), Senhora da Hora (2001), Póvoa de Varzim (2001), Vila do Conde (2001) and Pedrouços (2001).

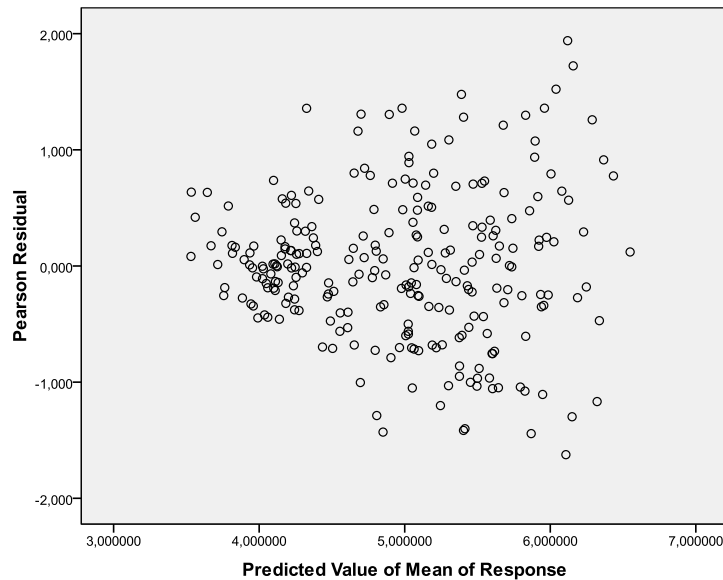


Figure 4.8-5: Residual analysis of the urban growth model.

There was not enough evidence of spatial autocorrelation: the p-value associated with the Moran's I was nonsignificant (index = 0,015299, $p = 0,567008$) suggesting a random spatial distribution (Mitchell, 2005). The threshold distance used in calculations was 5000 m.

Model visualization

The *profiler* option of Statistica 8 was used in order to better visualize the results of the model obtained.

4.8.7 Modeling water consumption with multiple regression

Multiple regression was chosen to model water consumption because it is a widely used statistical method whose advantages and limitations are well known. It is a simple method, easy to grasp and to carry out, although its reliability is only guaranteed when several assumptions are satisfied. Generally, multiple regression is employed to predict the variance in a dependent variable based on linear combinations of independent variables. Each predictor is assigned a coefficient representing the amount that the dependent variable changes when the corresponding independent changes one unit, and while all other variables are held constant. Nonlinear relationships can also be modeled through the addition of power terms, and interactions between variables can be tested by adding cross-product terms. Parameter

estimation is usually carried out by ordinary least squares. The most relevant limitation of multiple regression is the fact that only simple models can be tested. Additionally, unlike structural equations – where complex causal relationships can be forged and degrees of freedom are available to assess model fit – multiple regression uses up all available information in the estimation of parameters. Multiple regression can predict, but not explain (Garson, 2009; Quinn & Keough, 2002; StatSoft, 2007). Assumptions are referred below.

Procedure

Multiple regression was performed using the *general regression models* module of Statistica 8 according to process recommended by Quinn & Keough (2002):

1. the distribution of the dependent variable was checked;
2. the independent variables (their main effects) were added;
3. the option *best subsets*, available in Statistica, was selected. This useful tool chooses the combination of independent variables that minimizes Mallow's C_p , which is a common criterion to compare the fit of different subsets of variables. The method has great advantages over alternative methods of variable selection such as the stepwise entry or removal, whose use is currently discouraged because of its lack of consistency (Quinn & Keough, 2002; StatSoft, 2007). When more than one subset presented similar Mallow's C_p -values, the subset with the least number of variables was chosen for the sake of parsimony and generality;
4. nonlinear effects were tested subsequently as an addition to an equation already containing the main effects identified first. The coefficients of nonlinear terms can only be trusted when the main effects are also present, even if main effects become nonsignificant with the addition of the nonlinear terms (Carte & Russell, 2003; Cohen, et al., 2003; Cortina, 1993; Irwin & McClelland, 2001). All quadratic effects and two-way interactions of the main effect variables were added; their best subset was then selected through the method described in the previous point. Interactions were computed as the cross product of each pair of main effect variables. The combination of nonlinear effects minimizing Mallows' C_p was chosen;
5. residual analysis was performed to detect outliers and to verify the satisfaction of multiple regression assumptions. After deletion of outliers the process was repeated (points 2, 3 and 4) until an acceptable model was achieved. It is necessary to meet the assumptions of multiple regression so that parameter estimates and significance testing can be trusted.

Variables and cases

The cross-sectional dataset was used with $n = 45$ (only data from the municipalities of Espinho, Maia, Matosinhos and Porto were available). The dependent variable was *water consumption*

(2007). As independents the following were initially used (only the underlined variables were retained in the final model): aging/lone person households (2001), agriculture (1999), wage (2008), education (2001), birth rate (av. 2001–2006), income support (2007), unemployment (2008), density (2006), natural capital (2006), accessibility (2007), basic services (2001), damaged buildings (2001), economy (2005) and occupation regularity (2001). No nonlinear terms were retained.

Testing of assumptions

Water consumption followed a normal distribution as the Shapiro-Wilk test proved nonsignificant (Figure 4.8-6). All graphics reported were obtained after the elimination of outliers.

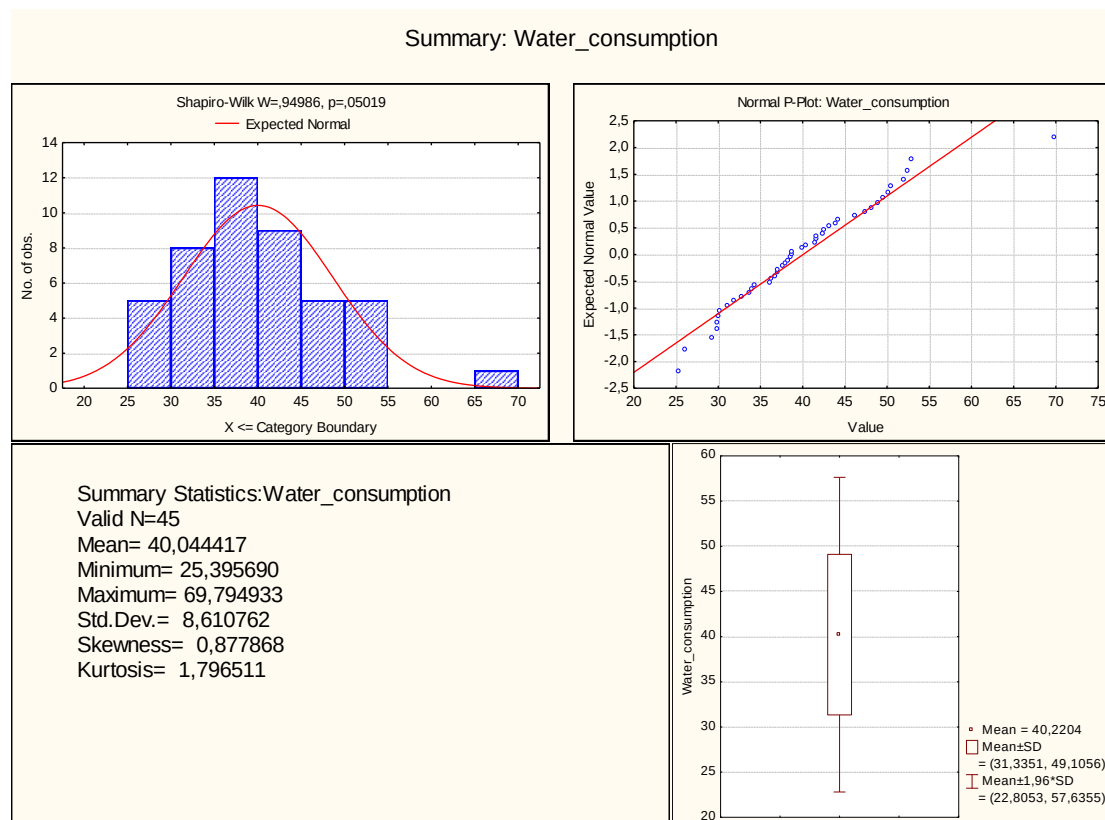


Figure 4.8-6: Histogram, descriptive statistics and normality evaluation for water consumption.

No multicollinearity problems existed since tolerances and variance inflation factors were far from the recommended cut-off values. Garson (2009) suggests that tolerance values $> 0,2$ or variance inflation factors > 4 indicate a multicollinearity problem (Table 4.8-3).

Table 4.8-3: Collinearity statistics for independent variables retained in the model of water consumption.

Effect	Collinearity statistics for terms in the equation Sigma-restricted parameterization	
	Tolerance	Variance Infl fac
Aging	0,789317	1,266919
Wage	0,966047	1,035146
Agriculture	0,792831	1,261304

Variances were fairly homogeneous across the sample, thus satisfying the assumption of homoscedasticity (Figure 4.8-7).

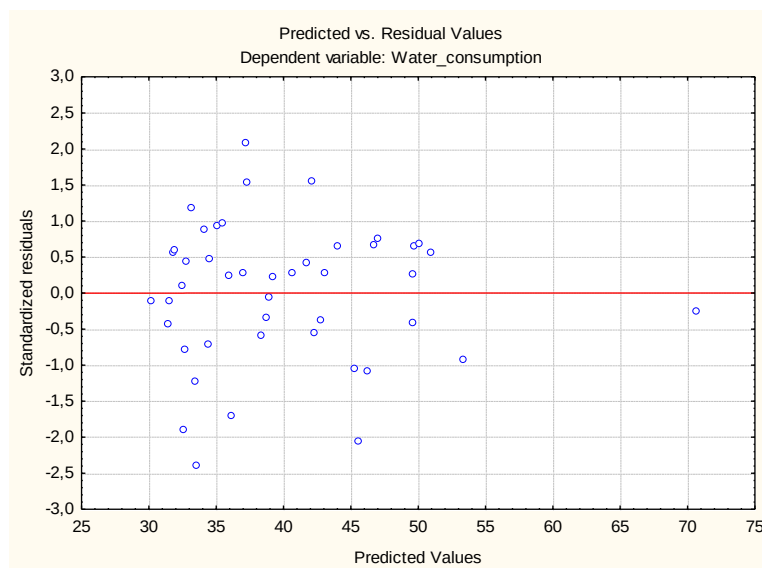


Figure 4.8-7: Scatter plot of predicted values vs. standardized residuals to test for homoscedasticity of the water consumption model.

Outliers and residual analysis

Residual analysis was carried out according to the recommendations of Cohen, Cohen et al. (2003), Garson (2009) and Quinn & Keough (2002). Plots of leverage, discrepancy (standardized residuals against studentized deleted residuals) and influence (Cook's distance) were examined. Cases exceeding cut-off values (leverage $\geq 0,5$; Cook's distance ≥ 1) – or, when these criteria proved too lax, cases clearly isolated from the others by visual inspection – were further analyzed and usually removed from the model. Specifically, the following outliers were deleted: Lavra, Foz do Douro and Nevogilde. Residual analysis of the final model suggests a correct specification and fit (Figure 4.8-8).

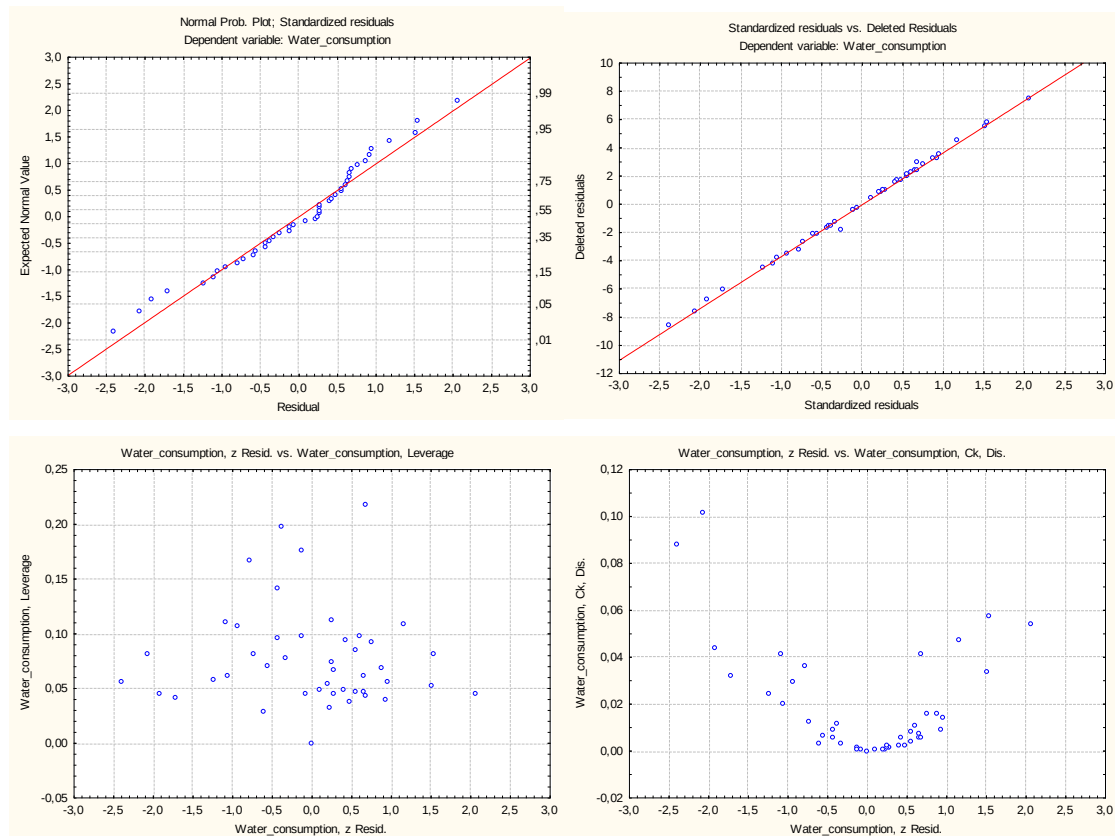


Figure 4.8-8: Residual analysis and identification of outliers in the water consumption model.

There was also not enough evidence of spatial autocorrelation: the p-value associated with the Moran's I was nonsignificant (index = 0,092016, $p = 0,134986$) suggesting a random spatial distribution (Mitchell, 2005). The threshold distance used in calculations was 4000 m.

Model visualization

The *profiler* option of Statistica 8 was used in order to better visualize the results of the model obtained.

4.8.8 Modeling electricity consumption with multiple regression

Procedure

The same procedure as described in modeling water consumption was followed.

Variables and cases

The cross-sectional dataset was used with $n = 103$ (data from Porto were not available). The dependent variable was *electricity consumption* (2007). As independents the following were initially used (only the underlined variables were retained in the final model): aging/lone person households (2001), birth rate (av. 2001–2006), building age (2001), density (2006),

unemployment (2008), wage (2008), education (2001), income support (2007), basic services (2001), agriculture (1999) and occupation regularity (2001). Nonlinear terms retained: aging/lone person households $\times$ wage, and unemployment $\times$ wage.

Testing of assumptions

Electricity consumption followed a normal distribution as the Shapiro-Wilk test proved nonsignificant (Figure 4.8-9). All graphics reported were obtained after the elimination of outliers.

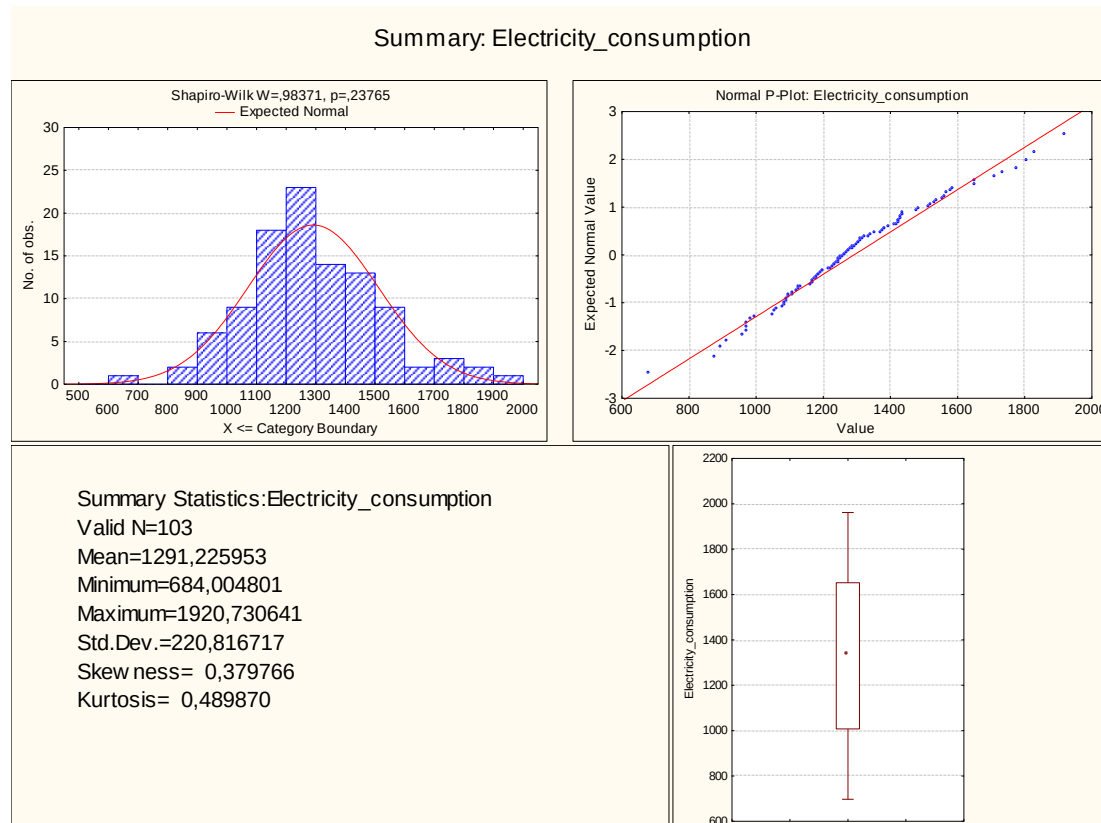


Figure 4.8-9: Histogram, descriptive statistics and normality evaluation for electricity consumption.

No multicollinearity problems existed since tolerances and variance inflation factors were far from the recommended cut-off values by Garson (2009) (Table 4.8-4).

Table 4.8-4: Collinearity statistics for the independent variables retained in the model of electricity consumption.

Effect	Collinearity statistics Sigma-restricted parameterization		
	Tolerance	Variance Infl fac	R square
Aging	0,542498	1,843325	0,457502
Birth_rate	0,910850	1,097876	0,089150
Unemployment	0,463925	2,155522	0,536075
Wage	0,301075	3,321426	0,698925
Density	0,585552	1,707791	0,414448
Aging*Wage	0,310303	3,222654	0,689697
Unemployment*Wage	0,365643	2,734906	0,634357

Variances were fairly homogeneous across the sample with a mean of zero thus satisfying the assumption of homoscedasticity (Figure 4.8-10).

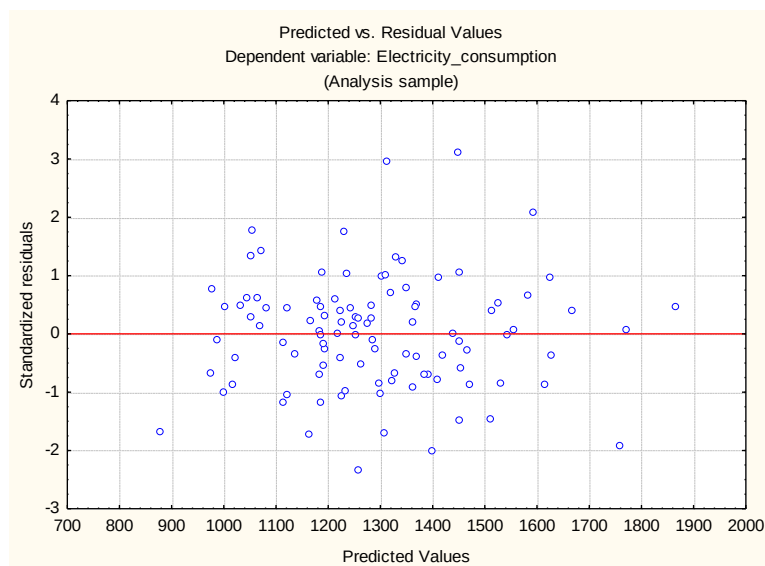


Figure 4.8-10: Scatter plot of predicted values vs. standardized residuals to test for homoscedasticity of the electricity consumption model.

Outliers and residual analysis

Residual analysis was carried out as described in modeling water consumption. The following outlier cases were deleted: Espinho, Lomba, Maia, Leça da Palmeira, Matosinhos, Mindelo, Tougues, Mafamude, Sandim, Vila Nova de Gaia (Santa Marinha), São Félix da Marinha and São Pedro da Afurada. Residual analysis of the final model suggests a correct specification and fit (Figure 4.8-11).

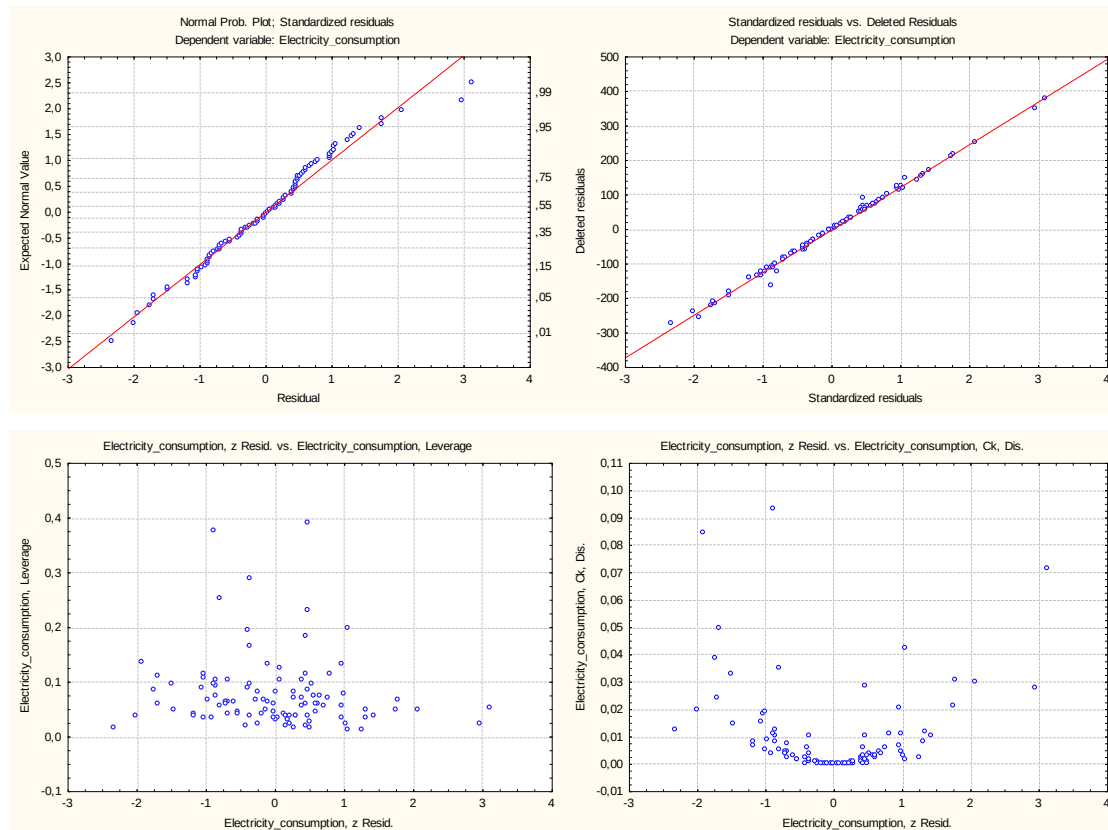


Figure 4.8-1 I: Residual analysis and identification of outliers in the electricity consumption model.

There was also not enough evidence of spatial autocorrelation: the p-value associated with the Moran's I was nonsignificant (index = 0,052337, $p = 0,192688$) suggesting a random spatial distribution (Mitchell, 2005). The threshold distance used in calculations was 5000 m.

Model visualization

The *profiler* option of Statistica 8 was used in order to better visualize the results of the model obtained.

4.8.9 Modeling criminality with a negative binomial log link function model

The modeling approach recommended to overdispersed¹⁹ ($\sigma^2 > \mu$) count data such as the number of crimes is to assume a negative binomial distribution of the response variable (Cohen, et al., 2003; Garson, 2009). A generalized linear model is needed to estimate parameters. Since the total number of crimes is being modeled (and not a normalized indicator), control variables such as *population* and *urban area* were added to the equation. The

¹⁹ When the population variance is higher than the mean.

interpretation of results is similar to that of the multiple regression, except for the fact that the dependent variable has been transformed into its natural logarithm.

Procedure

The *generalized linear models* module of SPSS 17.0 was used to carry out the analysis according to the recommendations of Cohen, et al. (2003), Garson (2009), and Quinn & Keough (2002).

1. all input variables were entered. Nonsignificant terms were then removed one at a time based on their p-values (the higher the value the more likely the variable was removed) and on theoretical grounds (variables likely to be related to criminality were removed later). As the terms were removed, goodness of fit statistics were checked to guarantee that model fit improved;
2. nonlinear effects were tested according to the previous point and as described in modeling water consumption;
3. residual analysis was performed to detect outliers. After deletion of outliers the process was repeated (points 1, 2 and 3) until an acceptable model was achieved. It is important to meet the assumptions log-linear models so that parameter estimates and significance testing can be trusted;
4. alternative link functions (identity and log) were tried, but, as the residuals from the identity link function exhibited spatial autocorrelation, the log link was preferred.

Variables and cases

The cross-sectional dataset was used with $n = 114$ (data from Espinho were not available). The dependent variable was *crimes against people* (2007) modeled with a log link function. As independents the following were initially used (only the underlined variables were retained in the final model): population (2006), aging/lone person households (2001), education (2001), resident's job diversity (2001), income support (2007), unemployment (2008), wage (2008), density (2006), building age (2001), accessibility (2007), economy (2005), economic diversity (2005), agriculture (1999) and occupation regularity (2001). Nonlinear terms were retained: population².

Testing of assumptions

The dependent variable was assumed to have a negative binomial distribution. While no test was available to check this assumption, goodness of fit statistics and residual analysis suggest a correct specification. Histogram and other statistics are presented in Figure 4.8-12. All graphics reported were obtained after the elimination of outliers.

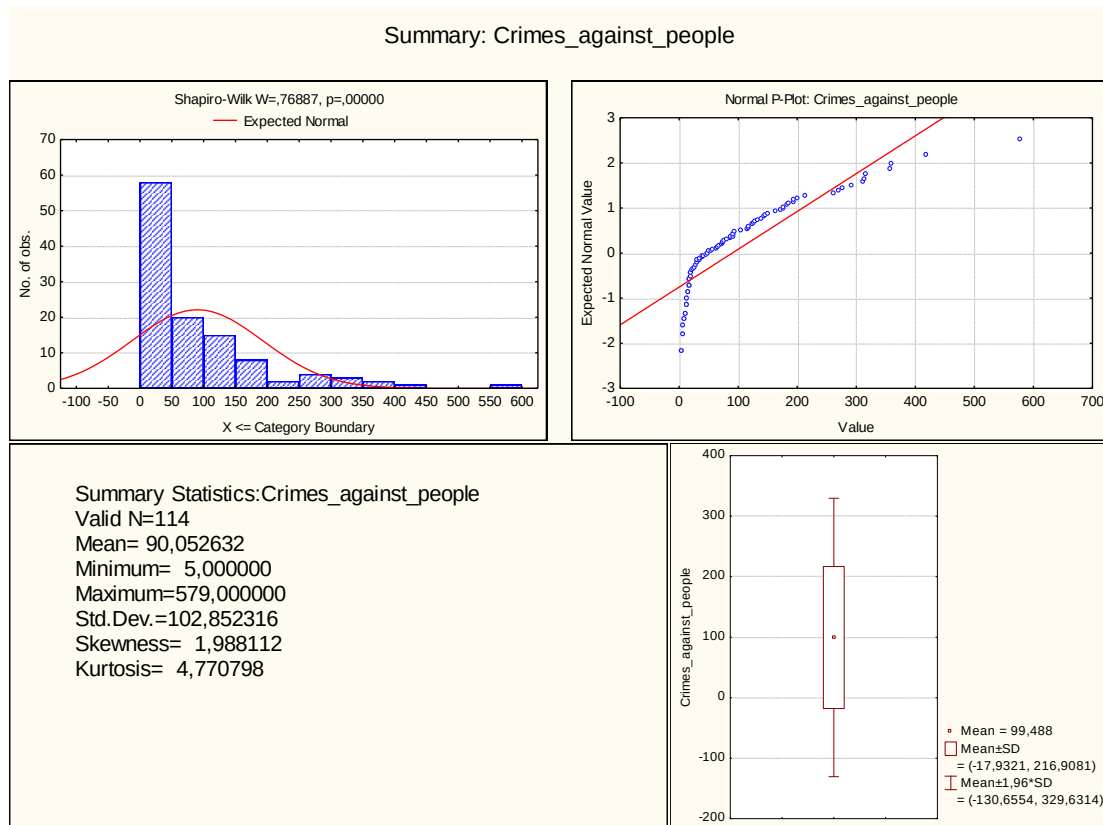


Figure 4.8-12: Histogram and descriptive statistics for crimes against people.

No serious multicollinearity problems existed since the Pearson correlation coefficients were below 0,8 (Table 4.8-5).

Table 4.8-5: Correlation matrix for all independent variables retained in the final model of crimes against people.

Correlations		Population	Aging	Populacao_2
Population	Pearson Correlation	1	,206*	,715**
	Sig. (2-tailed)		,028	,000
	N	114	114	114
Aging	Pearson Correlation	,206*	1	,139
	Sig. (2-tailed)	,028		,140
	N	114	114	114
Populacao_2	Pearson Correlation	,715**	,139	1
	Sig. (2-tailed)	,000	,140	
	N	114	114	114

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Although the generalized linear model does not assume homoscedasticity of residuals, the scatter plot of predicted values against the standardized residuals portrayed in Figure 4.8-13 is

useful to spot possible undesirable patterns in the data. In this case, the expected pattern of growing residual variance with increased predicted values was observed.

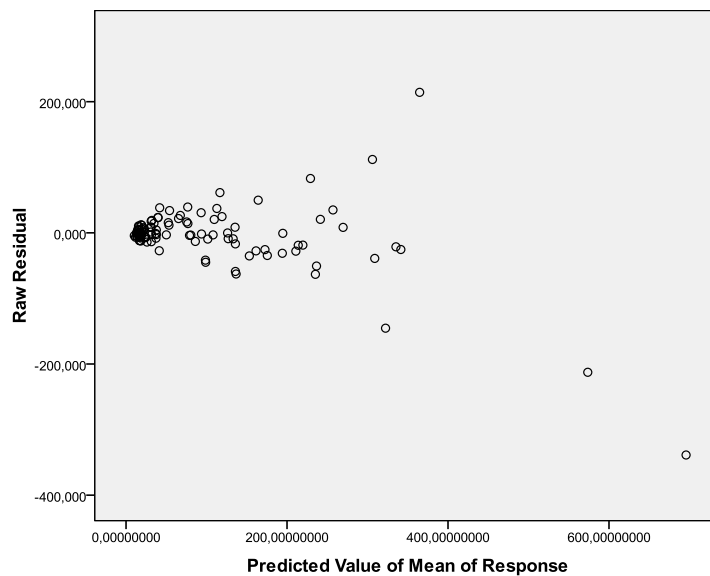


Figure 4.8-13: Scatter plot of predicted values vs. standardized residuals in the model of crimes against people.

Outliers and residual analysis

Residual analysis is not as straightforward in negative binomial regression models as in standard multiple regression (Cohen, et al., 2003). Still, outliers can be visually spotted with the aid of adequate residuals plots. Statistics of leverage, deviance (Pearson residuals and deviance residuals) and influence (Cook's distance) were examined. Cases clearly isolated from the others were further analyzed and usually removed from the model (plots below may erroneously suggest some outliers because the scale is very precise). Specifically, the following outlier cases were deleted: Rio Tinto, Paranhos, São Nicolau, Sé, Ermesinde, Azurara, Ferreiró, Malta, Vila Chã, Mafamude and Sermonde. Residual analysis of the final model suggests a correct specification and fit (Figure 4.8-14).

There was also not enough evidence of spatial autocorrelation: the p-value associated with the Moran's I was nonsignificant (index = -0,040821, $p = 0,392914$) suggesting a random spatial distribution (Mitchell, 2005). The threshold distance used in calculations was 5000 m.

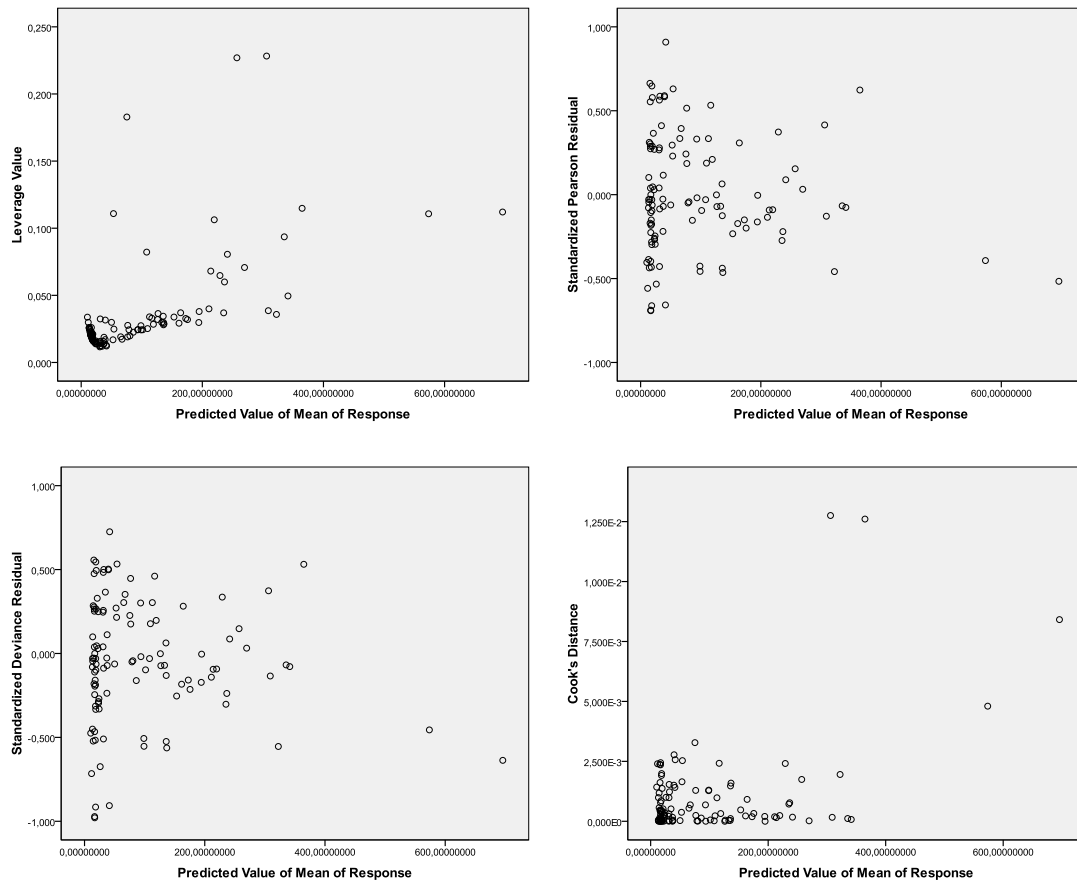


Figure 4.8-14: Residual analysis and identification of outliers in the crimes against people model.

4.8.10 Clustering selected urban sustainability domains using neural networks

Cluster analysis seeks to identify homogeneous subgroups of cases in a population (Garson, 2009). Kohonen networks are one of the most well known neural networks and are useful for discerning clusters and groups within a dataset. They primarily act as an unsupervised knowledge discovery technique. Kohonen networks are also known as *self-organizing maps* (SOM) because algorithms analyze variables until certain patterns emerge (Luan, 2002). In a SOM, the neurons (clusters) are organized into a grid, which exists in a space that is separate from the input space. A SOM tries to find clusters such that any two clusters that are close to each other in the grid space have codebook vectors close to each other in the input space. Results can be sensitive to the shape and dimensionality of the grid, but it is difficult to guess these parameters before analyzing the data (Sarle, 2009). Kohonen networks were preferred instead of traditional cluster analysis because they usually yield better results (Bação, Lobo, & Painho, 2005).

Variables and cases

The cross-sectional dataset was used with $n = 130$. Three fundamental domains were accessed:

- human capabilities: education (2001), aging/lone person households (2001), child mortality (2001), wage (2008) and income support (2001);
- territorial structure, transports and economy: population change (1991–2001), density (2006), natural capital (2006), accessibility (2007), bus net density (2008), metro stop distance (2007), economy (2005), agriculture (1999) and urban growth (2001–2006);
- mobility patterns: modal share of car (1991, 2001), modal share of PT (2001) and modal share of foot (2001).

Procedure and parameters

The human ecosystem framework presented in Figure 4.2-I was used as a source to derive thematic clusters. Territorial structure, transports, and economy were grouped in the same analysis because their indicators were highly correlated. Kohonen self-organizing maps were applied using Statistica 8. The various parameters were iteratively determined according to the recommendations of Jiang, Berry, & Schoenauer (2007) and of StatSoft (2007) so as to achieve both an acceptable error and an adequate number of neurons (clusters). (Error in Kohonen networks is a measure of the distance of the individual neurons from the train and test inputs.)

The following parameters were used:

- random sampling (70% for training, 15% for test and 15% for validation purposes);
- topological dimensions: 2×3 (human capabilities); 1×7 (territorial structure, transports and economy); 1×4 (mobility patterns);
- 2000 training cycles;
- learning rate: 0,5 (start); 0,02 (end);
- neighbors: 5 (start); 0 (end);
- normal randomization.

4.9 Synthesis

The large amount of data gathered was reduced through factor analysis. Factors, along with other single-indicators, formed a cross-sectional and a longitudinal dataset. These datasets were used as the source of multiple analyses. Relevant sustainability issues were modeled: water consumption, electricity consumption, criminality, urban growth and mobility patterns. Appropriate statistical methods were chosen according to the dataset used and to the distributional characteristics of the dependent variables. Each main sustainability domain was then studied through a neural network based cluster analysis.

5. Results

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5. Results

In this chapter, I present all results obtained from the several methods as described in the previous chapter. I start with a brief characterization of the study area, the Metropolitan Area of Porto, which is mainly based on the indicators I gathered (although other sources are also cited whenever necessary). Results from the cluster analysis are shown throughout the text as appropriate. Then, the various statistical models are presented: mobility patterns, urban growth, water consumption, electricity consumption, and crimes against people. Each of these sections starts with a description of the issue under investigation, followed by goodness of fit statistics and by the modeling results. In order to communicate results as simply and intuitively as possible, I resort to colored maps, tables and graphs as much as possible (I also believe that results should be beautiful to be better apprehended). Section 5.10 finishes with a synthesis and a brief discussion of results. Table 5.10-1 should be emphasized as it concentrates the bulk of results. Additional results are displayed in annex A.9 (partial residual plots for all empirical models) and in annex A.10 (detailed effects obtained from SEM).

One language remark is worth mentioning: in a particular model, the stated effects of independent variables on the dependent variable under study are *always* made assuming that the other independent variables (retained in the final model) are controlled for. Furthermore, results are *only* valid for the borough level. For the sake of brevity, these advertences shall be mostly skipped.

5.1 Variables used in data analysis

Datasets used in empirical models comprised factors and single-indicators (Table 4.5-1). Factors were obtained through factor analysis from raw indicators. The factors extracted can be understood as the main underlying dimensions in data: education, aging and lone person households, density, dispersion, accessibility, basic services, natural capital, green areas, economy, agriculture, and occupation regularity. As constructs, their names should be understood as possible designations and *not* as facts. In addition to factors, some single indicators were added to the datasets to ensure that relevant but apparently less well-represented dimensions were also taken into account: abstention, birth rate, child mortality, resident job diversity, income support, wage, unemployment, youth NGOs, native forests, bus net density, metro stop distance, train stop distance, economic diversity and urban expansion area available.

Table 5.1-I: Factors and single-indicators of the datasets.

Resources	Resources
Human capabilities	Urban form
(F) Education	(F) Density
(F) Aging / lone person households	(F) Dispersion
Abstention	(F) Accessibility
Birth rate	(F) Natural capital
Child mortality	(F) Basic services
Income support	Damaged buildings
Resident job diversity	Green space distance
Unemployment	Native forests
Wage	Transports
Youth NGOs	Bus net density
	Metro stop distance
	Train stop distance
Processes	Interactions
Economy	Flows
(F) Economy	Water consumption
(F) Agriculture	Electricity consumption
(F) Occupation regularity	Conflicts
Economic diversity	Crimes against people
Urban expansion area available proportion	Pedestrian crashes
	Mobility
	Modal share: car
	Modal share: PT
	Modal share: foot
	Trip time
	Land use changes
	(F) Urban growth

Factors are indicated with (F). Remainder variables are single indicators.

5.1.1 Relationships between variables in the dataset

Variables of urban data are often characterized by high intercorrelations and redundancy. To access this situation and be acquainted with the structure of the data, I computed a simple cluster analysis of variables (Figure 5.1-I) and correlation matrices (annex A.8). Education and

wage, for instance, are similar because the linkage distance between them is small; education and resident job diversity are farther from each other and, as a result, are less alike.

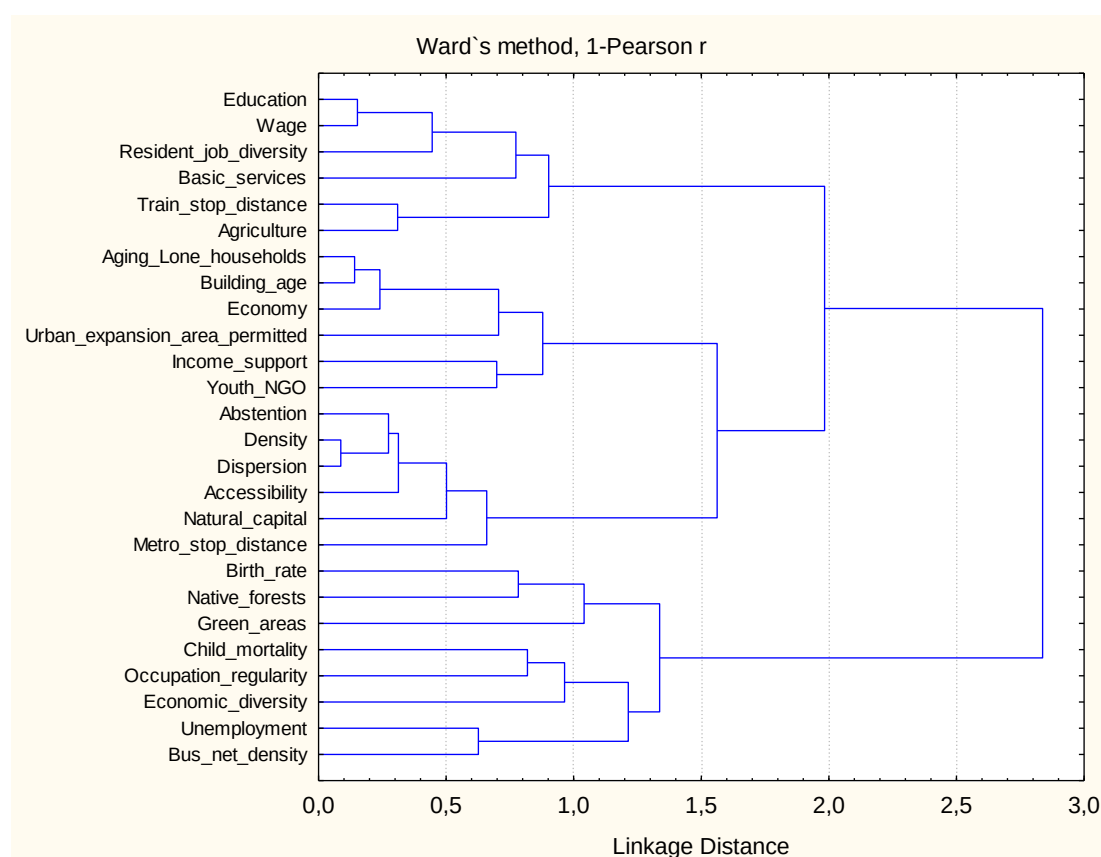


Figure 5.1-1: Similitude between variables in the cross-sectional dataset (2006). Divergence between two variables grows proportionally to their linkage distance.

5.2 Human capabilities

The highest levels of education and wealth are associated and show up in the urban core of the metropolitan area (Figure 5.2-1 and Figure 5.2-2). Social capital (as measured by the normalized number of youth NGOs), is usually very low with the exception of most boroughs in Porto and some boroughs in Gondomar, Valongo, and Vila Nova de Gaia.

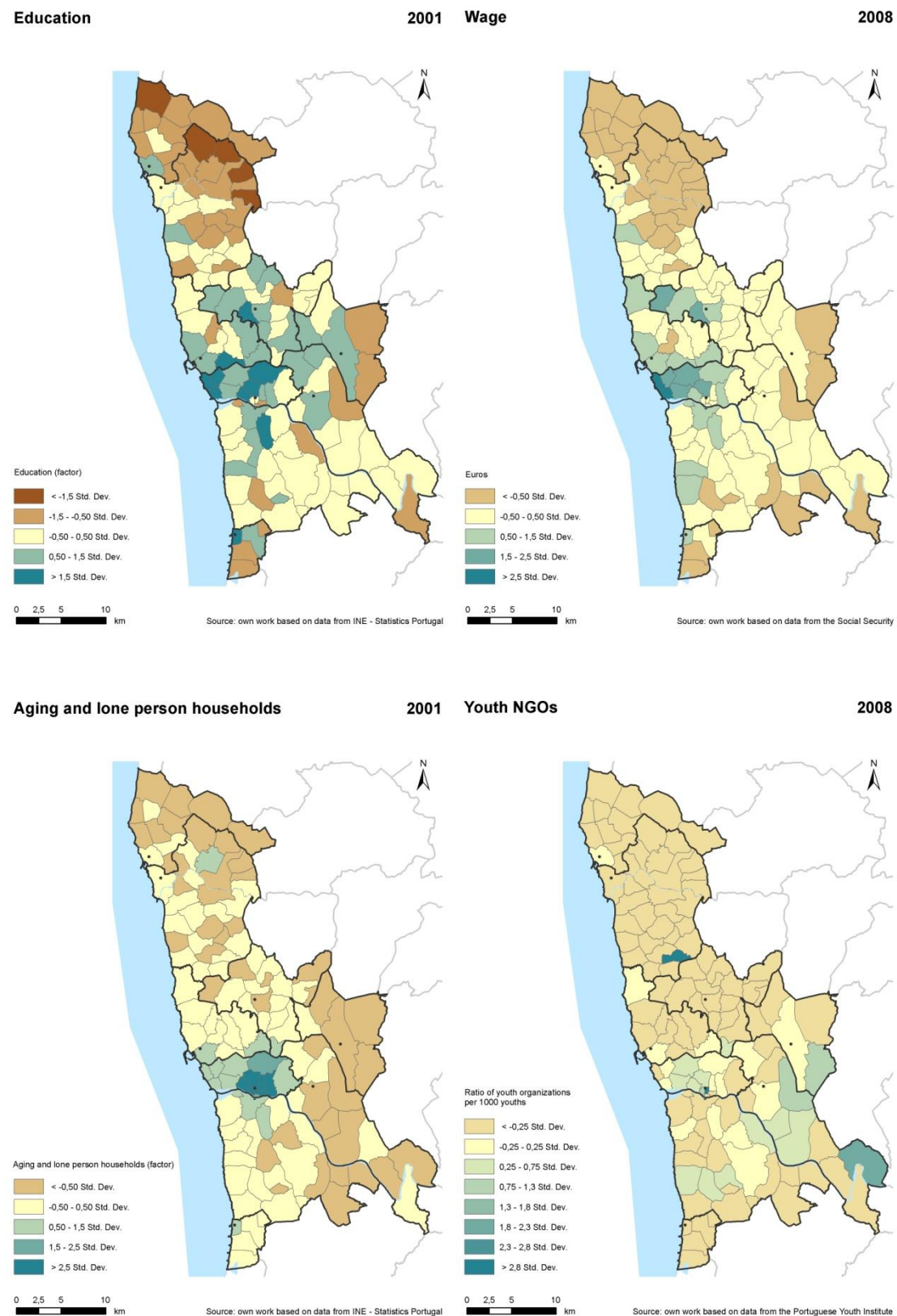


Figure 5.2-I: Human capabilities indicators.

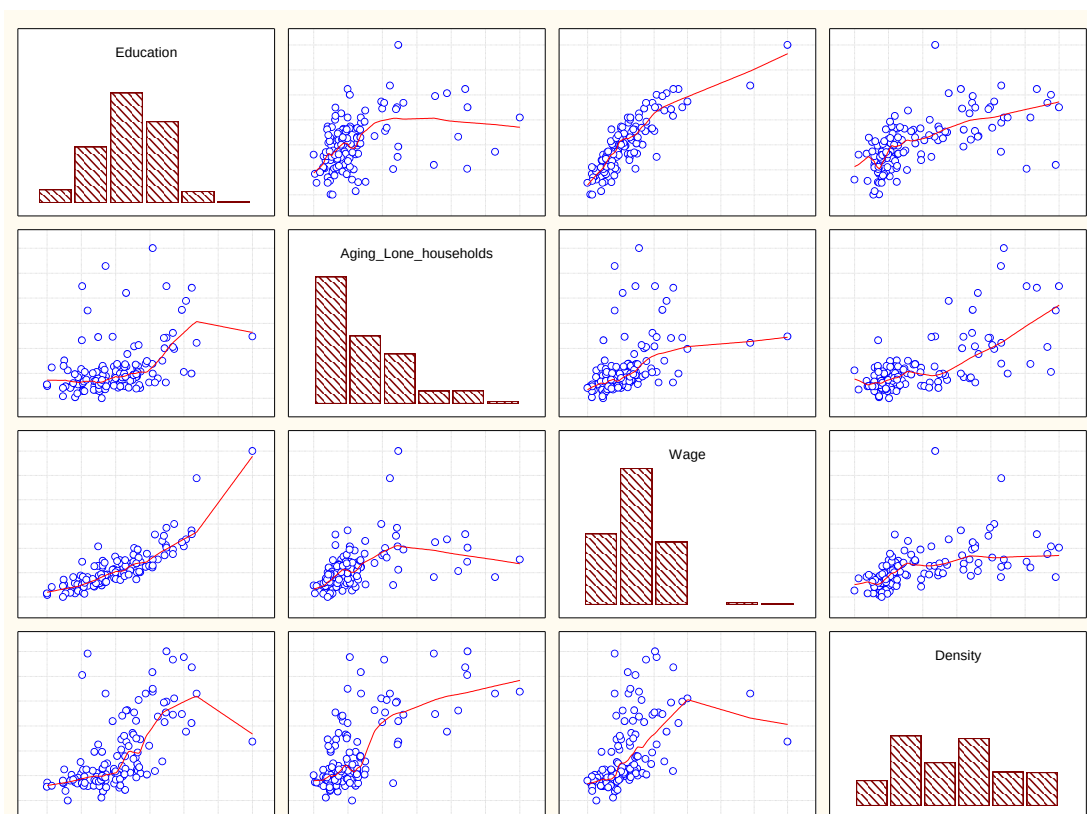


Figure 5.2-2: Matrix plot of human capabilities indicators and density.

Five main clusters of boroughs were found through cluster analysis (Figure 5.2-3 and Figure 5.2-4). One, mainly located in urban and coastal, comprises people with education and wealth above average. The second cluster is composed by educated, aged and wealthy communities, but because many persons belonging to this cluster are retired, social income support figures are high. The third cluster does not appreciably deviate from regional average capabilities. The fourth cluster includes mostly young communities with very low qualifications and wealth. The fifth cluster predominates in Vila do Conde. In addition to low qualifications, this cluster it is also characterized by high child mortality. It is important to note that this characterization is based on averaged values for each cluster. As there only five clusters were computed, some boroughs will inevitably seem wrongly classified on the basis of a single indicator. However, the objective of cluster analysis as a data exploration tool is just to detect typical patterns in data. Specific cases (outliers, for instance) are better analyzed by qualitative research methods, but this is beyond the scope of this thesis.

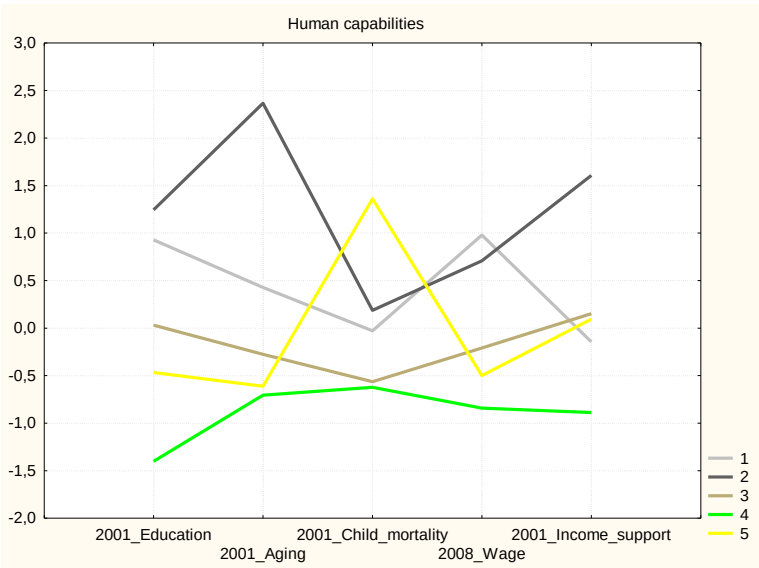


Figure 5.2-3: Variables comprising human capabilities clusters. Average values for each cluster is shown.

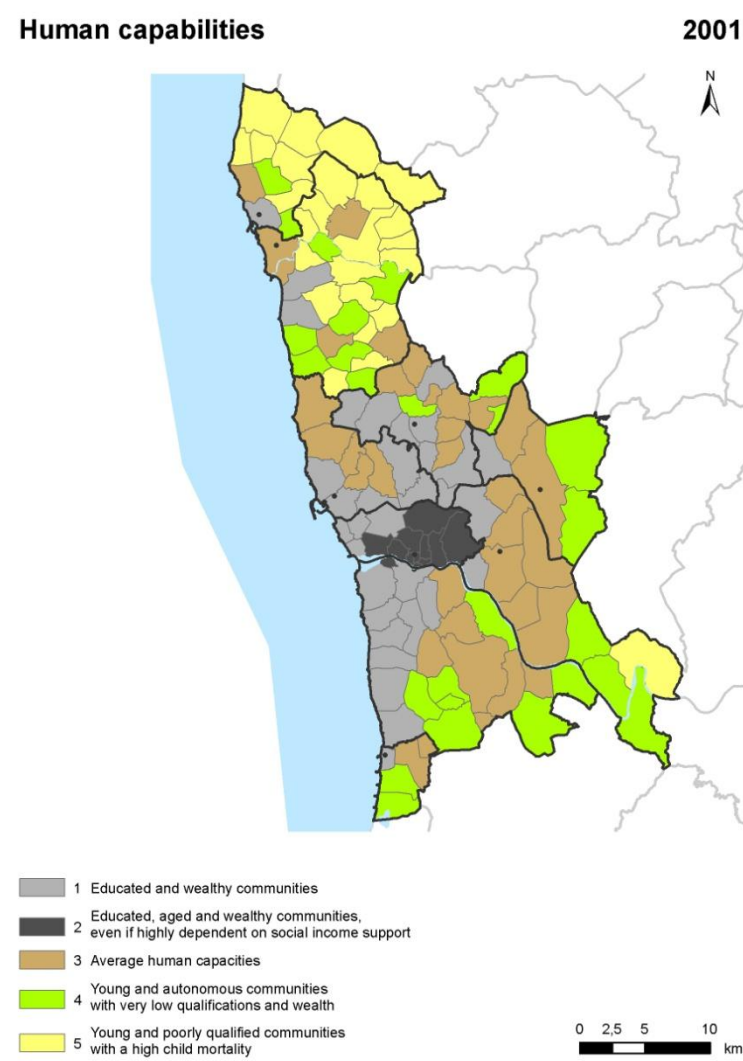


Figure 5.2-4: Human capabilities clusters.

5.3 Urban form, transports and economy

Generally speaking, high territorial contrasts are found in the metropolis. As would be expected, the highest densities are found in the historical center of Porto and surrounding boroughs (Figure 5.3-1, Figure 5.3-2 and Figure 5.3-3).



Figure 5.3-1: Overlooking the historical center of Porto (top) and the nineteenth century quarters (bottom). Source: Bing maps (top) and Google maps (bottom).

Densities generally decrease as we move away from the “gravity” center towards rural and forested areas. This center is an urban *continuum* formed by Porto, Matosinhos, and parts of Vila Nova de Gaia. The polynucleated nature of the region is also clearly visible in Figure 5.3-3. The decreasing density gradient is interrupted by the urban centers of Maia, Valongo, Gondomar, Espinho and Póvoa de Varzim.

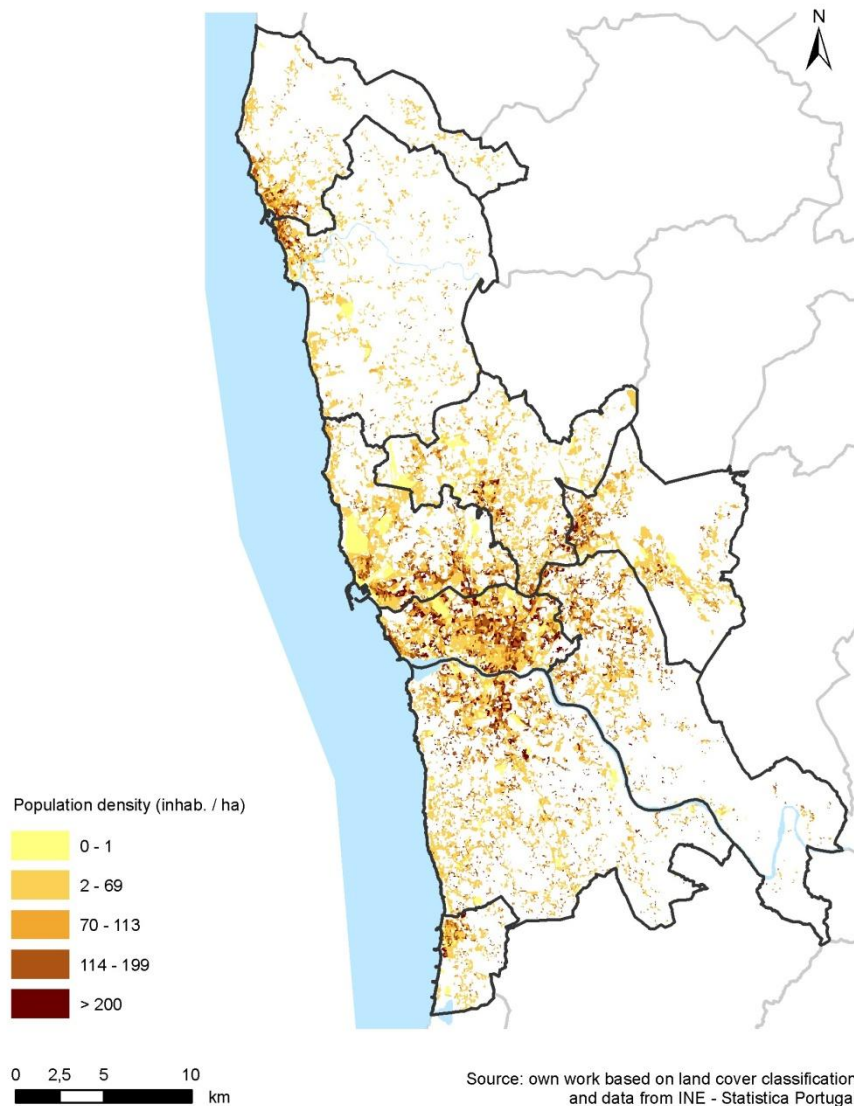
Population density**2001**

Figure 5.3-2: Dasymetric population density map.

Density and dispersion factors yielded very similar results and were highly correlated (Figure 5.3-4), although they were obtained by factor analysis based on different indicators. Density included mainly density indicators (dwellings per building, population density, urban patch average area, compactness) and dispersion included indicators possibly more related to sprawl (Gini index, standard distance, urban fabric proportion). Although more research is necessary, this suggests that both factors represent the same reality, and that no significant advantages are obtained from the use of both of them. This conclusion is valid only for the borough scale of analysis, but it does not corroborate the conclusions of Tsai (2005) and Irwin & Bockstael (2007) regarding the potential of novel urban form indicators in distinguishing different patterns of sprawl.

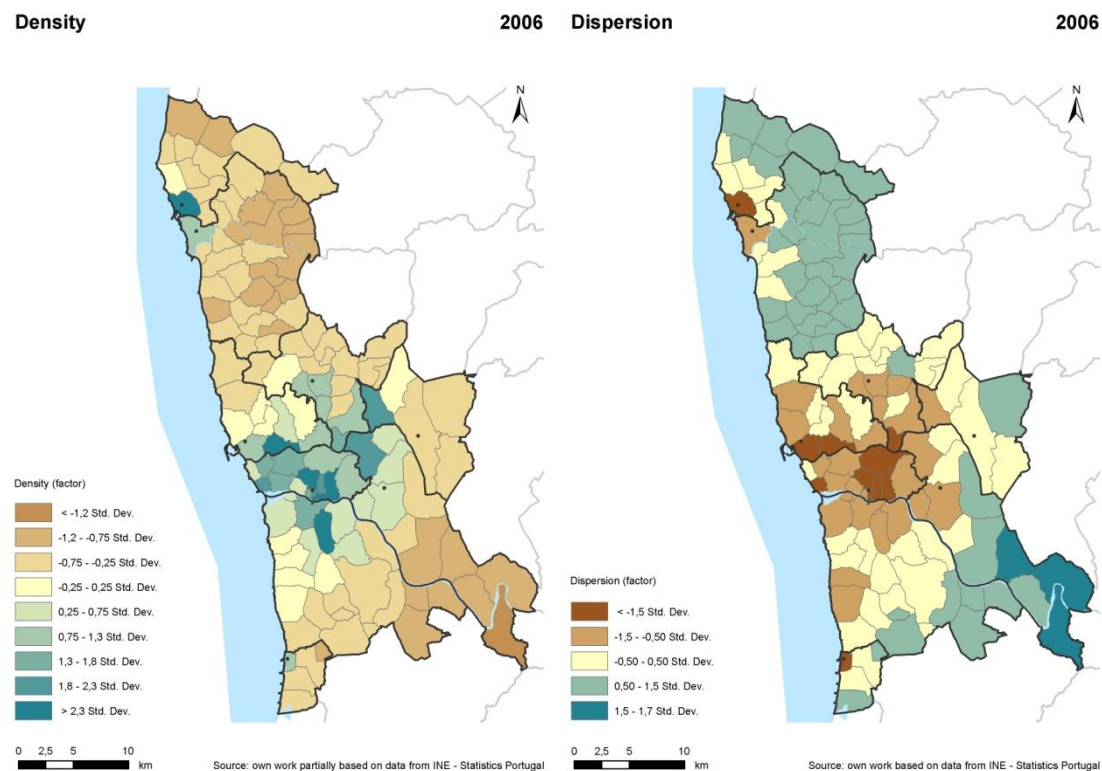


Figure 5.3-3: Density and dispersion maps.

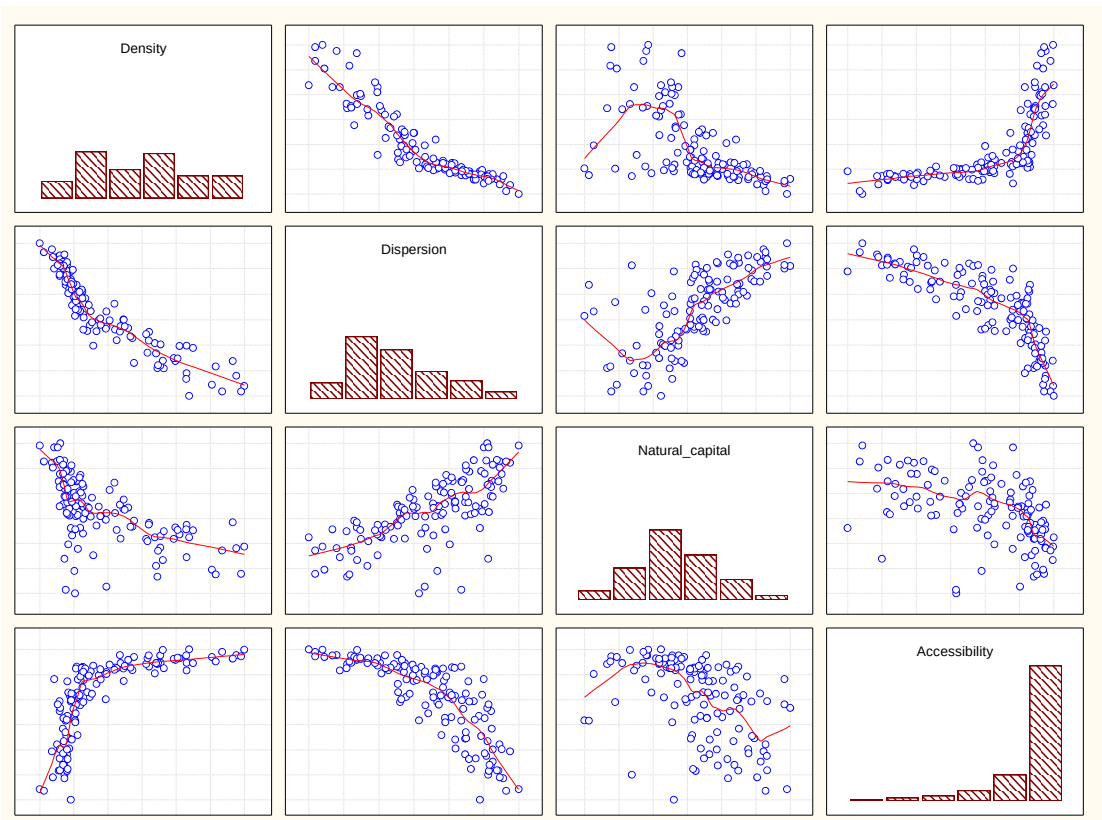


Figure 5.3-4: Matrix plot of territorial structure indicators.

Densities at the Metropolitan Area of Porto are generally low when compared with typical densities found in other cities (Figure 5.3-5). Sprawl dominates. The historical roots lie in the traditional rural lifestyle, as people lived near the fields. In the North (Póvoa de Varzim and Vila do Conde), this territorial pattern is still common, whilst in most of Vila Nova de Gaia agriculture became residual as most land has been converted to urban uses.

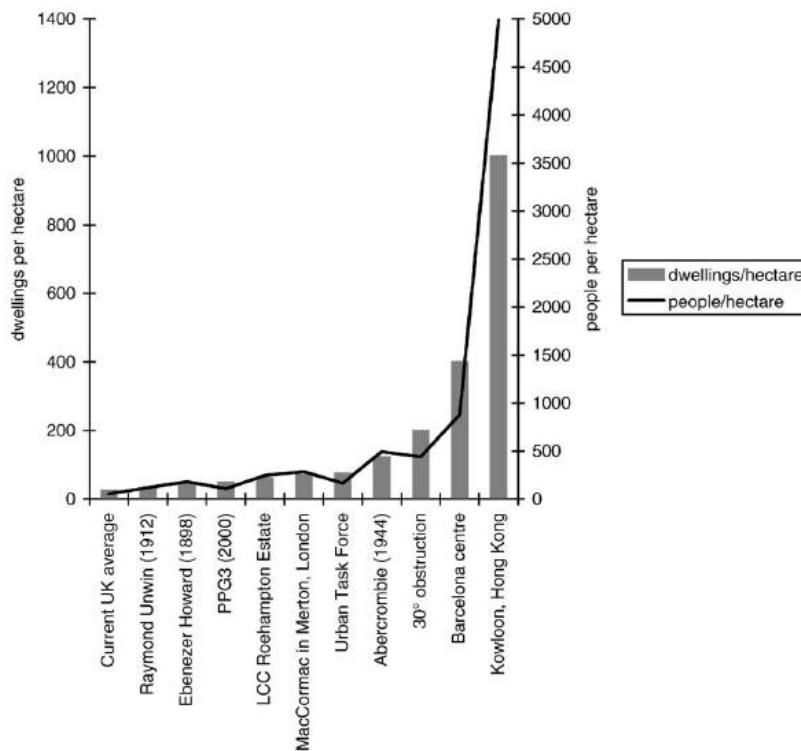


Figure 5.3-5: Densities of housing. Source: Steemers, 2003.

The accessibility factor was composed by accessibility to public equipments (schools, health centers and sports facilities) and by accessibility to highways. At the first glance this could sound suspicious, but the results of factor and reliability analysis were clear: all these variables formed a single factor. Results show that the highest accessibility levels are clearly associated with the highest densities (Figure 5.3-6). On the other side of the spectrum, most boroughs in Vila do Conde and Póvoa de Varzim, and some boroughs in Gondomar are extremely peripheral from the point of view of accessibility. However, this is not particularly worrisome as their resident populations are very low, and it is not possible to provide these persons the same level of service as to people living in denser areas. The situation of green spaces is not so satisfactory, as some dense areas in Vila Nova de Gaia, Gondomar and Matosinhos are rather badly equipped (Figure 5.3-6). Nevertheless, population-weighted average accessibilities are generally satisfactory for the region as a whole (Table 5.3-1).

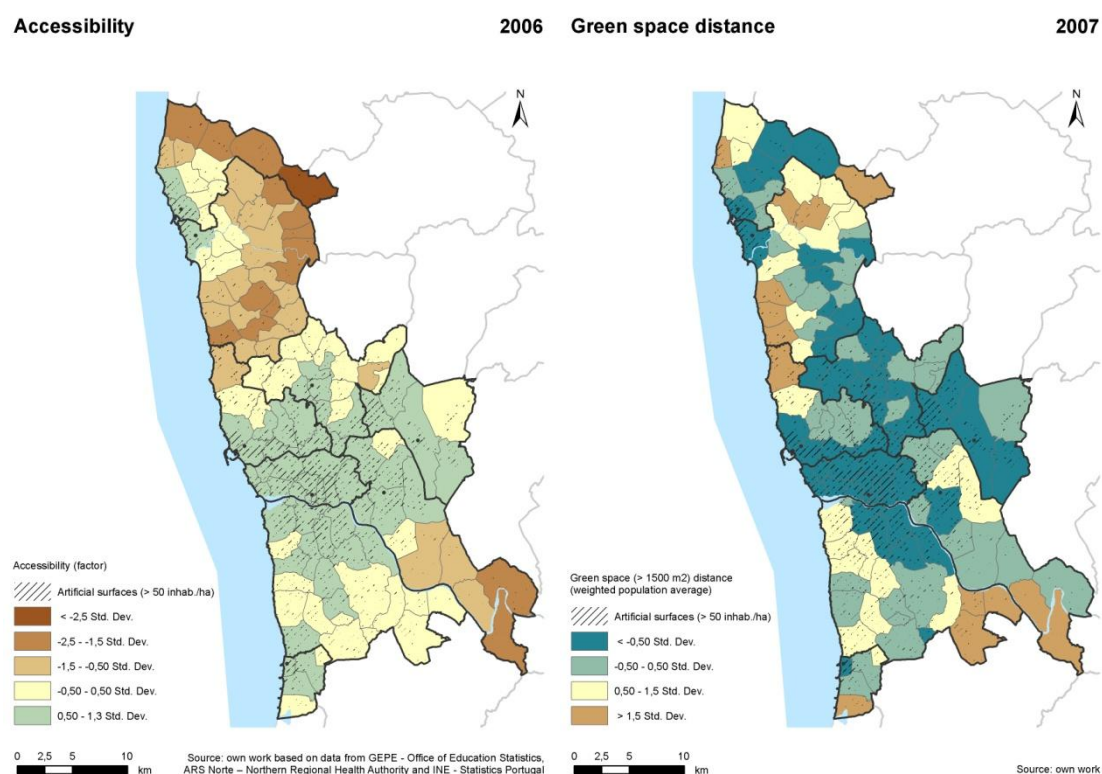


Figure 5.3-6: Accessibility and green space distance indicators.

Table 5.3-1: Averaged accessibility measures for the Metropolitan Area of Porto.

Accessibility indicator	Average distance (m)		
	2006	2001	1991
Healthcare distance	996		
Junior school distance	947		
Secondary school distance	1615		
Green space distance	1110	1267	1403
Highway distance	1496	1764	2217

Note: distances are weighted according to the resident population (disaggregated at census track level).

Natural capital, measured as the proportion of forested area, is inversely correlated with density (cf. Figure 5.3-4). The Southern boroughs of Gondomar and Vila Nova de Gaia are the most forested. *Serra de Valongo*, considered the “lung” of the region, has been ravaged by fires, which probably explains the lower than expected share of natural capital in this territory. Still, it is the main biodiversity hotspot and, along with *Barrinha de Esmoriz*, these are the only metropolitan sites part of the Natura 2000 network (Figure 5.3-7).

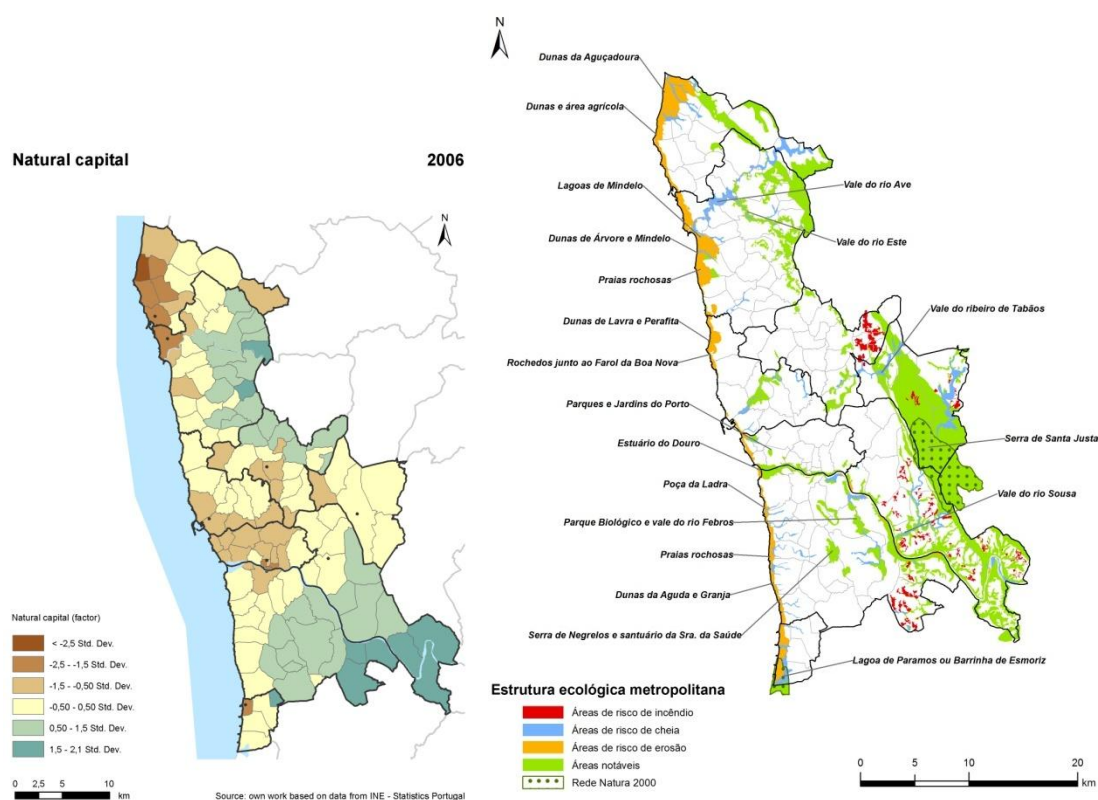


Figure 5.3-7: Natural capital (left) and ecological structure of the Metropolitan Area of Porto (right). Source (right): Quental, 2005; this map is based on data from Andresen, et al., 2004.

The public transport system consists of public and private bus operators, metro and train (Figure 5.3-8). Most of the dense areas are well served, and the level of service increased significantly since 2002 with *Metro do Porto*. As the system is being expanded and the network of existing lines improved, a proportionally larger than linear increase in the number of public transport users is expected.

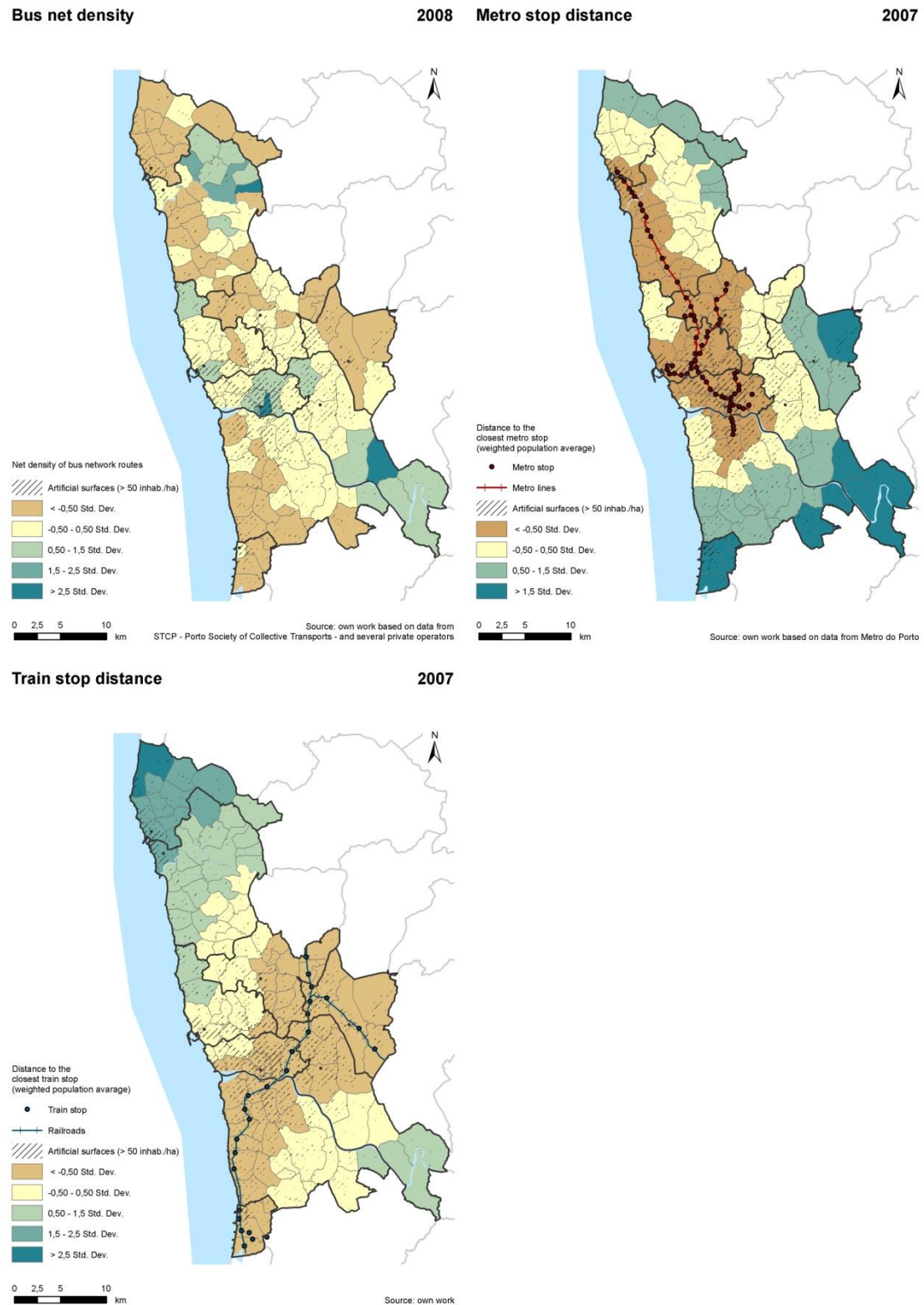


Figure 5.3-8: Accessibility to public transports.

The pattern of economic activity is, again, similar to the pattern of density (Figure 5.3-9 and Figure 5.3-10). Two distinctions are worth mentioning: economy is even more concentrated in the Porto center than density; and the highest levels of economy are not as extreme as levels

reached by density. Agriculture and fisheries are mainly concentrated in Póvoa de Varzim and Vila do Conde, although other municipalities (Maia, for instance) still conserve some of their former rurality. With time and urban growth, the tendency is for these traces of agriculture to be lost. Non-governmental organizations constantly advise that it would be wise to save a large share of existing agricultural areas from urbanization, but the real estate market dynamics is difficult to control.

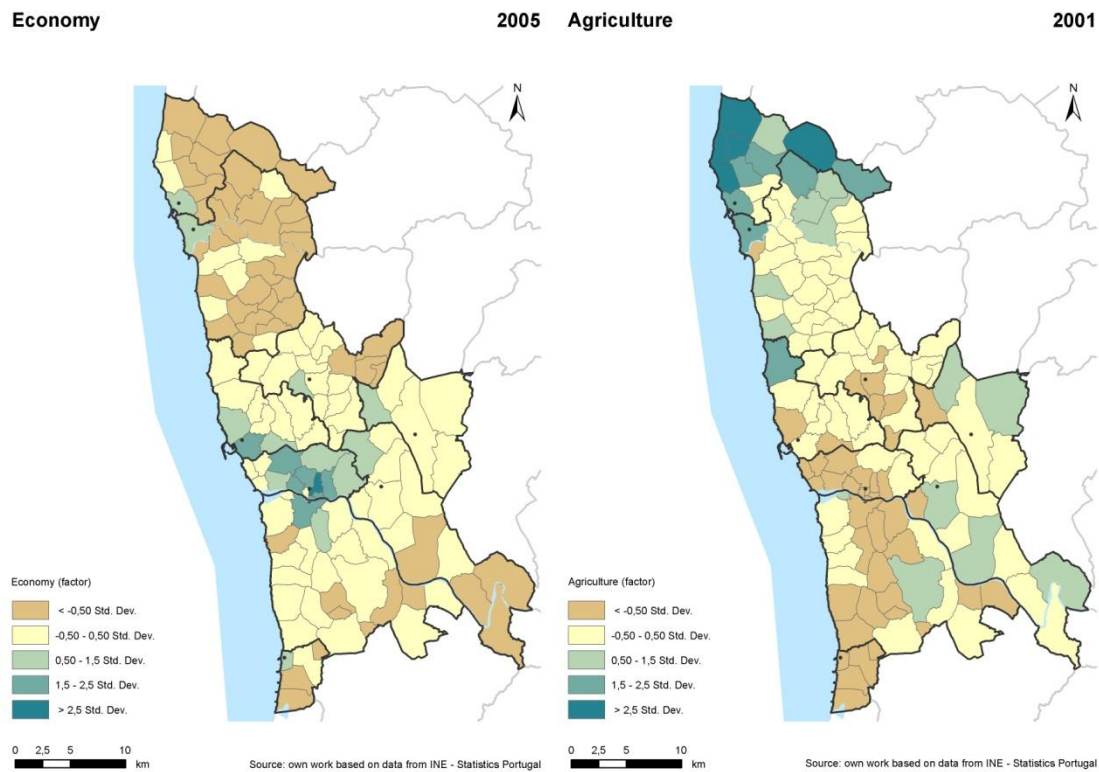


Figure 5.3-9: Economic indicators.

It is important to note that the factor *agriculture* reflects not only the land use but also to the number of jobs in agriculture and fisheries. As such, it is an economic rather than a land use indicator.



Figure 5.3-10: Matrix plot of economic indicators and density.

Cluster analysis detected the existence of seven main typologies of territorial structures (Figure 5.3-11 and Figure 5.3-12). Geographically, these clusters form several quasi-concentric rings around Porto. The core is formed by a dense territory with high accessibility, excellent transports and strong economy, but the tendency is to decline, at least in terms of population (cluster 1). Around the core there are a number of urban boroughs, i.e., boroughs with high densities (though lower than those of the previous cluster) whose urbanized area have been growing faster than population (cluster 2). People from these boroughs also enjoy high accessibilities and a good public transport service. Around this ring there is a group of suburban boroughs characterized by lower densities and high growth rates both in population and in urbanized area (cluster 3). The economic performance and the transportation service in these boroughs are modest. Mainly in Vila do Conde, there is another group of boroughs with low densities, modest growth rates, and higher than average share of forests (cluster 5). This cluster has the particularity of being served by the metro in spite of its peri-urban characteristics (the line B of *Metro do Porto*). The outer layer is formed by two low-density and highly forested clusters. Cluster 6, found in Vila do Conde, and to a lesser degree in the South of Gondomar, is differentiated by its good bus service and agricultural activity, which form the typical *bouças*, or patchwork of forests intermingled with forage crops (see Andresen, et al., 2004); cluster 7 is characterized by higher densities and urban growth than cluster 6. A last

group of boroughs clearly dominated by agriculture (especially horticulture) is found in Póvoa de Varzim (cluster 4). Accessibility and transportation indicators in this cluster are also typically rural. Aerial images exemplifying each cluster are shown in Table 5.3-2.

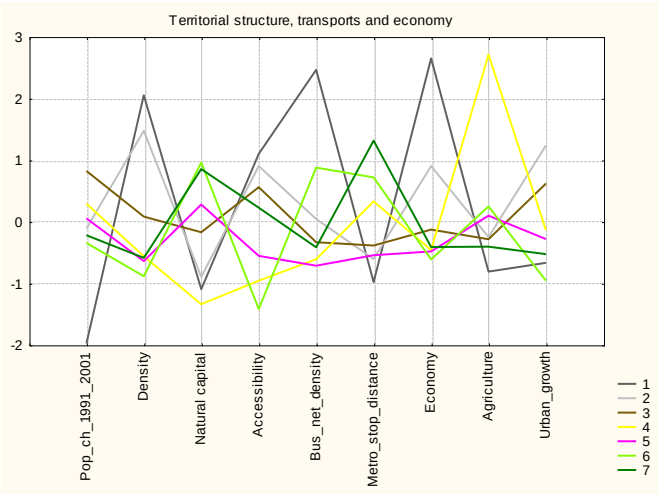


Figure 5.3-II: Variables comprising territorial structure clusters. Average values for each cluster is shown.

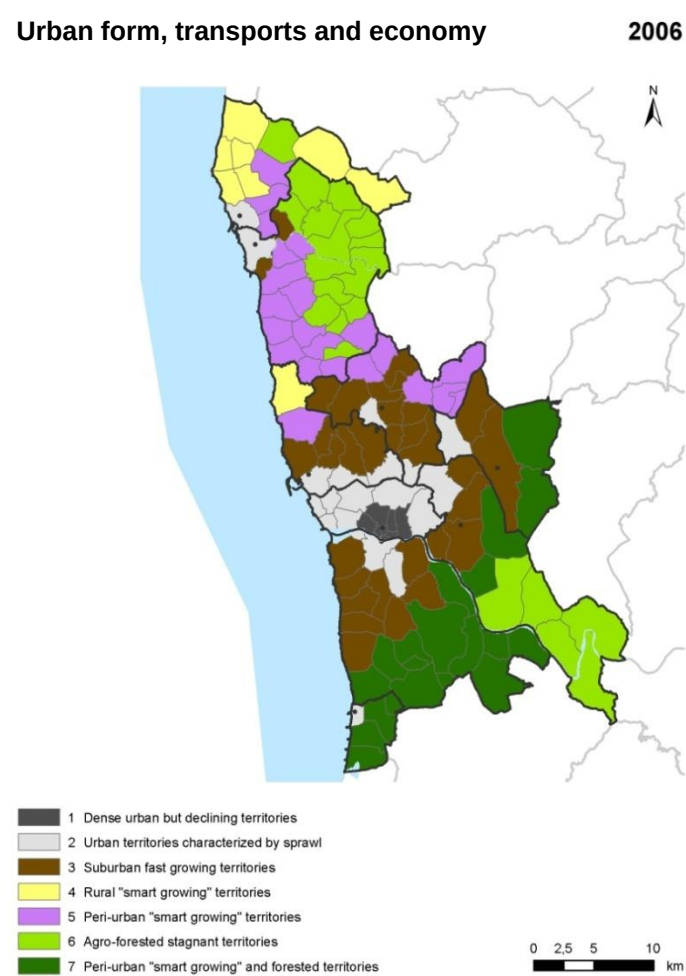


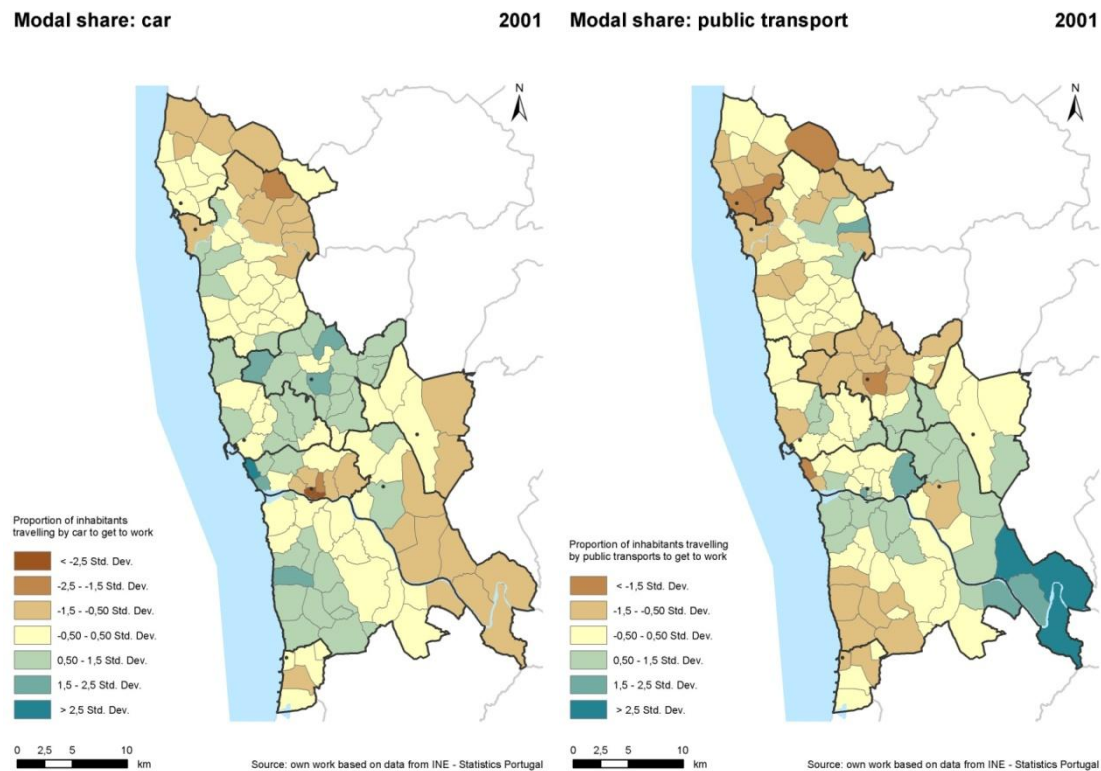
Figure 5.3-I2: Territorial structure clusters.

Table 5.3-2: Examples of aerial photographs for each territorial structure cluster. Source: Google Maps.

Cluster and aerial photograph	Cluster and aerial photograph
1: Dense urban but declining territories	5: Peri-urban “smart growing” territories
	
2: Urban territories characterized by sprawl	6: Agro-forested stagnant territories
	
3: Suburban fast growing territories	7: Peri-urban “smart growing” and forested territories
	
4: Rural “smart growing” territories	
	

5.4 Mobility patterns

Mobility patterns in the Metropolitan Area of Porto are becoming more dependent on private automobiles and less on public transportation. According to the official statistics, in 2001 more than half of the region residents used some kind of individual transportation in their home to work trips. Only in Porto, Valongo and Gondomar the proportion was smaller (Figure 5.4-1). Public transport did not attract more than 34% of the population in any municipality. The pattern was profoundly different in 1991, when mobility in the region was mainly based on public transports and car shares were as low as 23%. In a 10-year period (1991–2001), car journeys from home to work or school grew from 23% to almost 50%. Grow in car use was more pronounced in Gondomar and Valongo, although these municipalities still showed, in 2001, the highest metropolis' shares of public transport. Walking has also suffered a significant reduction.



Modal share: foot

2001

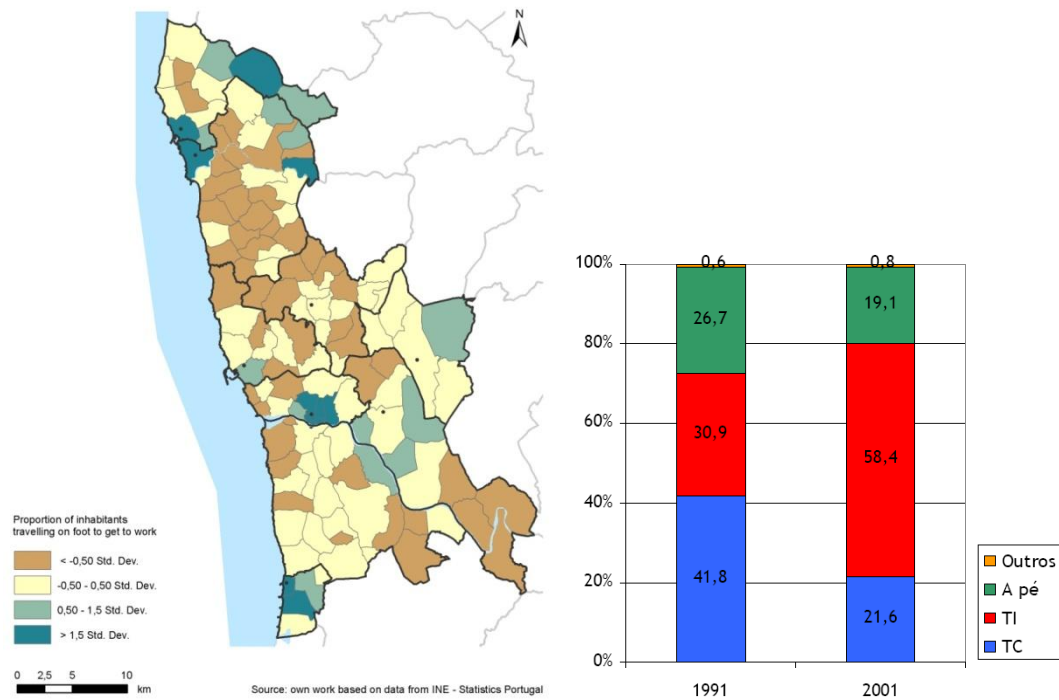


Figure 5.4-1: Modal shares in the Metropolitan Region of Porto.

Cluster analysis revealed four main types of mobility patterns (Figure 5.4-2 and Figure 5.4-3). The first cluster is made up by boroughs where commuting to work by foot is the preferred mode (around 37%) and car dependency is the lowest in the region (ca. 35%). The second cluster comprises boroughs where the share of public transports is the highest in the region (around 35%) although car became the dominant mode. The third cluster includes boroughs where car shares faced the most dramatic increases from 1991 to 2001 (from 14% to 47%). Lastly, there is a group of boroughs with the highest car dependencies (around 57%) and the lowest shares of public transportation (around 22%). Except for the first cluster, walking is the least preferred mode with shares around 18–21%.

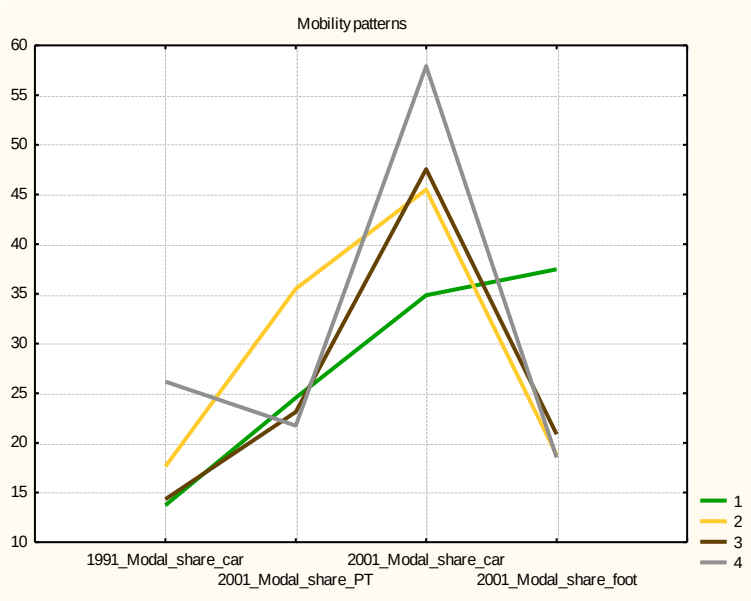


Figure 5.4-2: Variables comprising mobility patterns clusters. Average values for each cluster are shown.

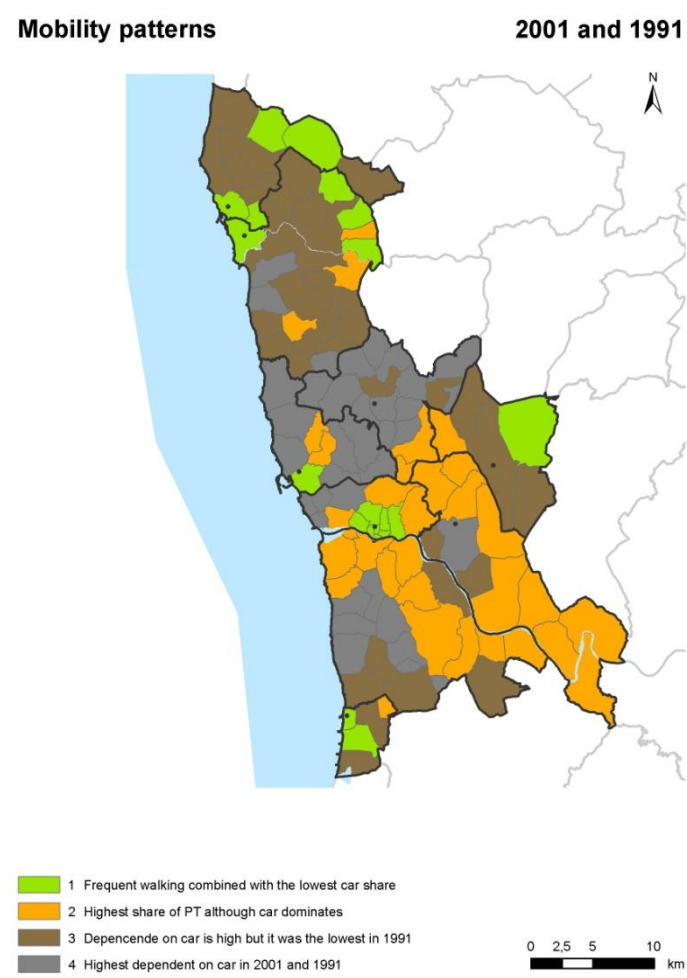


Figure 5.4-3: Mobility patterns clusters.

5.4.1 Modeling with structural equations

Three structural equation models were built, one for each main dependent variable: modal share of car, modal share of public transport, and modal share of foot. Goodness of fit statistics are presented for the three models simultaneously. Results are shown separately.

Goodness of fit

Goodness of fit statistics suggest that models explaining car and foot shares fitted data very well (chi-squared test proved nonsignificant in both cases), and that the public transport model fitted data reasonable well (chi-squared test was significant, but goodness of fit is overall acceptable if other statistics are considered) – Table 5.4-1. In addition, the explanatory power of car shares was high ($R^2 > 0,8$) but rather low for public transport and foot shares (R^2 usually $< 0,3$). Most probably, this is an indication of missing variables such as trip time. However, given the modest sample size available, models would become too complex and lacking power if time was also included.

Table 5.4-1: Goodness of fit statistics for the structural equation models.

Fit measure	Assessment of models ¹		
	Car	PT	Foot
<u>Tests of significance²</u>			
χ^2 (p-value)	0,49 (Good)	0,03 (Acceptable)	0,21 (Good)
χ^2 / df	0,98 (Good)	1,91 (Good)	1,31 (Good)
<u>Descriptive measures of overall model fit</u>			
RMSEA	0,00 (Good)	0,09 (Poor)	0,02 (Good)
SRMR	0,02 (Good)	0,04 (Good)	0,02 (Good)
<u>Descriptive measures based on model comparisons</u>			
CFI	1,00 (Good)	0,98 (Good)	1,00 (Good)
NNFI	1,02 (Good)	0,93 (Poor)	0,99 (Good)
GFI	0,98 (Good)	0,96 (Good)	0,98 (Good)
<u>Variance explained of the main dependent variable</u>			
R^2	0,85 (1991)	0,21 (1991)	0,30 (1991)
	0,82 (2001)	0,33 (2001)	0,56 (2001)

R^2 , although not usually provided in SEM, is of great importance to assess the explanatory capability of the model for each dependent variable.

¹ Based on robust estimators.

² Based on the Yuan-Bentler residual-based test statistic.

Results

There are three structural equation models which differ only in their main dependent variables (modal shares of car, public transport and foot). Results for the common part of the models are shown first, and for the specific part of each model afterwards. Partial residual plots are displayed in annex A.9.

☐ Common part to the three structural equation models

Figure 5.4-4 may be used to visualize the common part to all structural equation models (everything except the effects directed towards CAR1 and CAR2). The main results obtained were:

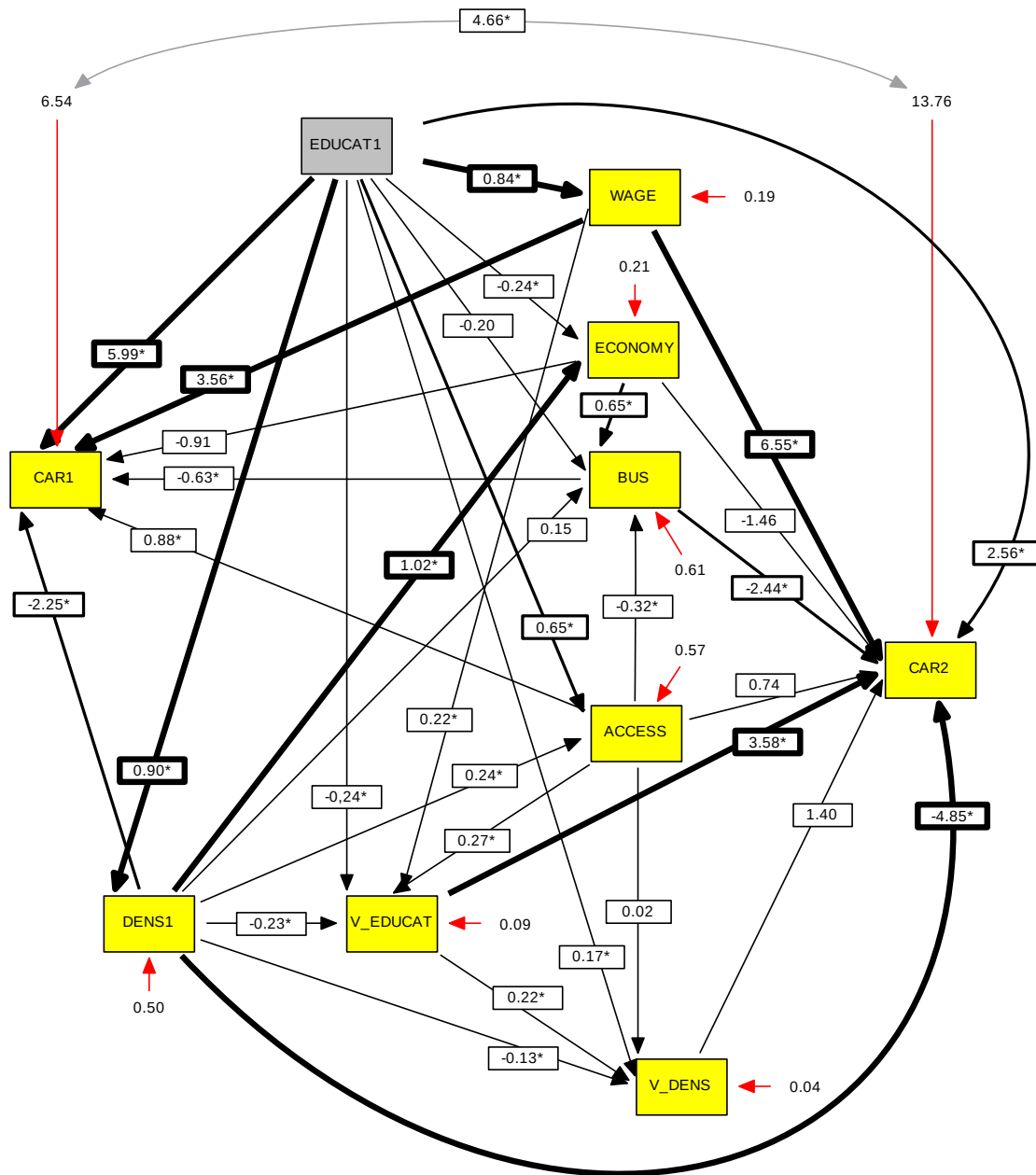
- higher levels of education originated higher wages;
- levels of education were strongly associated with density and accessibility. Accessibility was more strongly associated education than with density, suggesting the existence and relevance of residential self-selection;
- changes in education (1991–2001) were negatively associated with density in 1991 because of the movement of people from dense central areas to suburban boroughs. The total effect of education (1991) on changes in education (1991–2001) was not significant;
- changes in density (1991–2001) were negatively associated with density in 1991, and positively associated with changes in education (1991–2001). The total effect of education (1991) on density changes was not significant;
- levels of density and economy were strongly associated;
- bus net density was more strongly associated with economy than with density. Therefore, bus routes are proportionally denser near central areas providing jobs and services than near the people's residence. Accessibility had a negative modest effect on bus net density.

☐ Modal share: car

Figure 5.4-4 graphically displays the results obtained with the structural equation model of car shares. Table 5.4-2 complements this information with the estimated total effects caused by each variable. The main results can be summarized as follows:

- education (1991) and wage significantly and positively influenced car shares in both time periods, and the effect size was large. However, the total effect of education (1991) on car shares (2001) was not significant. This is probably explained by population movements between boroughs: the most educated boroughs in 1991 lost population and experienced small increases in education and in car shares, and the least educated boroughs in 1991 gained population and experienced large increases in education and in car shares;
- changes in education (1991–2001) were also significantly and positively associated with car shares in 2001;

- density (1991) significantly and negatively influenced car shares in both time periods, and the (direct) effect size was moderate in 1991 and large in 2001. Comparing with direct effects, total effects of density (1991) on car shares (1991, 2001) were larger. This is explained by the population movements referred in the first point: very high densities stimulated the relocation of car dependent people into less dense boroughs;
- changes in density (1991–2001) were not significantly associated with car shares in 2001;
- bus net density significantly and negatively influenced car shares in both time periods. The effect size was small in 1991 and moderate in 2001;
- accessibility significantly and positively influenced car shares in 1991, but in 2001 no significant relationship was found. The direct effect size was small in 1991. Total effects of accessibility were significant in both time periods, and their sizes were moderate. It is important to recall that the factor accessibility is also an indicator of accessibility to highways;
- no significant direct effects of economy on car shares were found in any time period. However, total effects were significant. Effect sizes were small in 1991 and moderate in 2001.



Robust statistics: Chi Sq.=11.7, $p=0.49$, $df=12$, SRMS=0.02, RMSEA=0.00 (0.00 < 90% CI < 0.07), CFI=1.00, NNFI=1.02, GFI=0.98

Figure 5.4-4: Structural equation model explaining car shares. Numbers indicate direct effects. CAR1: modal share of car (1991); CAR2: modal share of car (2001); EDUCAT1: education (1991); V_EDUCAT: education change (1991–2001); DENS1: density (1991); V_DENS: density change (1991–2001); BUS: bus net density (2008).

Table 5.4-2: Effects decomposition for the structural equation model of car shares.

Causal variable	Endogenous variable			
	Modal share of car (1991)		Modal share of car (2001)	
	Direct effects	Total effects	Direct effects	Total effects
Education (1991)	5,992* (0,713) 8,400	7,033* (1,332) 5,282	3,581* (1,250) 2,864	3,029 (2,362) 1,282
Education change (1991–2001)			2,558* (0,969) 2,640	3,881* (1,146) 3,386
Wage (2008)	3,556* (0,520) 6,835	3,556* (0,520) 6,835	6,550* (0,614) 10,676	7,386* (0,712) 10,381
Density change (1991)	-2,252* (0,667) -3,374	-3,431* (0,327) -10,000	-4,849* (0,961) -5,046	-8,780* (0,564) -16,000
Density (1991–2001)			1,394 (1,424) 0,979	1,394 (1,424) 0,979
Economy (2005)	-0,911 (0,612) -1,488	-1,318* (0,587) -2,245	-1,458 (0,842) -1,732	-3,046* (0,869) -3,504
Bus net density (2008)	-0,626* (0,251) -2,497	-0,626* (0,251) -2,497	-2,444* (0,491) -4,974	-2,444* (0,491) -4,974
Accessibility (2001)	0,884* (0,264) 3,351	1,085* (0,251) 4,330	0,737 (0,534) 1,380	2,608* (0,537) 4,859

Parameter estimates are presented in the first line of each row (robust standard errors in parenthesis); robust test statistics are presented in the second line. Statistics significant at the 5% level are marked with *. Significant total effects are colored according to their influence on the modal share.

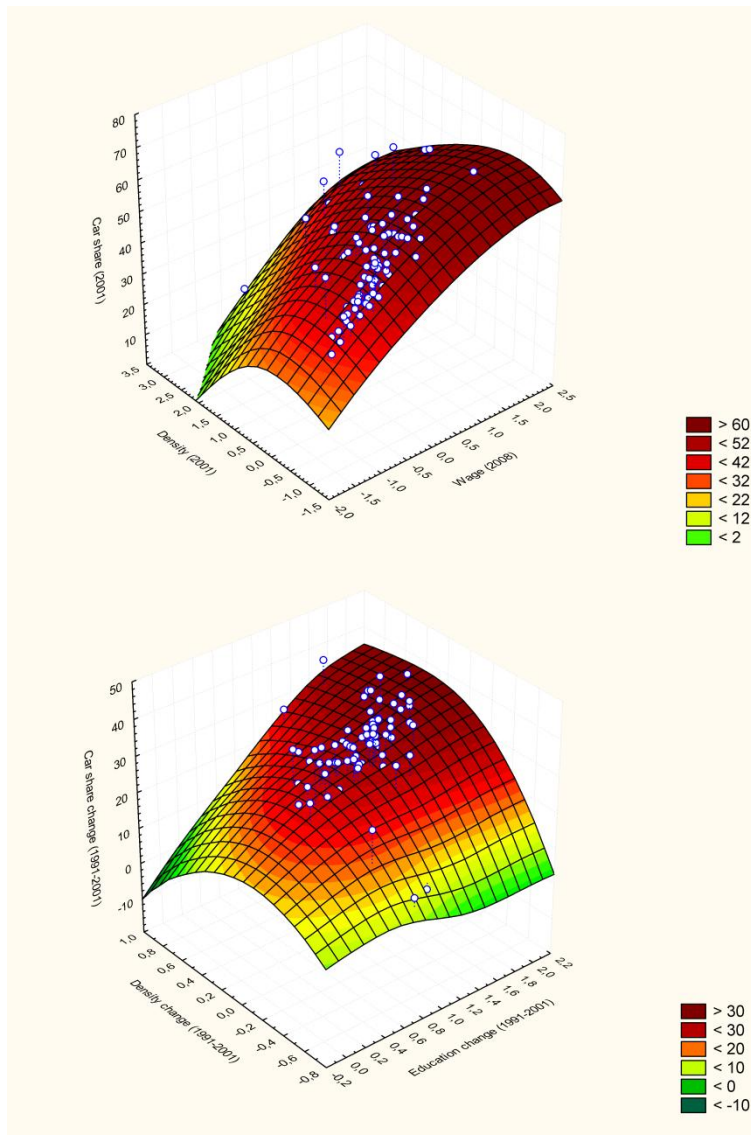


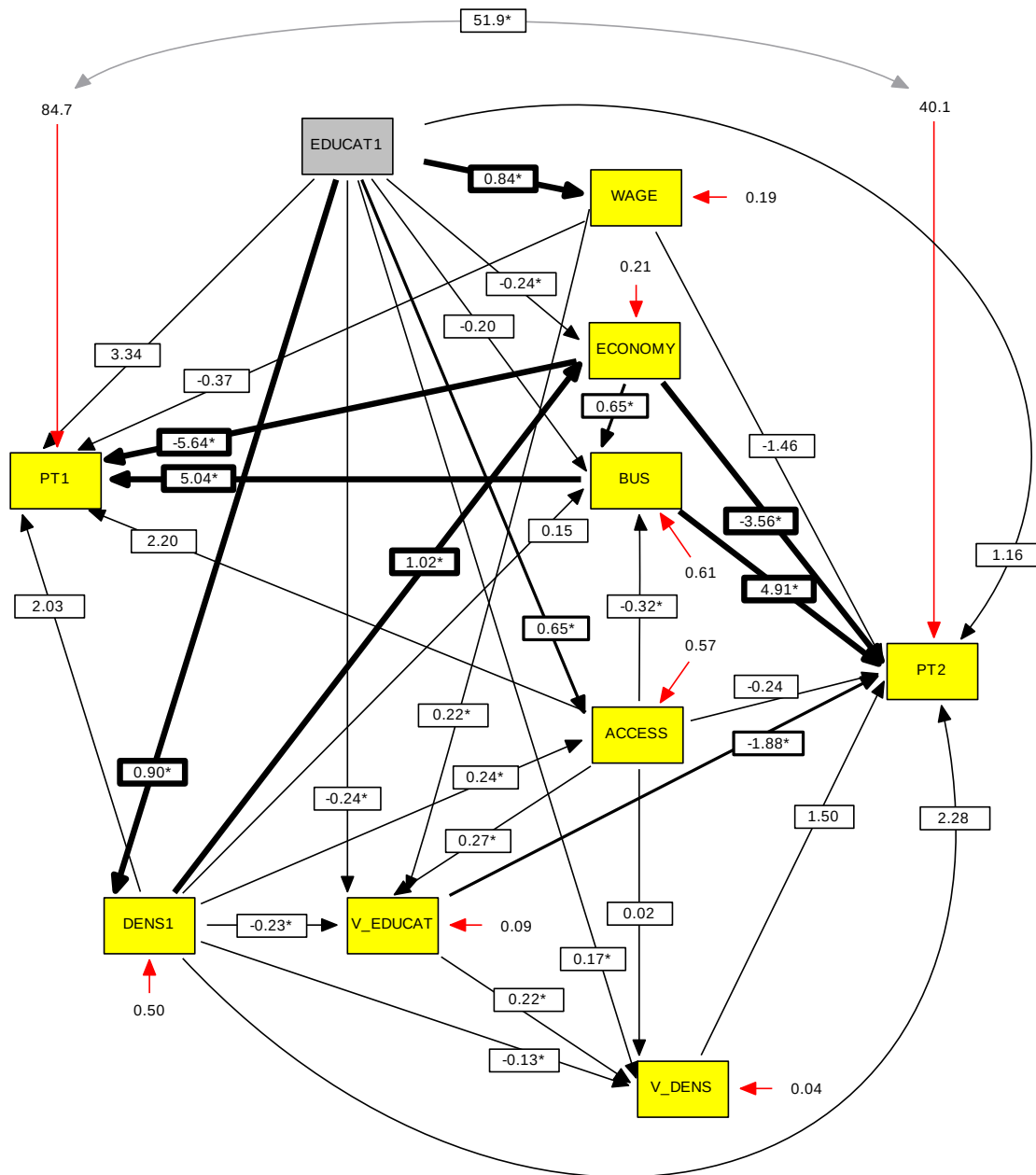
Figure 5.4-5: Fitted 3D curves to the real data points and having car shares and their longitudinal changes as dependent variables.

□ Modal share: public transports

Figure 5.4-6 graphically displays the results obtained with the structural equation model of car shares. Table 5.4-3 complements this information with the estimated total effects caused by each variable. The main results can be summarized as follows:

- probably because of the (only) acceptable fit of this model, most effects on public transport shares were not significant. Nonsignificant effects include those from education, wage and density change (1991–2001), and the direct effects from density and accessibility. There are, however, some exceptions to this pattern, as explained below;
- the largest effect was that of bus net density on public transport shares. It was positive and large in both periods;

- the direct effect of education change (1991–2001) on public transport shares (2001) was significant and negative, although of modest size. The total effect was not significant;
- direct effects of economy on public transport shares were negative and large, but total effects were not significant. This is explained by the indirect effects via the positive influence of economy on bus net density;
- there was a significant positive total effect of density (1991) on public transport shares (2001). The effect size was moderate. The explanation lies mainly in the paths linking density and car shares through bus net density and through education change (1991–2001);
- similarly, there was a significant and moderate, although negative, total effect of accessibility on public transport shares in 2001. The reason for this had to do with the negative effect of accessibility on bus net density.



Robust statistics: Chi Sq.=22.9, p=0.03, df=12, SRMS=0.04, RMSEA=0.09 (0.03 < 90% CI < 0.14), CFI=0.98, NNFI=0.93, GFI=0.96

Figure 5.4-6: Structural equation model explaining public transport shares. Numbers indicate direct effects. PT1: modal share of public transports (1991); PT2: modal share of public transports (2001); EDUCAT1: education (1991); V_EDUCAT: education change (1991–2001); DENS1: density (1991); V_DENS: density change (1991–2001); BUS: bus net density (2008).

Table 5.4-3: Effects decomposition for the structural equation model of public transports share.

Causal variable	Endogenous variable			
	Modal share of PT (1991)		Modal share of PT (2001)	
	Direct effects	Total effects	Direct effects	Total effects
Education	3,342 (2,838)	3,444 (5,482)	1,163 (1,468)	0,031 (3,152)
(1991)	1,178	0,628	0,792	0,010
Education change			-1,881* (0,846)	-1,559 (0,813)
(1991–2001)			-2,223	-1,917
Wage	-0,367 (2,163)	-0,367 (2,163)	-1,458 (1,196)	-1,796 (1,193)
(2008)	-0,170	-0,170	-1,219	-1,505
Density	2,028 (1,944)	0,504 (1,014)	2,276 (1,383)	2,269* (0,701)
(1991)	1,043	0,497	1,646	3,237
Density change			1,500 (1,270)	1,500 (1,270)
(1991–2001)			1,181	1,181
Economy	-5,643* (1,518)	-2,367 (1,557)	-3,555* (1,120)	-0,367 (1,221)
(2005)	-3,717	-1,501	-3,175	-0,300
Bus net density	5,042* (1,085)	5,042* (1,085)	4,907* (0,831)	4,907* (0,831)
(2008)	4,646	4,646	5,904	5,904
Accessibility	2,198 (1,331)	0,582 (1,435)	-0,243 (0,979)	-2,214* (1,117)
(2001)	1,651	0,405	-0,248	-1,982)

Parameter estimates are presented in the first line of each row (robust standard errors in parenthesis); robust test statistics are presented in the second line. Statistics significant at the 5% level are marked with *. Significant total effects are colored according to their influence on the modal share.

Figure 5.4-7 shows two 3D curves fitted to the real data points having the two most important variables as the x and y axis.

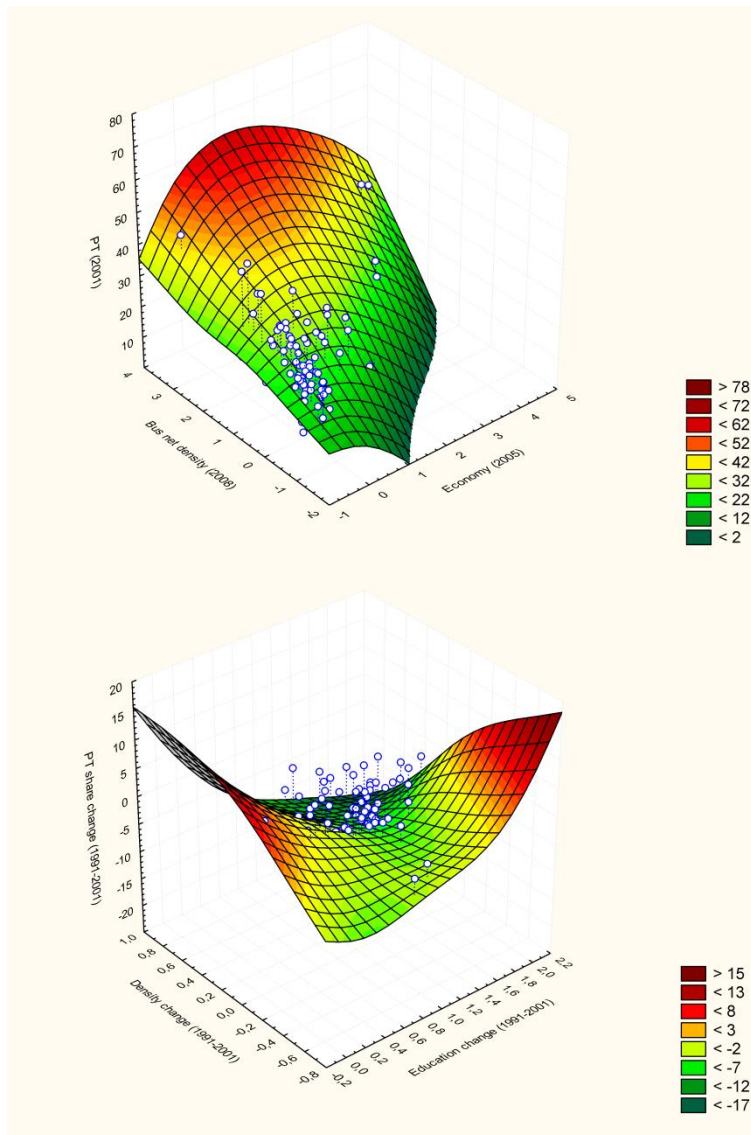


Figure 5.4-7: Fitted 3D curves to the real data points and having public transport shares and their longitudinal changes shares as dependent variables.

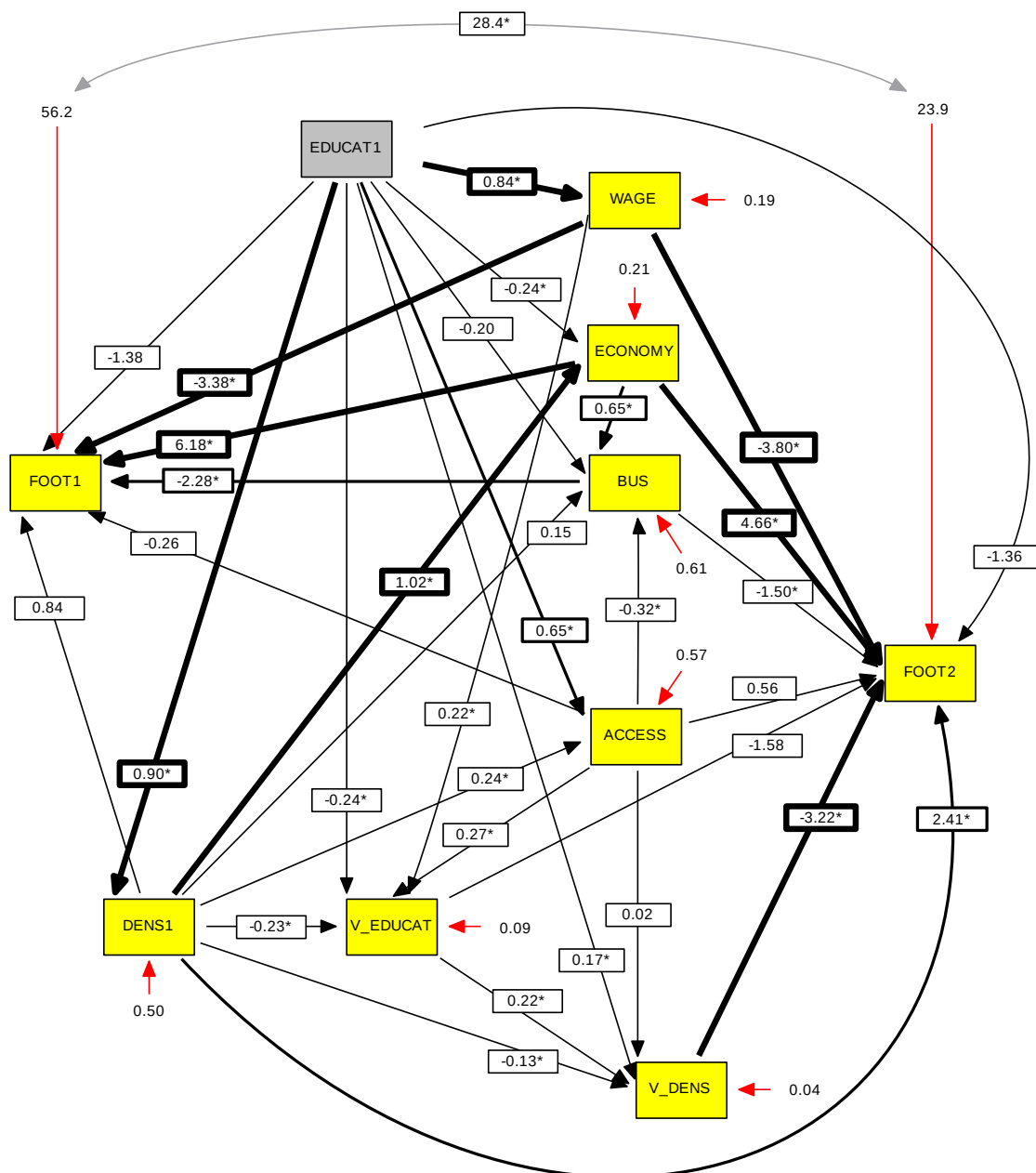
□ Modal share: foot

Figure 5.4-8 graphically displays the results obtained with the structural equation model of foot shares. Table 5.4-4 complements this information with the estimated total effects caused by each variable. The main results can be summarized as follows:

- none of the effects of education and accessibility on foot shares were significant; the total effect of education change (1991–2001) on foot shares (2001), however, proved significant. The effect was moderate and negative;
- the largest effect was that of economy on foot shares. It was positive and large in both periods;
- density (1991) had a nonsignificant direct effect on foot shares in 1991 and a moderately positive direct effect on foot shares in 2001. This longitudinal influence was due to the

large positive effect of density on economy which, in turn, was also positively associated with commuting by foot. Total effects of density on foot shares were large and positive in both periods;

- contrasting with the above effect, density change (1991–2001) was negatively and moderately associated with foot shares;
- the effects of wage on foot shares were negative and large in both time periods;
- bus net density exerted a significant and moderately negative effect on foot shares in both periods.



Robust statistics: Chi Sq.=15.7, p=0.21, df=12, SRMS=0.02, RMSEA=0.02 (0.00 < 90% CI < 0.10), CFI=1.00, NNFI=0.99, GFI=0.98

Figure 5.4-8: Structural equation model explaining foot shares. Numbers indicate direct effects. FOOT1: modal share of foot (1991); FOOT2: modal share of foot (2001); EDUCAT1: education (1991); V_EDUCAT: education change (1991–2001); DENS1: density (1991); V_DENS: density change (1991–2001); BUS: bus net density (2008).

Table 5.4-4: Effects decomposition for the structural equation model of foot shares.

Causal variable	Endogenous variable			
	Modal share of foot (1991)		Modal share of foot (2001)	
	Direct effects	Total effects	Direct effects	Total effects
Education (1991)	-1,382 (1,782) -0,776	0,293 (3,337) 0,000	-1,362 (1,133) -1,202	0,991 (2,304) 0,430
Education (1991–2001)			-1,586 (1,161) -1,366	-2,277* (0,998) -2,282
Wage (2008)	-3,378* (1,020) -0,252	-3,378* (1,443) -2,342	-3,800* (0,883) -4,305	-4,294* (0,892) -4,815
Density (1991)	0,841 (1,603) 0,525	5,425* (0,807) 6,720	2,408* (1,054) 2,285	6,990* (0,565) 12,369
Density (1991–2001)			-3,215* (1,353) -2,377	-3,215* (1,353) -2,377
Economy (2005)	6,185* (1,053) 5,874	4,703* (1,074) 4,380	4,668* (0,712) 6,552	3,692* (0,722) 5,113
Bus net density (2008)	-2,281* (0,840) -2,716	-2,281* (0,840) -2,716	-1,502* (0,569) -2,641	-1,502* (0,569) -2,641
Accessibility (2001)	-0,258 (1,020) -0,252	0,473 (0,961) 0,493	0,565 (0,765) 0,738	0,364 (0,756) 0,481

Parameter estimates are presented in the first line of each row (robust standard errors in parenthesis); robust test statistics are presented in the second line. Statistics significant at the 5% level are marked with *. Significant total effects are colored according to their influence on the modal share.

Figure 5.4-9 shows two 3D curves fitted to the real data points having the two most important variables as the x and y axis.

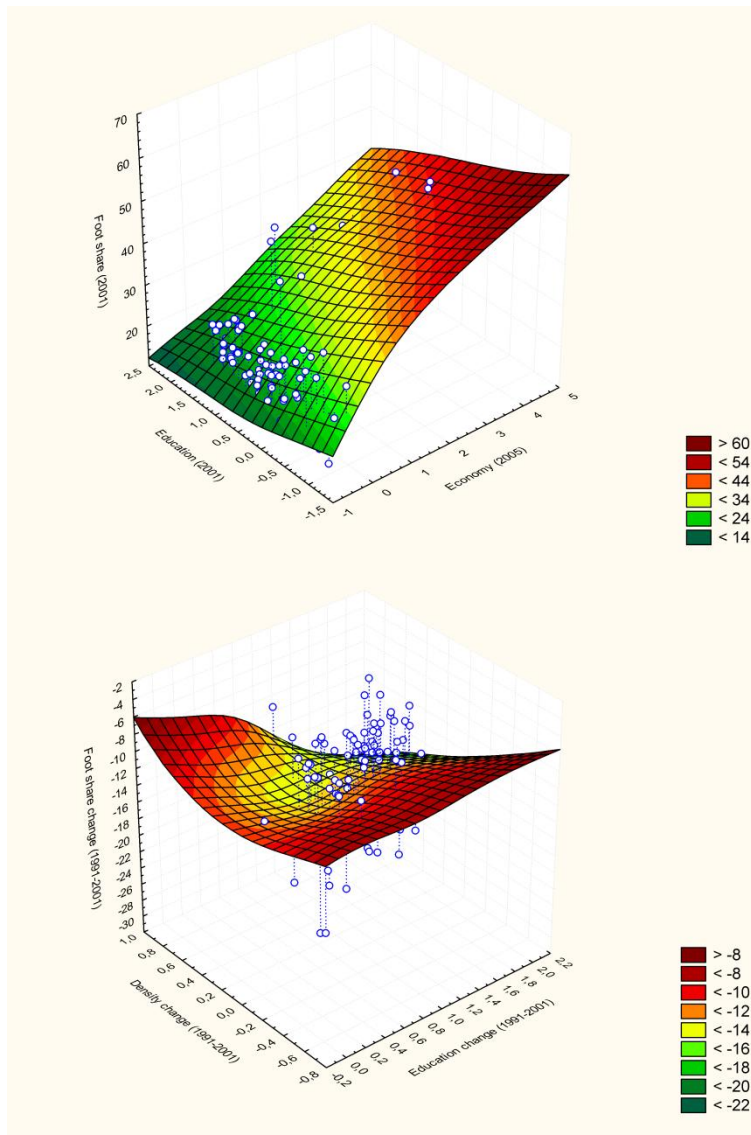


Figure 5.4-9: Fitted 3D curve to the real data points and having foot shares and their longitudinal changes as dependent variables.

5.4.2 Modeling with support vector machines

Three models were built, one for each dependent variable: modal share of car, modal share of public transport, and modal share of foot. Goodness of fit statistics and results are presented for the three models simultaneously.

Goodness of fit

Similarly to what has been found for SEM, goodness of fit statistics suggest that support vectors explaining car and foot shares fit data well, and public transport shares less well. This is visible by comparing model errors and the correlation coefficients between the actual data and the predicted values (Table 5.4-5 and Figure 5.4-10).

Table 5.4-5: Goodness of fit statistics for the structural equation models.

	Summary Goodness of Fit (SVM PT) Observed variable: Modal_share_PT				
	1 Mean square error	2 Mean absolute error	3 Mean relative squared error	4 Mean relative absolute error	5 Correlation coefficient
Modal_share_PT	64,3933547	6,00558811	0,0938645805	0,214713709	0,586851103
Modal_share_foot	41,1673507	5,07036668	0,0466092597	0,175906965	0,813772253
Modal_share_car	13,0596172	2,68892041	0,0208354621	0,103348914	0,97965026

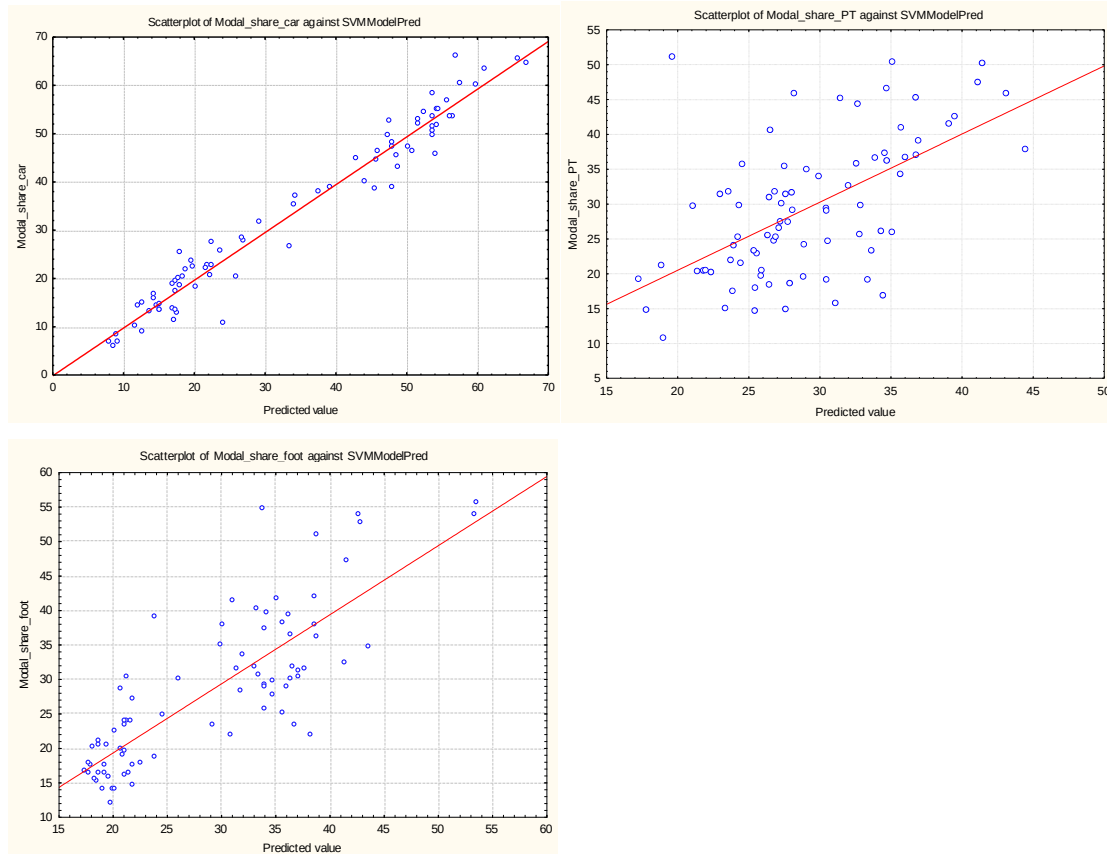


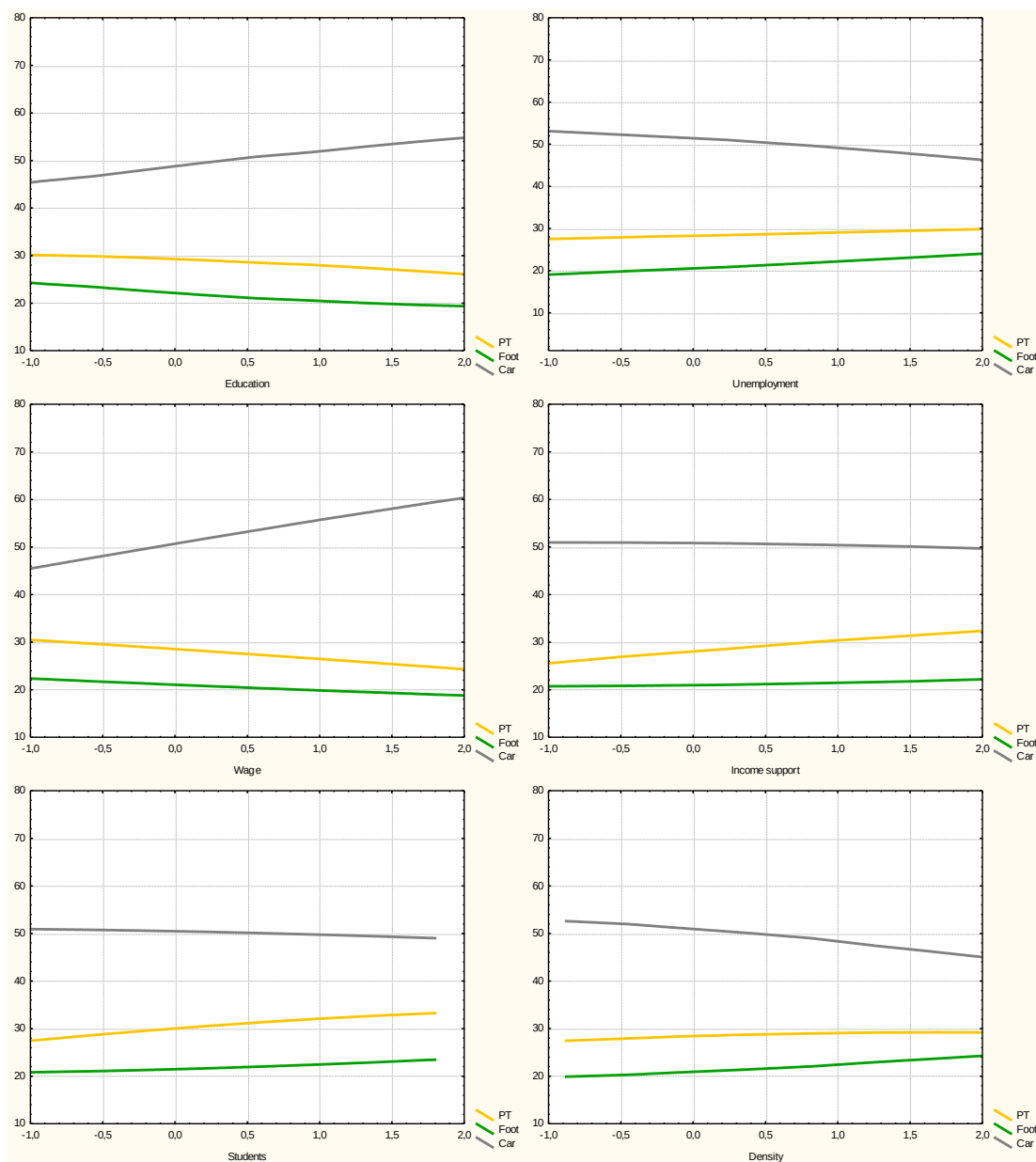
Figure 5.4-I0: Goodness of fit scatter plots for the support vector machines models.

Results

Unlike the results of SEM, no indirect effects may be tested through support vector machines. However, possible nonlinearities could become evident. The influence of each independent variable on the three modal shares is shown in Figure 5.4-II. The main results can be summarized as follows:

- car shares rose sharply with education and wage, decreased sharply with density and bus net density, and decreased moderately with unemployment. Car shares did not seem to be significantly influenced by the proportion of students in the population, by economy nor by agriculture;

- public transport shares increased most strongly with bus net density and moderately with the proportion of students. They decreased moderately with education, wage, economy and agriculture. Public transport shares did not seem to be significantly influenced by unemployment not density;
- foot shares rose moderately with economy, and slightly with unemployment and density. They decreased with education and were largely independent from the proportion of students, wage, bus net density and agriculture;
- results suggest the existence of two nonlinearities: the decrease of foot shares almost halt at around 0,75 education standard deviations; and the effect of density on shares of car and foot is amplified at values higher than 1 standard deviation.



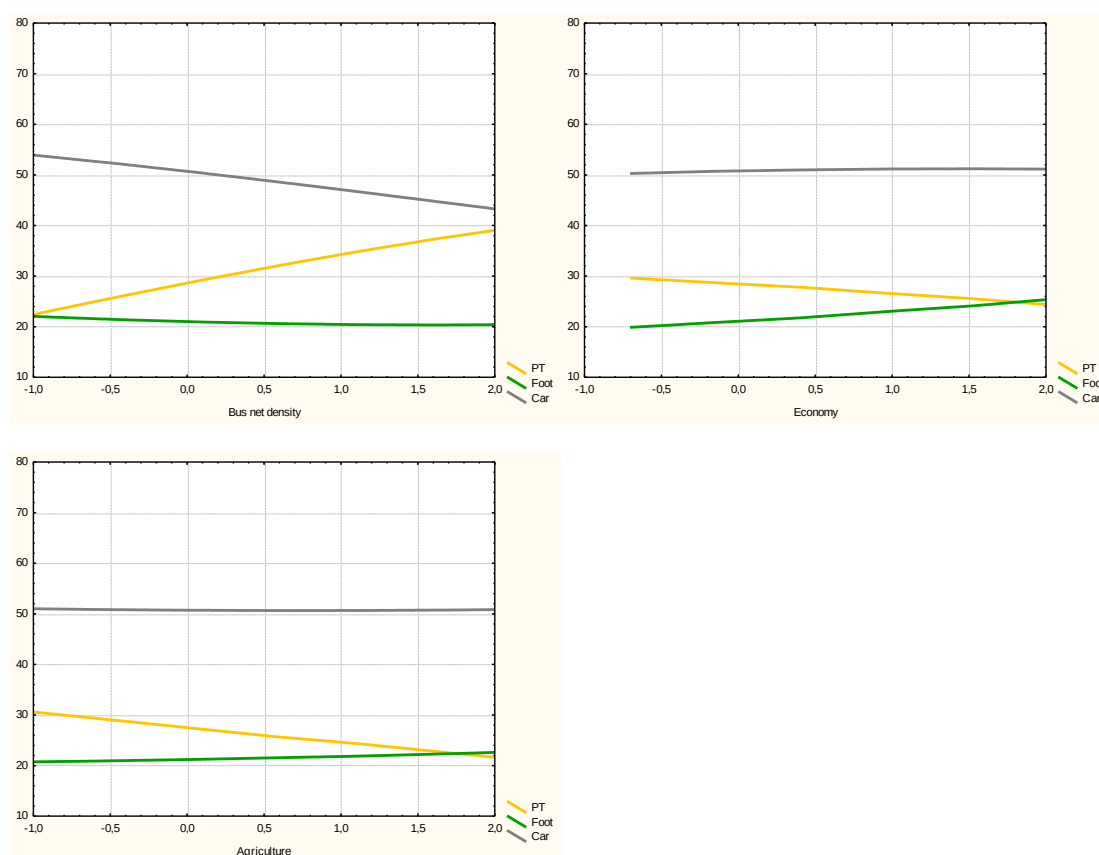


Figure 5.4-I I: Visualization of the support vector machine models.

5.5 Urban growth

The Metropolitan Area of Porto has been experiencing a rapid urban growth. Classification of satellite images into four land cover classes revealed that, from 1990 until 2006, the region urbanized around 8,5 thousand ha of land. Urban growth was particularly significant in the municipalities of Vila Nova de Gaia, Maia and Valongo (Table 5.5-I and Figure 5.5-1). A longer time-series (1958–1997) is visible in Figure 5.5-2 for the core of the region.

Table 5.5-I: Urban expansion in the municipalities of the Metropolitan Area of Porto.

Municipality	Urban expansion (ha)	Urban expansion (ha)	Total
	2000–2006	1990–2000	
Espinho	49	78	127
Gondomar	392	579	971
Maia	508	831	1339
Matosinhos	301	716	1017
Porto	169	276	445
Póvoa de Varzim	102	497	600

Municipality	Urban expansion (ha)	Urban expansion (ha)	Total
	2000–2006	1990–2000	
Valongo	426	840	1266
Vila do Conde	154	752	907
Vila Nova de Gaia	603	1266	1869
Total	2704	5835	8539

Urban expansion

From 1990 to 2006

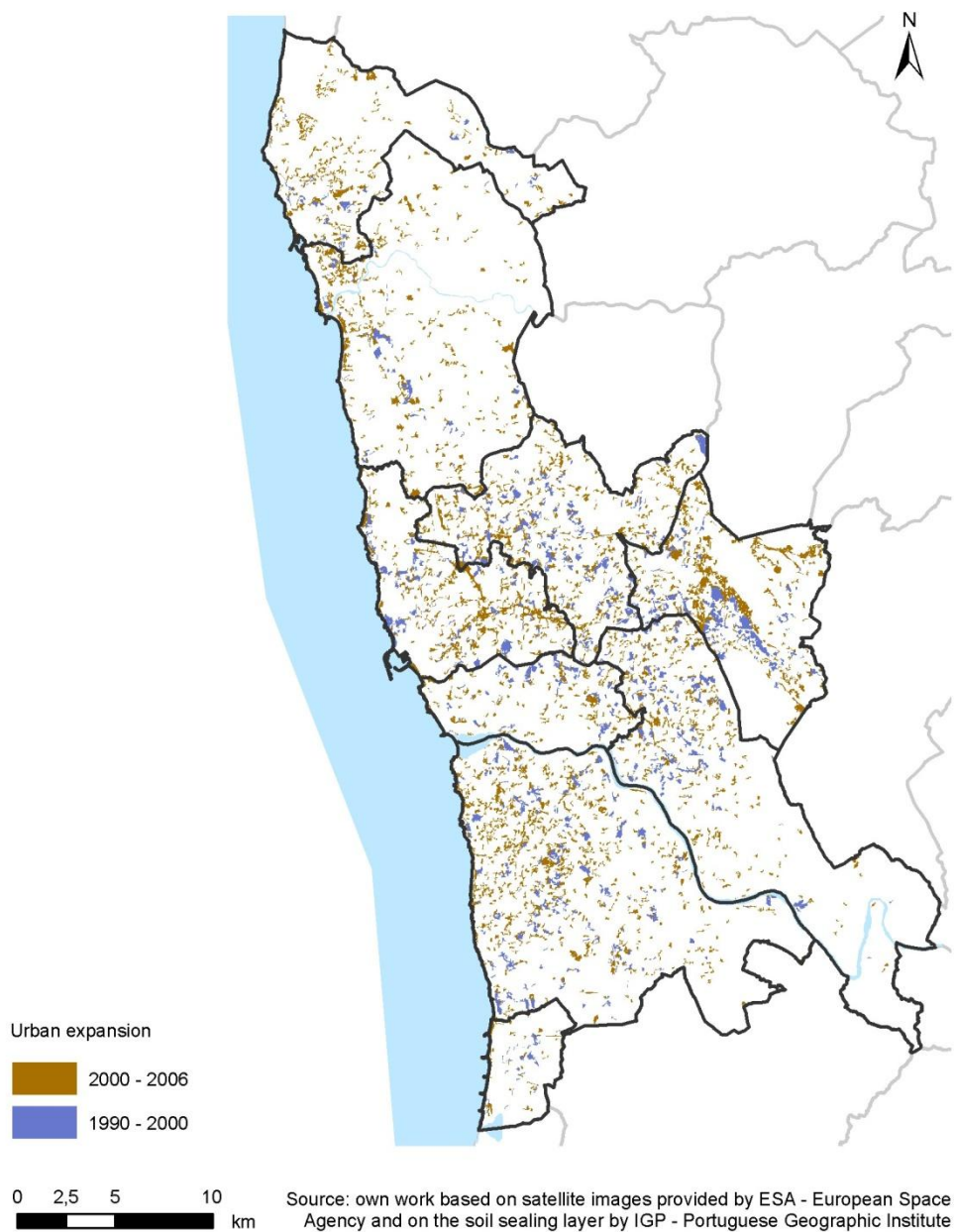


Figure 5.5-1: Dasymetric map of urban expansion in the Metropolitan Area of Porto.

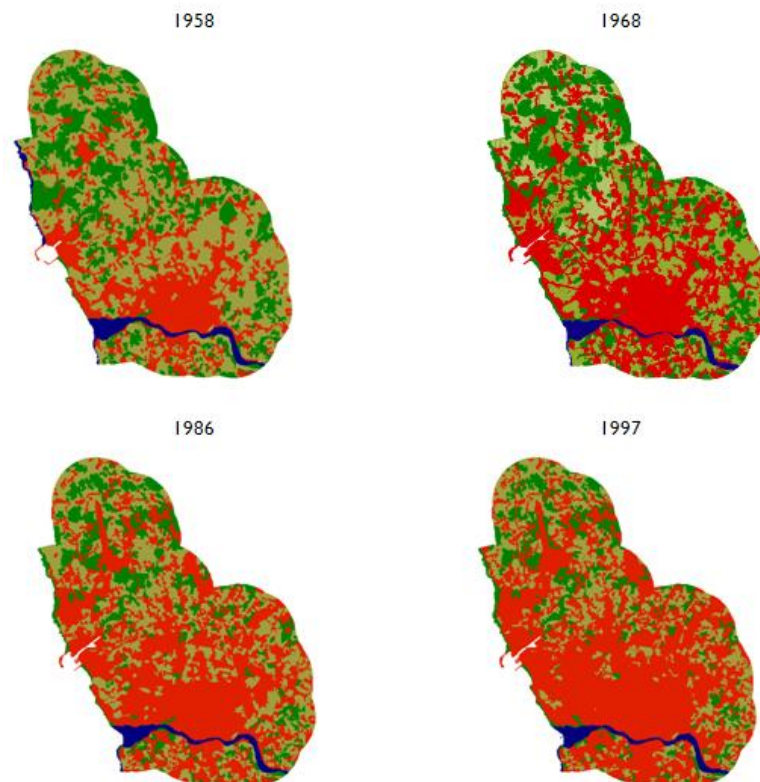


Figure 5.5-2: Evolution of land cover in the Porto region since 1958. Source: Lavalle, et al., 2002.

A worrying phenomenon related to urban growth is the so-called “donut effect”: boroughs with the highest densities in the inner city have been losing population to boroughs in the suburbs (Figure 5.5-3). The process was described in detail in section 3.3. Although obtained from different indicators, density change and urban growth are highly correlated (Figure 5.5-4). From the perspective of density change, boroughs in the municipalities of Vila Nova de Gaia, Maia and Valongo again show the greatest increases.

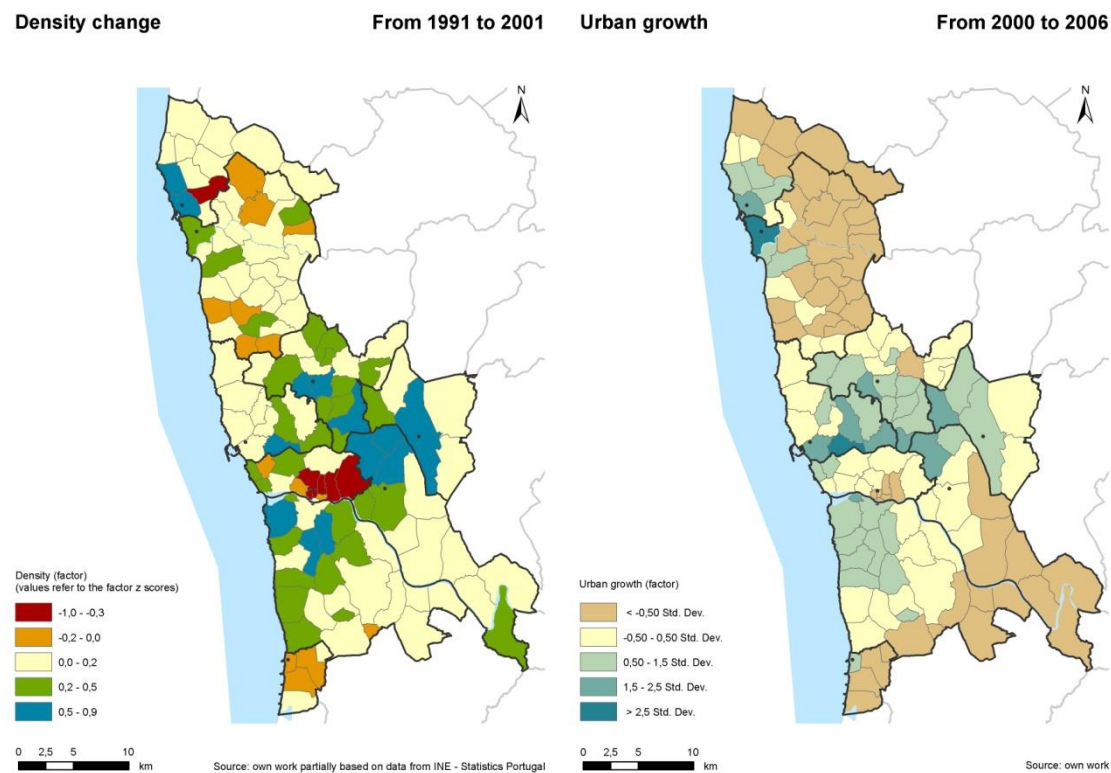


Figure 5.5-3: Change in density and urban growth.

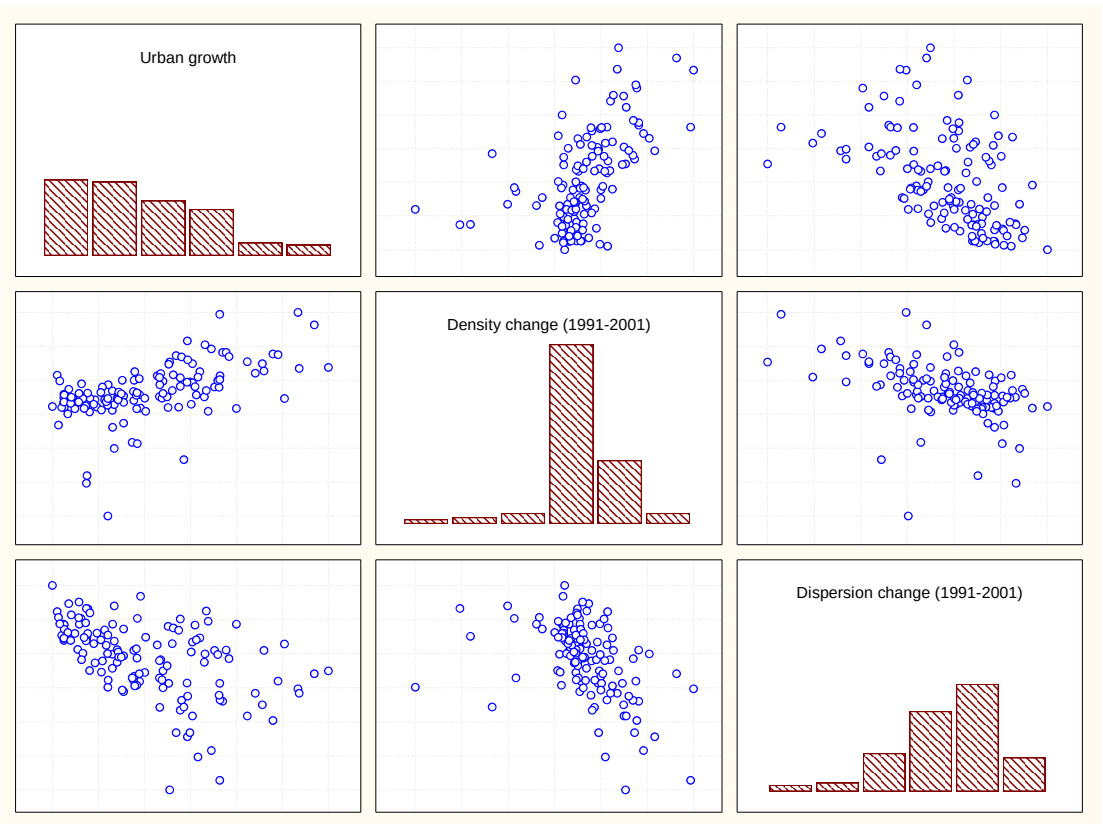


Figure 5.5-4: Matrix plot of urban growth, and longitudinal changes in education and density.

Typical population density trajectories are plotted in Figure 5.5-5. Santo Ildefonso is a good example of a markedly declining territory right in the center of the “donut.” Population densities, however, are nowadays still much larger than the average. Other high-density boroughs such as Ramalde are also declining, but the decrease is much less pronounced. In Gaia, Vilar de Andorinho serves as an example of an averaged density borough which is growing very fast. Beiriz serves as contrast because has been declining, perhaps because of its rural environment. There are other examples in-between.

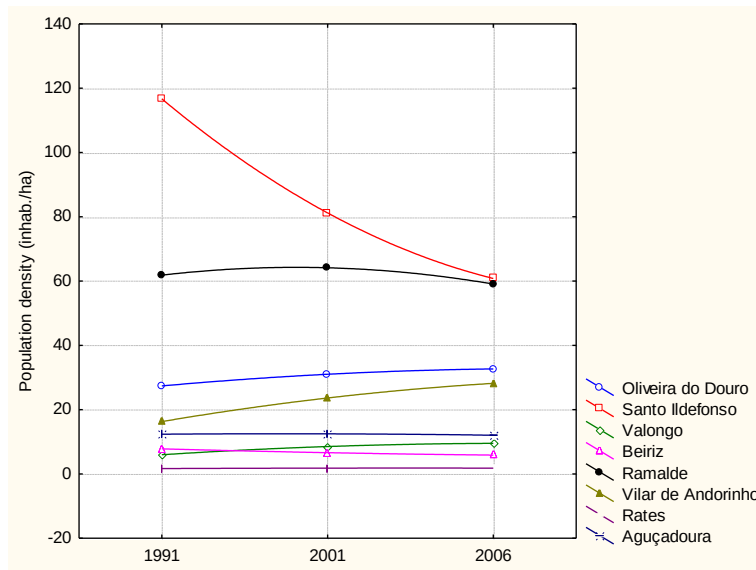


Figure 5.5-5: Typical population density trajectories.

5.5.1 Modeling with generalized estimating equations

Goodness of fit

Available goodness of fit statistics were rather limited for the generalized estimating equations, and they were used mainly to determine the best correlation structure (Figure 5.5-2). Still, the scatter plot of the predicted values against the actual data suggests a good model fit (Figure 5.5-6).

Table 5.5-2: Goodness of fit statistics for the generalized estimating equations model.

Goodness of Fit ^b	
	Value
Quasi Likelihood under Independence Model Criterion (QIC) ^a	111,889
Corrected Quasi Likelihood under Independence Model Criterion (QICC) ^a	110,040

Dependent Variable:
Urban_growth
Model: (Intercept),
Distancia_Porto,
Distancia_Douro, Accessibility,
Agriculture,
Distancia_Porto_Accessibility,
Distancia_Douro_2,
Accessibility_2

a. Computed using the full log quasi-likelihood function.

b. Information criteria are in small-is-better form.

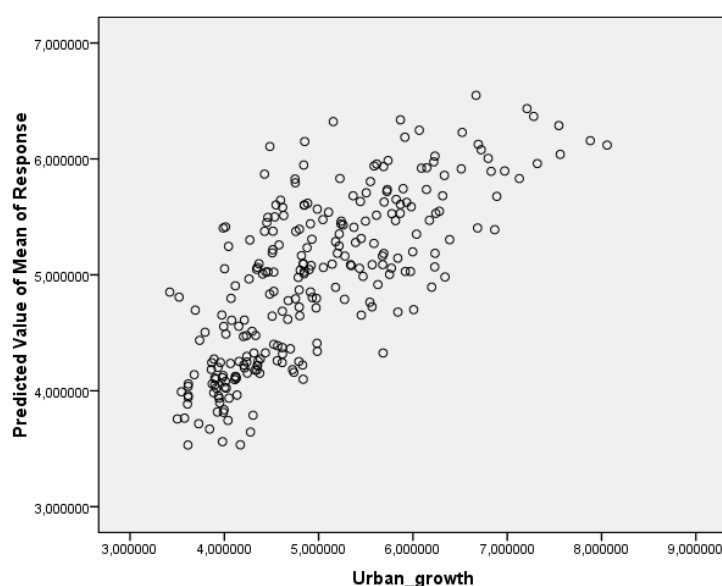


Figure 5.5-6: Goodness of fit scatter plot for the generalized estimating equations model.

Results

Parameter estimates are presented in Table 5.5-3. Exponentiated parameter estimates should be preferred in accessing variable importance. Figure 5.5-7 complements this information with simulated curves, and annex A.9 displays partial residual plots. Results can be summarized as follows:

- accessibility played the most important role in explaining urban growth. Its effect was positive and exponential. The effect size was small, however, when accessibility levels were below average and when distances from the center of Porto were short;

- the role of agriculture was positive but less relevant, and was probably related to the lower land prices of agricultural areas;
- shorter distances from the amenity river Douro were associated with lower rates of growth. This is probably explained by the fact that some riverside boroughs were already densely built up and had little room to grow, and by the fact that only recently the “appetite” for river fronts have emerged in boroughs where urban expansion land is available;
- growing distances from Porto were associated with lower rates of urban growth;
- birth rate, density and natural capital were not significantly associated with urban growth when the retained model variables were controlled for.

Table 5.5-3: Parameter estimates for the model explaining urban growth.

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	1,624	,0202	1,584	1,663	6459,747	1	,000
Distancia_Porto	-,034	,0177	-,068	,001	3,627	1	,057
Distancia_Douro	,029	,0129	,004	,055	5,217	1	,022
Accessibility	,159	,0175	,125	,193	82,559	1	,000
Agriculture	,033	,0118	,010	,056	7,975	1	,005
Distancia_Porto_Accessibility	,029	,0103	,009	,049	7,850	1	,005
Distancia_Douro_2	-,077	,0180	-,112	-,042	18,261	1	,000
Accessibility_2	,060	,0106	,039	,081	32,047	1	,000
(Scale)	,385						

Dependent Variable: Urban_growth

Model: (Intercept), Distancia_Porto, Distancia_Douro, Accessibility, Agriculture, Distancia_Porto_Accessibility, Distancia_Douro_2, Accessibility_2

Parameter	Exp(B)	95% Wald Confidence Interval for Exp(B)	
		Lower	Upper
(Intercept)	5,073	4,876	5,278
Distancia_Porto	,967	,934	1,001
Distancia_Douro	1,030	1,004	1,056
Accessibility	1,172	1,133	1,213
Agriculture	1,034	1,010	1,058
Distancia_Porto_Accessibility	1,029	1,009	1,050
Distancia_Douro_2	,926	,894	,959
Accessibility_2	1,062	1,040	1,084
(Scale)			

Dependent Variable: Urban_growth

Model: (Intercept), Distancia_Porto, Distancia_Douro, Accessibility, Agriculture, Distancia_Porto_Accessibility, Distancia_Douro_2, Accessibility_2

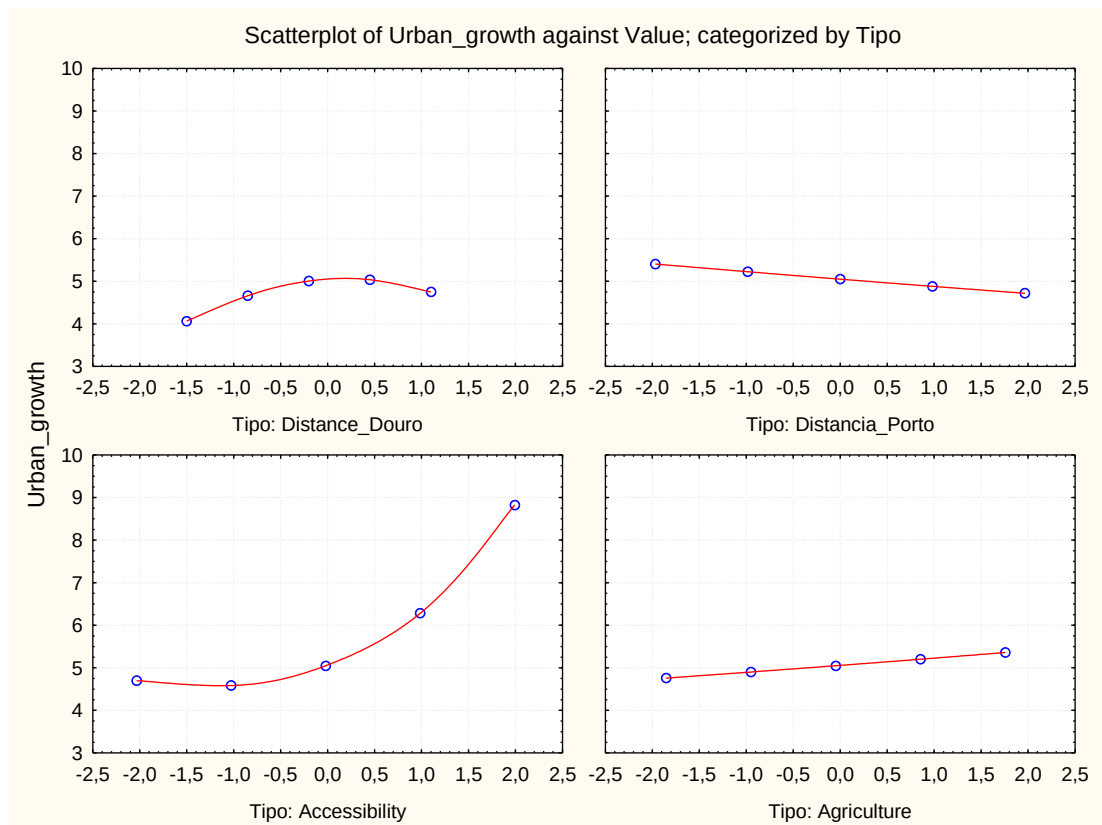


Figure 5.5-7: Visualization of the model explaining urban growth.

The importance of accessibility is spatially displayed in Figure 5.5-8. Most of the urban expansion areas concentrate around highway nodes and are located in boroughs with accessibility levels.

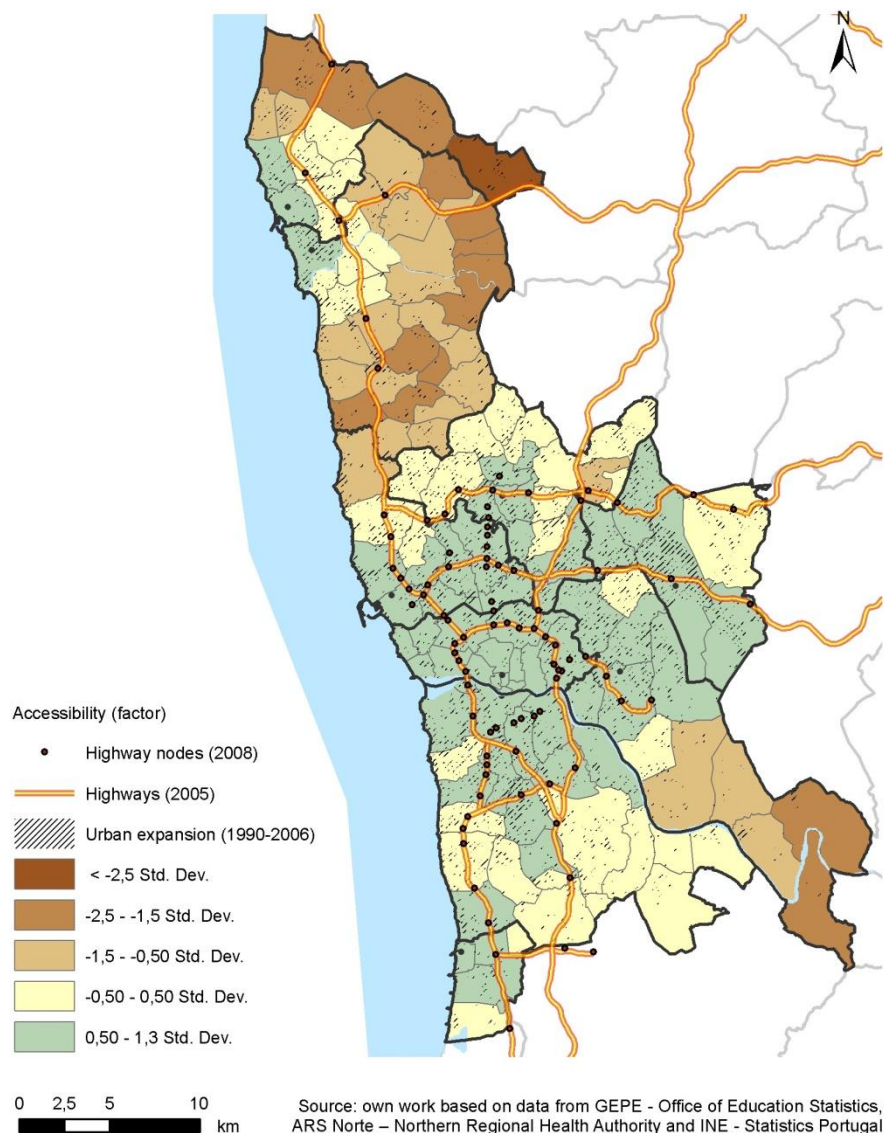
Accessibility**2006**

Figure 5.5-8: Accessibility and urban expansion in the Metropolitan Area of Porto.

5.6 Residential water consumption

Residential water consumption averaged 40 m³ *per capita* in 2006. Consumption was higher in Porto, lower in Maia, and even lower in Matosinhos and Espinho (Figure 5.6-1). Data for the remainder municipalities were unavailable or unreliable.

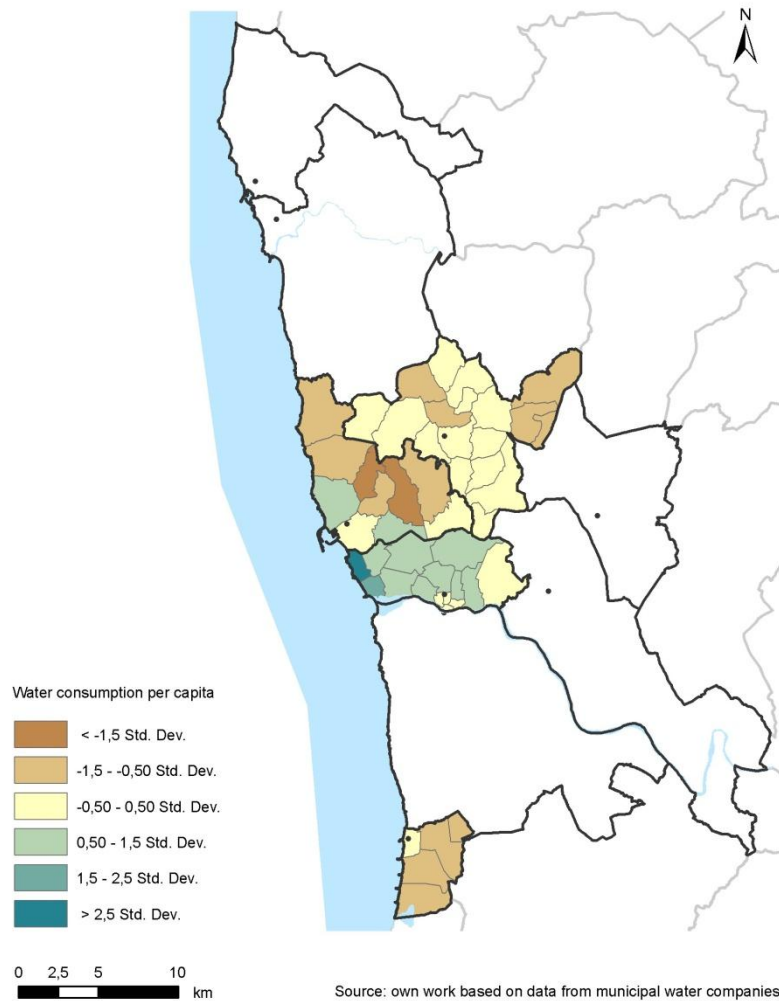
Water consumption**2006**

Figure 5.6-1: Water consumption in the Metropolitan Area of Porto.

5.6.1 Modeling with multiple regression*Goodness of fit*

Goodness of fit statistics indicate a model with a high explanatory power (adjusted $R^2 = 0,78$) – cf. Table 5.6-1. The scatter plot of the predicted values against the actual data also supports a good model fit (Figure 5.5-6).

Table 5.6-1: Goodness of fit statistics for the multiple regression model.

Dependent Variable	Test of SS Whole Model vs. SS Residual						
	Multiple R	Multiple R ²	Adjusted R ²	SS Model	df Model	F	p
Water_consumption	0,892619	0,796768	0,781526	1878,127	3	52,27328	0,000000

Univariate Tests of Significance for Water_consumption Sigma-restricted parameterization Effective hypothesis decomposition						
Effect	SS	Degr. of Freedom	MS	F	p	
Intercept	13568,61	1	13568,61	1132,951	0,000000	
Aging/Lone hh.	383,89	1	383,89	32,054	0,000001	
Wage	840,70	1	840,70	70,197	0,000000	
Agriculture	57,35	1	57,35	4,789	0,034544	
Error	479,05	40	11,98			

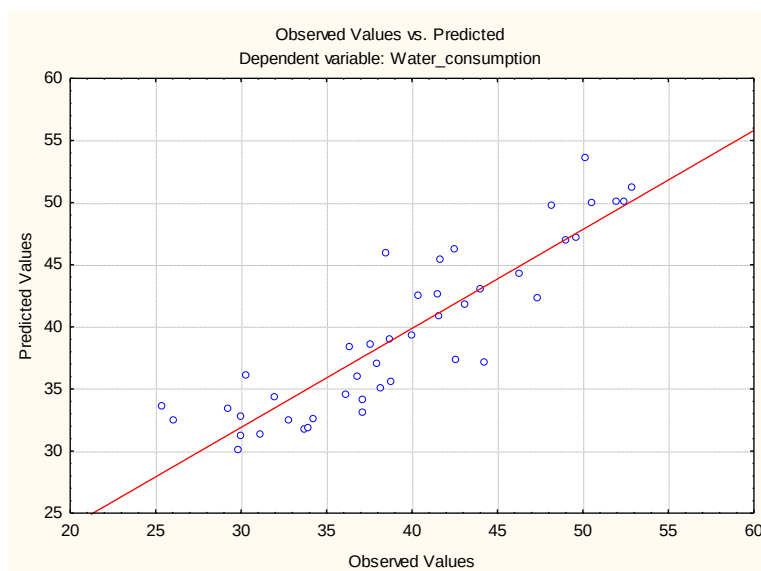


Figure 5.6-2: Goodness of fit scatter plot for the multiple regression model.

Results

Parameter estimates are presented in Table 5.5-3. Because there are many missing values, it is better to assess variable importance with the standardized regression coefficients (β) than with the normal parameter estimates. Figure 5.5-7 complements this information with simulated curves, and annex A.9 displays partial residual plots. Results can be summarized as follows:

- wage played the most important role in explaining residential water consumption;
- older or single-person households consumed more water *per capita* than younger or larger households. This effect was smaller than the effect of wage but it was still large;

- agriculture was associated with lower *per capita* consumption of water. This is most probably attributable to self-consumption from farm wells thereby reducing the amount of water bought to the municipal water companies;
- no nonlinear terms were found significant;
- education, birth rate, income support, density, natural capital, accessibility, basic services, damaged buildings, economy and occupation regularity were not significantly associated with water consumption when the retained model variables were controlled for.

Table 5.6-2: Parameter estimates for the model explaining water consumption.

Effect	Parameter Estimates (FINAL in 2009-07-06 - T20.stw)						
	Water_consumption Param.	Water_consumption Std.Err	Water_consumption t	Water_consumption p	-95,00% Cnf.Lmt	+95,00% Cnf.Lmt	Water_consumption Beta (β)
Intercept	33,02599	0,981183	33,65934	0,000000	31,04295	35,00904	
Aging	2,46938	0,436158	5,66165	0,000001	1,58787	3,35088	0,454742
Wage	5,67725	0,677607	8,37837	0,000000	4,30775	7,04674	0,606976
Agriculture	-3,58298	1,637296	-2,18835	0,034544	-6,89208	-0,27388	-0,174492

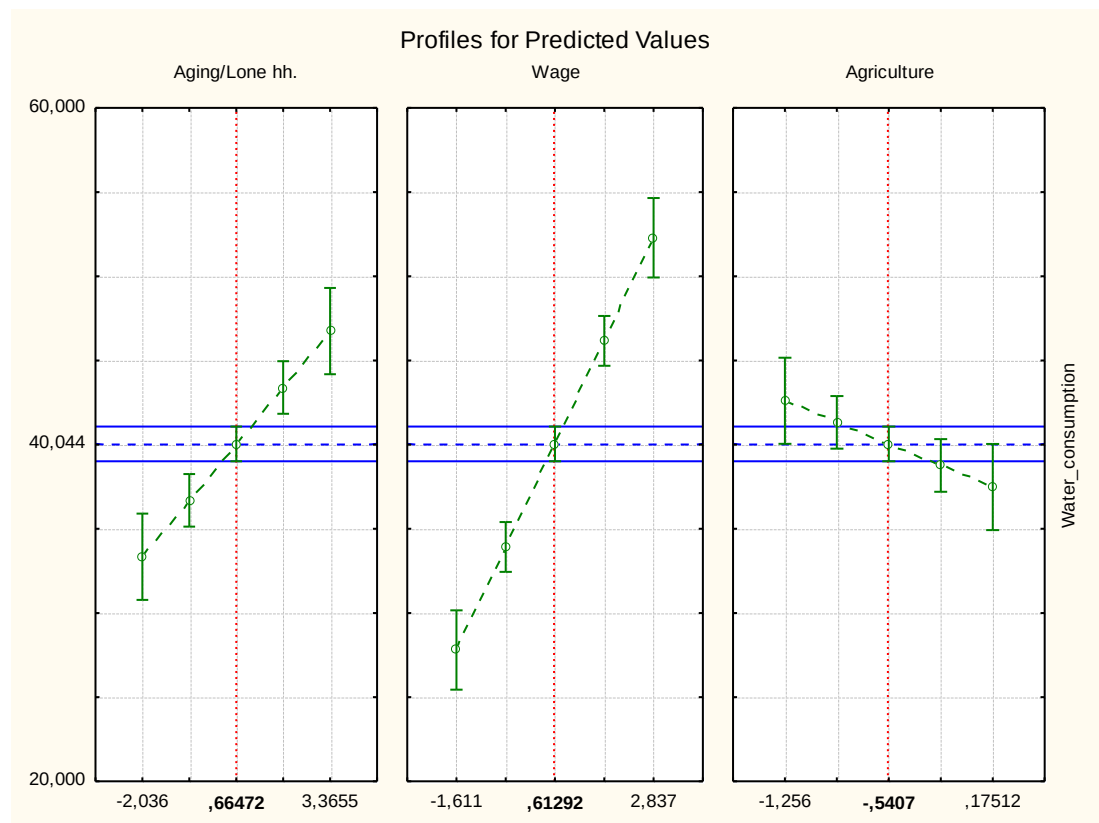


Figure 5.6-3: Visualization of the model explaining residential water consumption.

Figure 5.6-4 shows a 3D curve fitted to the real data points having the two most important variables as the x and y axis.

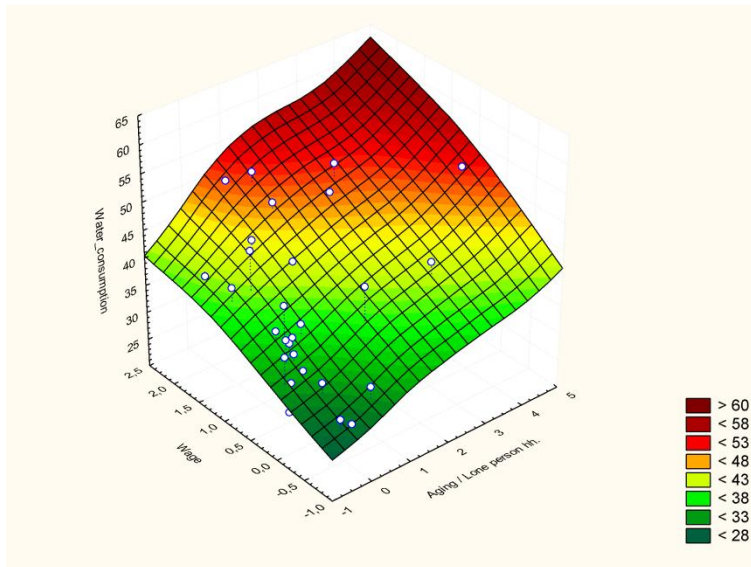


Figure 5.6-4: Fitted 3D curve to the real data points having water consumption as the dependent variable.

5.7 Residential electricity consumption

Residential electricity consumption averaged 1330 kWh *per capita* in 2007. The pattern is not very clear, but at the first glance more urbanized places seem to be more intensive consumers (Figure 5.6-1).

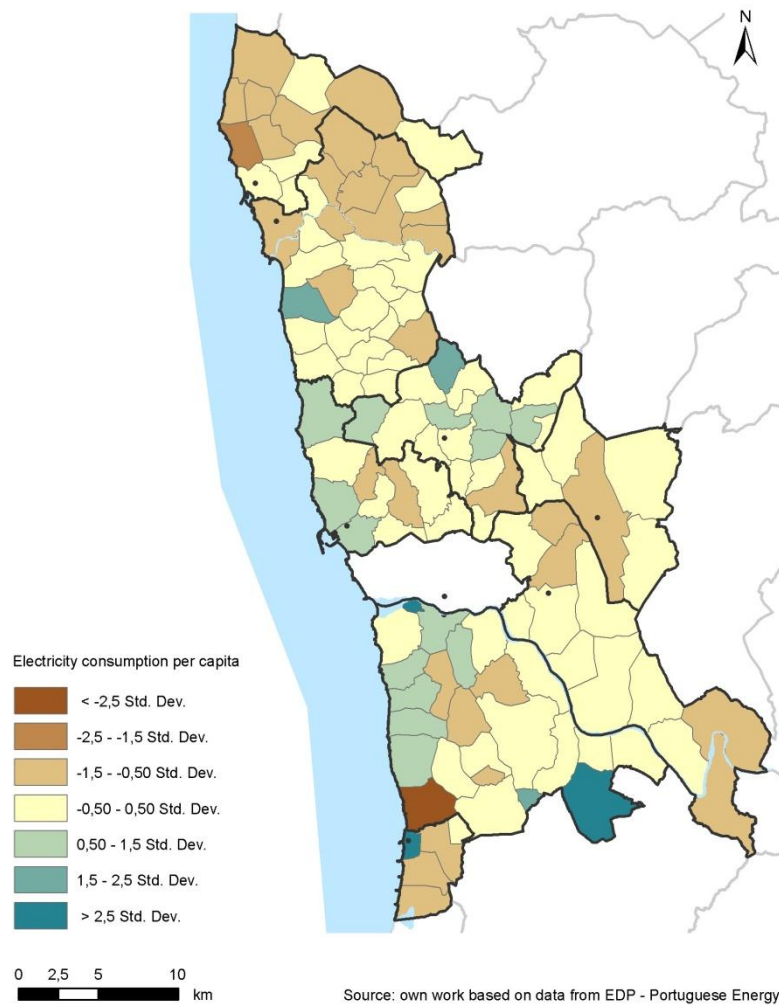
Electricity consumption**2007**

Figure 5.7-1: Electricity consumption in the Metropolitan Area of Porto.

5.7.1 Modeling with multiple regression*Goodness of fit*

Goodness of fit statistics a model with a high explanatory power (adjusted $R^2 = 0,72$) – cf. Table 5.7-1. The scatter plot of the predicted values against the actual data also supports a good model fit (Figure 5.7-2).

Table 5.7-1: Goodness of fit statistics for the multiple regression model.

Dependent Variable	Test of SS Whole Model vs. SS Residual					
	Multiple R	Multiple R ²	Adjusted R ²	df Model	F	p
Electricity_consumption	0,864316	0,747042	0,728403	7	40,07954	0,00

Univariate Tests of Significance for Electricity_consumption Sigma-restricted parameterization Effective hypothesis decomposition					
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	96490603	1	96490603	7286,124	0,000000
Aging	111846	1	111846	8,446	0,004553
Birth_rate	298348	1	298348	22,529	0,000007
Unemployment	449433	1	449433	33,937	0,000000
Wage	1329225	1	1329225	100,371	0,000000
Density	85283	1	85283	6,440	0,012787
Aging*Wage	81722	1	81722	6,171	0,014737
Unemployment*Wage	35065	1	35065	2,648	0,107005
Error	1258091	95	13243		

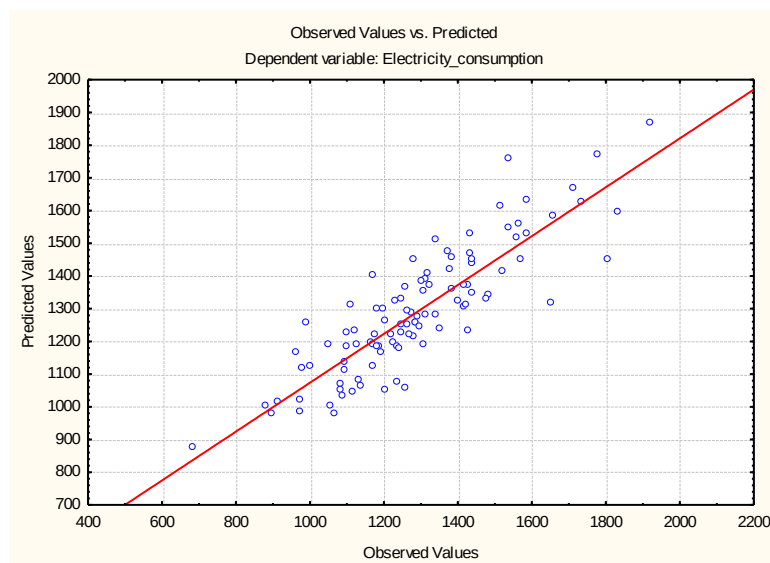


Figure 5.7-2: Goodness of fit scatter plot for the multiple regression model.

Results

Parameter estimates are presented in Table 5.7-2. Figure 5.7-3 complements this information with simulated curves, and annex A.9 displays partial residual plots. Results can be summarized as follows:

- wage played the most important role in explaining residential electricity consumption;
- older or lone person households consumed more electricity *per capita* than younger or larger households. This effect was considerably smaller than the effect of wage;

- unemployment was associated with higher *per capita* consumption of electricity. This might be explained by the longer time spent at home by unemployed people;
- birth rate was positively associated with electricity consumption. The effect size was similar to the effect of aging / lone person households;
- the effect of density on electricity consumption was negative and only slightly lower than the effect of aging / lone person households;
- two nonlinear terms were found significant. In both cases, when wage was higher than average it acted as an intensifier of the effect of aging / lone person households and unemployment on residential electricity consumption; when it was lower than average, wage acted as an attenuator of the effects of aging / lone person households and unemployment. These interactions, however, do not appear to be of great importance;
- education, income support, basic services, agriculture and occupation regularity were not significantly associated with electricity consumption when the retained model variables were controlled for.

Table 5.7-2: Parameter estimates for the model explaining electricity consumption.

Effect	Parameter Estimates Sigma-restricted parameterization						
	Electricity_c onsumption Param.	Electricity_c onsumption Std.Err	Electricity_c onsumption t	Electricity_c onsumption p	-95,00% Cnf.Lmt	+95,00% Cnf.Lmt	Electricity_co nsumption Beta (β)
Intercept	1403,100	16,43768	85,35880	0,000000	1370,467	1435,733	
Aging/Lone hh.	118,955	40,93249	2,90614	0,004553	37,694	200,217	0,203601
Birth_rate	56,988	12,00639	4,74644	0,000007	33,152	80,823	0,256629
Unemployment	118,742	20,38282	5,82557	0,000000	78,277	159,207	0,441344
Wage	352,085	35,14330	10,01855	0,000000	282,317	421,853	0,942170
Density	-51,536	20,30848	-2,53768	0,012787	-91,854	-11,219	-0,171126
Aging/Lone hh.*Wage	140,730	56,65123	2,48414	0,014737	28,263	253,197	0,230115
Unemployment*Wage	44,435	27,30763	1,62721	0,107005	-9,777	98,648	0,138860

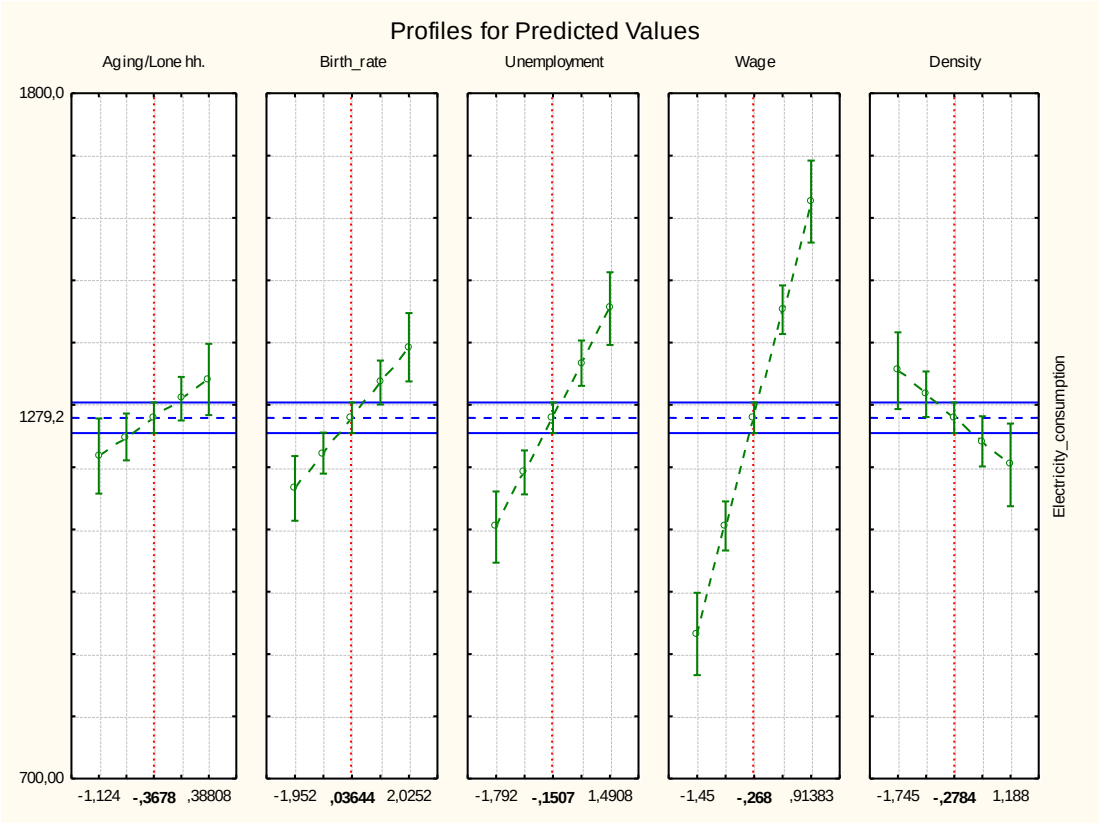


Figure 5.7-3: Visualization of the model explaining electricity consumption.

Figure 5.7-4 shows a 3D curve fitted to the real data points having the two most important variables as the x and y axis.

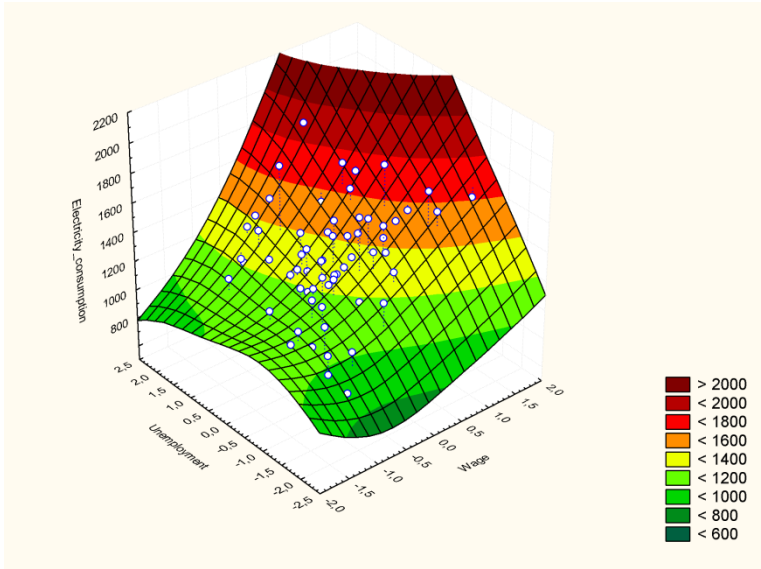


Figure 5.7-4: Fitted 3D curve to the real data points having electricity consumption as the dependent variable.

5.8 Crimes against people

The number of crimes against people averaged 100 in each borough during 2007. There are, however, large discrepancies. This type of criminality seems to be more concentrated in the center of Porto and in some boroughs of Vila do Conde (Figure 5.8-1).

Crimes against people

2007

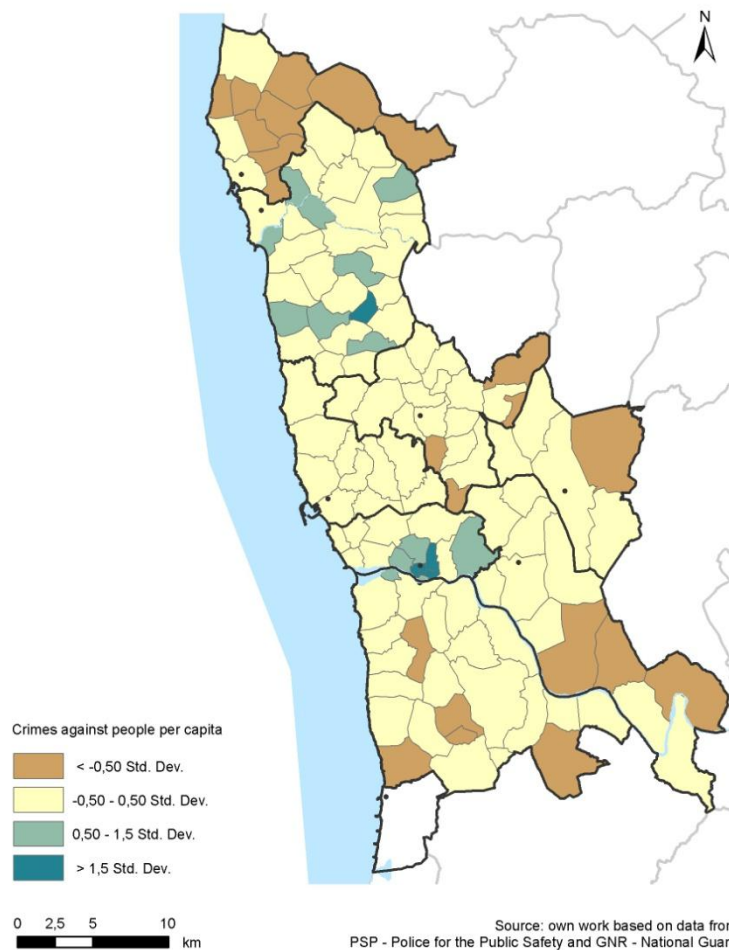


Figure 5.8-1: Crimes against people in the Metropolitan Area of Porto.

5.8.1 Modeling with a negative binomial log link function model

Goodness of fit

Goodness of fit statistics suggest a good model fit because the ratio of deviance to the number of degrees of freedom is lower than 1 (Table 5.8-1). The scatter plot of the predicted values against the actual data also supports a good model fit (Figure 5.7-2). It is important to recall that, for statistical reasons, the variable modeled was the total number of crimes against people, and not a normalized version of this indicator (such as the one used in Figure 5.8-1).

Table 5.8-1: Goodness of fit statistics for the negative binomial log link function model.

Goodness of Fit ^b			
	Value	df	Value/df
Deviance	14,368	110	,131
Scaled Deviance	14,368	110	
Pearson Chi-Square	12,844	110	,117
Scaled Pearson Chi-Square	12,844	110	
Log Likelihood ^a	-565,021		
Akaike's Information Criterion (AIC)	1138,041		
Finite Sample Corrected AIC (AICC)	1138,408		
Bayesian Information Criterion (BIC)	1148,986		
Consistent AIC (CAIC)	1152,986		

Dependent Variable: Crimes_against_people
Model: (Intercept), Population, Aging, Populacao_2

- a. The full log likelihood function is displayed and used in computing information criteria.
b. Information criteria are in small-is-better form.

Omnibus Test ^a		
Likelihood Ratio Chi-Square	df	Sig.
125,310	3	,000

Dependent Variable:
Crimes_against_people
Model: (Intercept), Population,
Aging, Populacao_2
a. Compares the fitted model
against the intercept-only model.

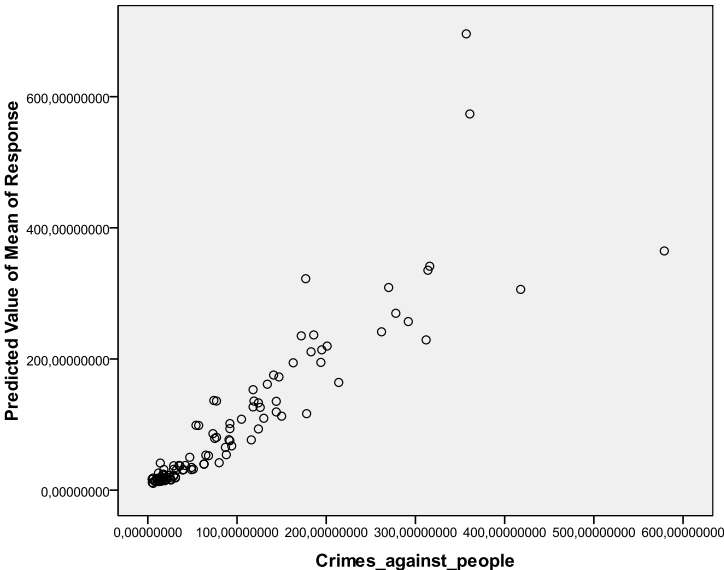


Figure 5.8-2: Goodness of fit scatter plot for the negative binomial log link function model.

Results

Parameter estimates are presented in Table 5.8-2. Exponentiated parameter estimates should be preferred in accessing variable importance. Figure 5.8-3 complements this information with simulated curves, and annex A.9 displays partial residual plots. Results can be summarized as follows:

- resident population played the most important role in explaining criminality against people. The effect seemed sigmoidal, so that, at very high population levels, the marginal effect of population on criminality tended to decrease;
- older or lone person households were associated with higher criminality rates;
- education, resident's job diversity, income support, unemployment, wage, density, building age, accessibility, economy, economic diversity, agriculture and occupation regularity were not significantly associated with crimes against people when the retained model variables were controlled for.

Table 5.8-2: Parameter estimates for the model explaining crimes against people.

Parameter Estimates							
Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	4,280	,1356	4,014	4,545	996,588	1	,000
Population	1,279	,1504	,984	1,574	72,304	1	,000
Populacao_2	-,322	,0982	-,514	-,130	10,765	1	,001
Aging	,341	,1000	,145	,537	11,621	1	,001
(Scale)	1 ^a						
(Negative binomial)	1						

Dependent Variable: Crimes_against_people
Model: (Intercept), Population, Populacao_2, Aging

a. Fixed at the displayed value.

Parameter Estimates			
Parameter	Exp(B)	95% Wald Confidence Interval for Exp(B)	
		Lower	Upper
(Intercept)	72,206	55,359	94,182
Population	3,592	2,675	4,824
Populacao_2	,725	,598	,878
Aging	1,406	1,156	1,711
(Scale)			
(Negative binomial)			

Dependent Variable: Crimes_against_people
Model: (Intercept), Population, Populacao_2, Aging

a. Fixed at the displayed value.

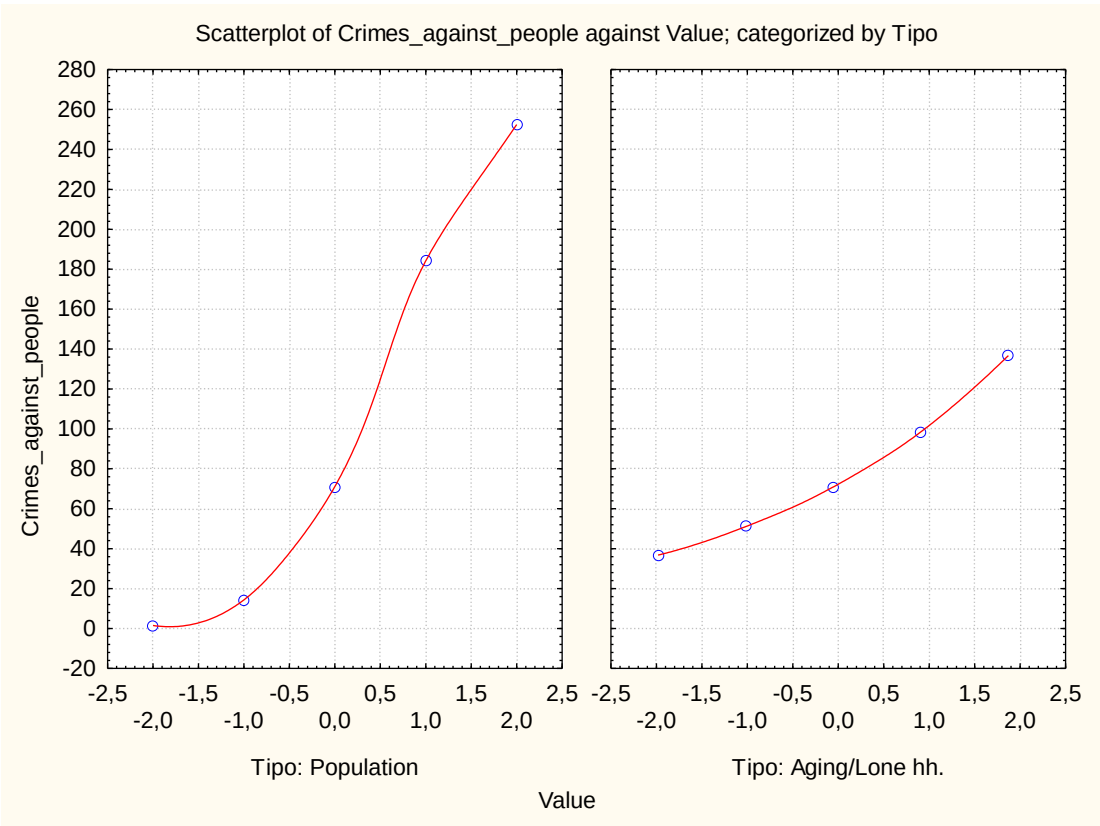


Figure 5.8-3: Visualization of the model explaining crimes against people. Note: population is z scored (aging / lone person households is a factor obtained through factor analysis).

Figure 5.8-4 shows a 3D curve fitted to the real data points having the two most important variables as the x and y axis.

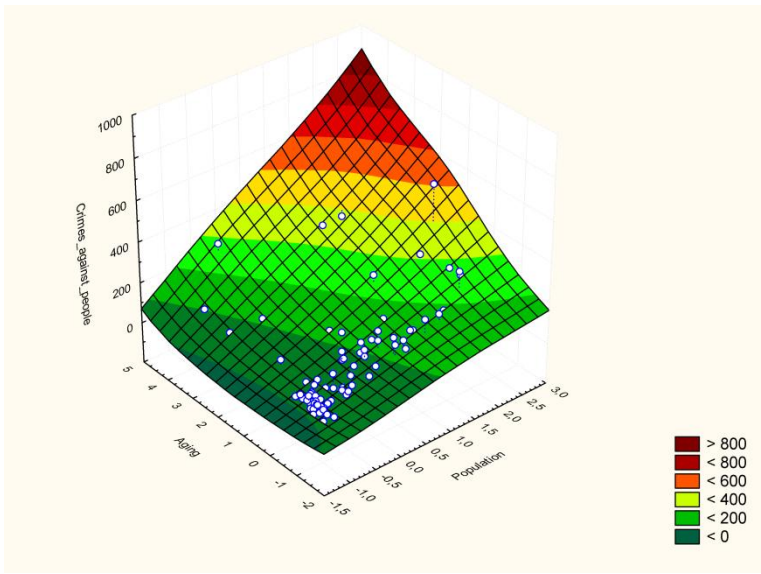


Figure 5.8-4: Fitted 3D curve to the real data points having crimes against people as the dependent variable.

5.9 Sustainability classification of the territorial structure

Sustainability assessment requires the use of scientific sound methods such as multicriteria analysis or the established guidelines of impact assessments. Since it was not possible to carry out such a detailed assessment at this stage (perhaps it can be a possible sequence of this work), I devised a very simple sustainability classification for territorial structure based on human capabilities and mobility patterns (Table 5.9-1). The rationale was that human capabilities conditioned the maximum achievable level, and that mobility patterns worked as a supplementary criterion. Territories with low human capabilities, therefore, were considered unsustainable regardless of their mobility patterns. However, only a territorial structure scoring well in both human capabilities and mobility patterns was considered sustainable.

Table 5.9-1: Simplified sustainability classification of the territorial structure.

		Human capabilities		
		High (1, 2)	Average (3)	Low (4, 5)
Mobility patterns	High Foot (1)	😊	😊	😞
	High PT (2)	😊	😊	😞
	High car, low foot / PT (3, 4)	😊	😊	😞

Green: sustainable territorial structure; **orange:** mixed performance territorial structure; **red:** unsustainable territorial structure. Numbers inside parenthesis indicate the cluster number used in sections 5.2 and 5.4.

Results are presented in three maps to facilitate visualization (Figure 5.9-1 and Figure 5.9-2). Sustainable territorial structures were mainly found in central urban areas or suburban territories around them. Territorial structures with a mixed performance were essentially localized in a ring of suburban areas around Porto. Unsustainable territorial structures coincided with rural areas located in large parts of the municipalities of Vila do Conde and Póvoa de Varzim, but also in parts of Gondomar, Valongo, Vila Nova de Gaia and Espinho. Results suggest that sustainable territorial structures at the borough level are more likely to be achieved in the most densely populated areas.

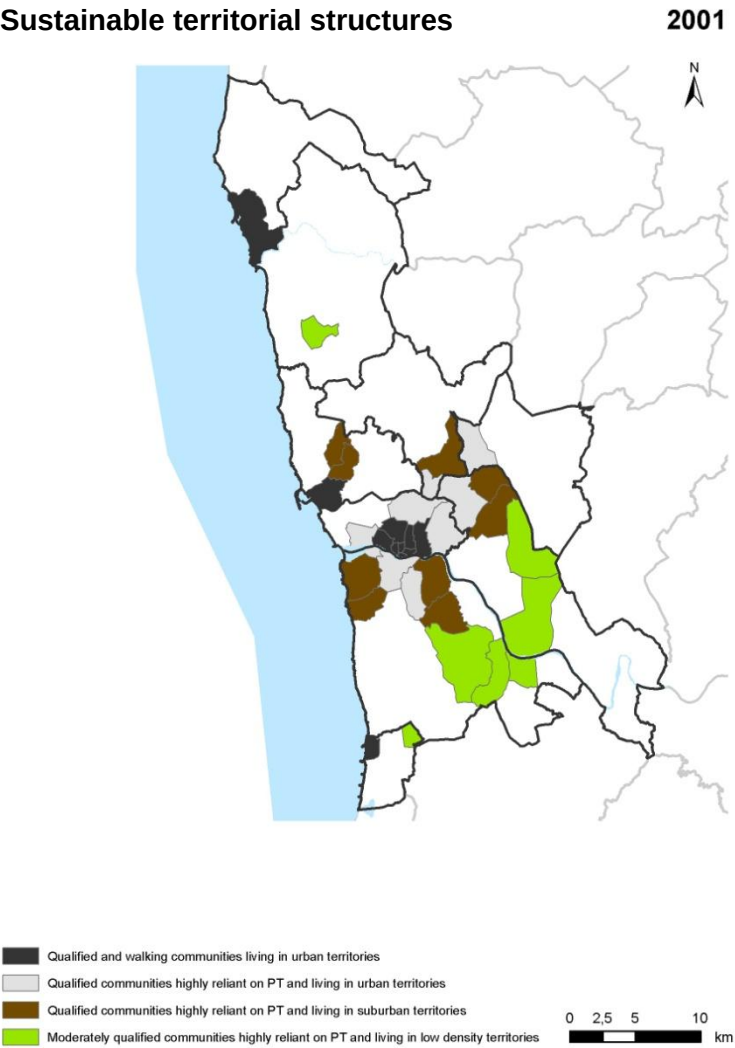
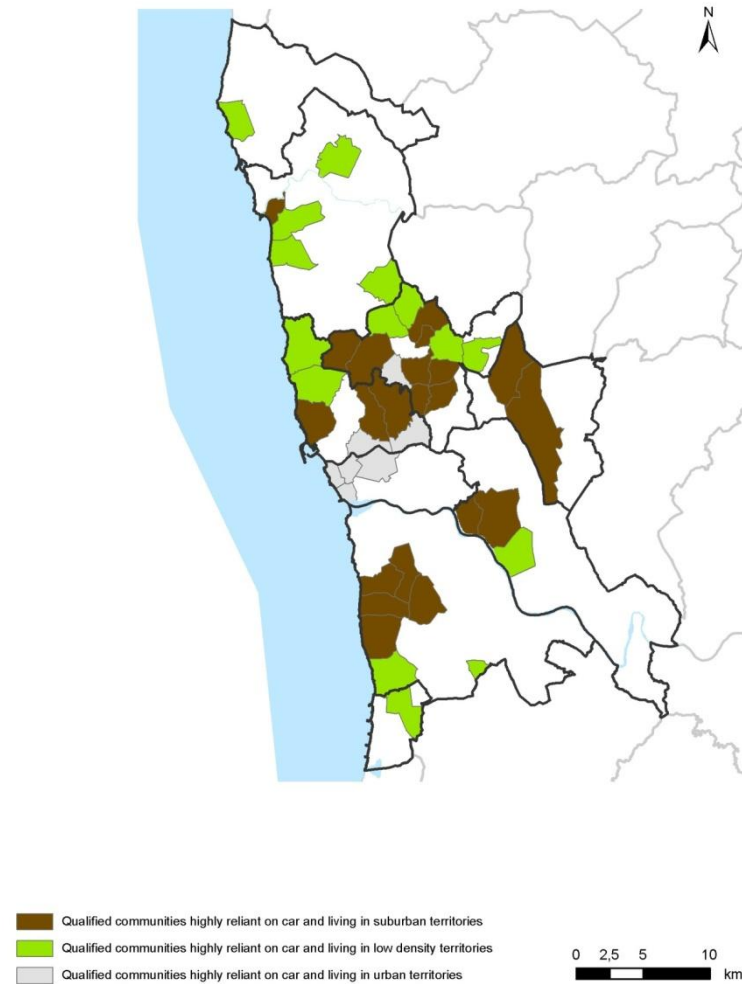


Figure 5.9-I: Boroughs with sustainable territorial structures.

Mixed performance territorial structures

2001



Unsustainable territorial structures

2001

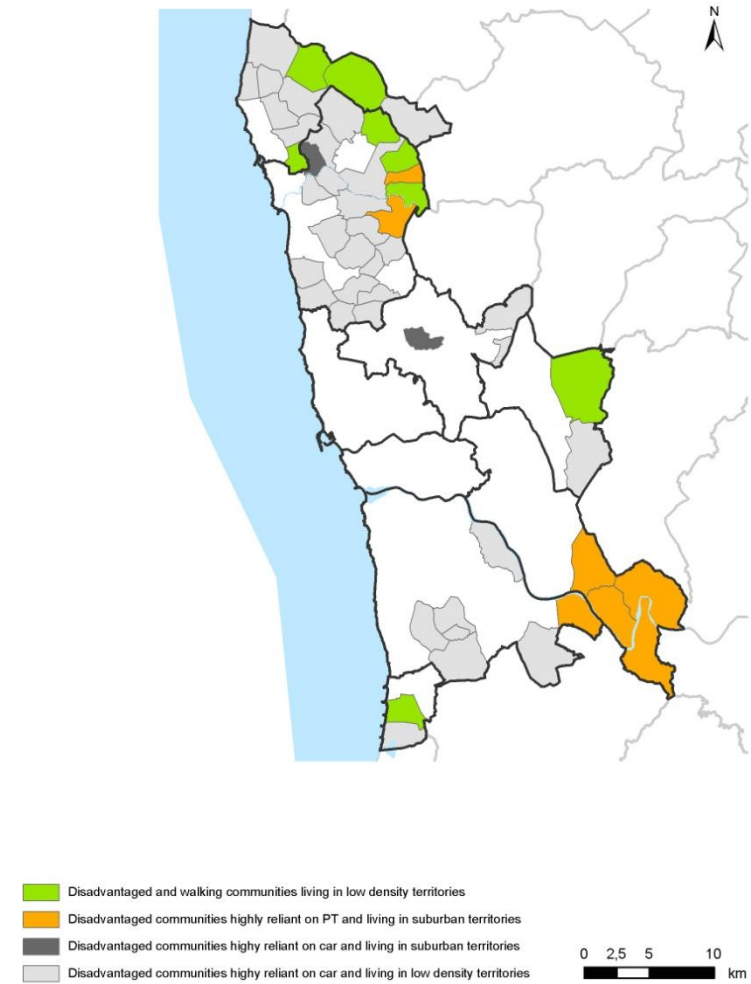


Figure 5.9-2: Boroughs with mixed performance (left) and unsustainable (right) territorial structures.

5.10 Synthesis

I developed several models to explain relevant urban sustainability domains: mobility patterns (shares of car, public transport, and foot), urban growth, residential water consumption, residential electricity consumption, and crimes against people. Not every independent variable is important in every model, as would be expected, but the effect of urban form is quite consistent towards environmental-friendly mobility and electricity consumption patterns.

This section starts with a synthesis concerning variables with significant effects in various models, then comments on variables systematically found nonsignificant, and finally concentrates on specific findings for each of the empirical models. Table 5.10-1 and Table 5.10-2 aid in providing a global summary for these results.

Variables found relevant in various empirical models

Some variables played a significant role in more than one empirical model. The main one was wage, which had a large influence on mobility patterns, on water consumption and on electricity consumption. In all cases, its effect was towards higher environmental burdens. Density contrasts with wage: all of its effects stimulated environmental-friendly mobility and consumption patterns. However, the magnitude of this effect was always lower than the effect of wage. Unemployment behaved in a mixed way: it decreased the car use and stimulated walking, but at the same time was associated with higher electricity consumption. This may be explained by the larger amount of time that unemployed people spend at home.

Aging / lone person households were also found significant in the models explaining water and electricity consumption, and crimes against people – but interpretations differ. With respect to consumption patterns, results suggest the existence of moderate size economies of scale: larger families consume less on a *per capita* basis. In Norway, Holden (2004) reported similar conclusions regarding the *per capita* ecological footprints. The effect of aging / lone person households on crimes against people is probably related to the central boroughs of Porto. These territories are aged, concentrate social problems, and experience high crime rates.

Variables found nonsignificant in various empirical models

Several variables were found nonsignificant in all models. Examples include abstention, child mortality, resident job diversity, youth NGOs, basic services, green space distance, economic diversity, and occupation regularity. It must be noted that, in order to minimize the possibility of spurious relationships, only independent variables that could in theory be a cause of the dependent variable were tested.

From the urban sustainability point of view, however, statistical nonsignificance is not necessarily synonym of irrelevance. Some variables have an intrinsic importance regardless of their role in statistical models.

Mobility patterns

Personal characteristics were determinant in explaining car shares, but urban form was more important in predicting which of the alternative transport modes was chosen. Even though wage and education were the most important predictors of car use, urban form indicators (density, bus net density, and economy) were also of great relevance in understanding mobility patterns at the borough scale. Bus net density was more important in predicting public transport shares, and economy in predicting foot shares. Accessibility was associated with higher car shares, which is hardly surprising since this factor also indicated proximity to a highway node, and since home-work trips were the only ones covered by the database.

The direct effect of some variables on modal shares is aggravated or attenuated by their indirect effects through causal mechanisms on other variables. Density, for instance, exerted a large part of its influence because of its positive effect on economy and accessibility; the influence of education was inflated because of its positive effect on wage.

There was evidence of residential self-selection: more educated people tended to live in denser and more accessible areas. This path acted as a mitigator of the effect of education on car shares. Another interesting finding was that longitudinal changes in density were not significantly associated with car shares, but were negatively associated with foot shares. Rickwood, et al. (2007, p. 14) suggested precisely this: “it is not uncommon for studies of US cities by economists to fail to find any marginal effects of increased density”. Moreover, educational changes significantly promoted car dependency, suggesting that both phenomena are associated with the movement of people with a predisposition to use their cars, from dense urban boroughs to suburban boroughs. This is in line with the findings of Camagni, et al. (2002) who found that higher mobility impacts were associated with greater rates of population growth.

Urban growth

When considering accessibility as a proxy for transportation infrastructure, results are in agreement with the literature review presented in section 3.3. Short distances from highway nodes were the most important factor explaining urban growth in the Metropolitan Area of Porto. The “gravitational” influence of Porto was also detected, as boroughs farther from the center of the region tended to grow less. The importance of land prices was suggested by the higher urban growth levels observed in rural boroughs when the other variables were controlled for.

Water consumption

Besides the economies of scale provided by larger families and the influence of income in residential water consumption, the curious influence of agriculture also appeared as a significant in the multiple regression model. This effect is probably associated with water consumption from farm wells and the consequent reduction in the amount of water bought to the municipal water companies.

Electricity consumption

Although the borough scale is obviously not the best option to study the impacts of urban form on electricity consumption, the effect of density was significant when other important variables were controlled for. Some studies have found that energy consumption *per capita* in detached houses is higher than in attached dwellings (Holden & Norland, 2005; Rickwood, et al., 2007; Steemers, 2003). The underlying reason behind the observed negative effect of density on residential electricity consumption should be related to this.

Crimes against people

Only two variables were found significantly associated with criminality against people: resident population and aging. Resident population was the most important but, as it reached very high levels, the marginal effect tended to decrease. Aging may be explained by the high incidence of crimes in the center of Porto.

Sustainability classification of the territorial structure

Results suggest that sustainable territorial structures at the borough level are more likely to be achieved in the most densely populated areas. The geographical distribution of sustainable is surprisingly clear: sustainable territorial structures concentrate in the center of Porto and surrounding boroughs; mixed performance territories form a ring surrounding the core area; and unsustainable territories occupy the remainder, which are mostly constituted by rural and forested areas. This exercise does not intent to be a sustainability assessment, as that would require taking into account other indicators and the employment of valuation methodologies.

Table 5.10-I: Summary of independent variable effects (left column) on dependent variables (top row).

Factor or single indicator ¹	Modal shares (SEM) ²			Modal shares (SVM)			Urban growth	Water consumption	Electricity consumption	Crimes against people
	Car	PT	Foot	Car	PT	Foot				
<u>Human capabilities</u>										
Population										↑↑↑↑
Education	↑↑↑↑	■	■	↑↑↑↑	↓↓↓	↓↓↓		■	■	■
Students				■	↑↑	■				
Wage	↑↑↑↑	■	↓↓↓	↑↑↑↑	↓↓↓	■		↑↑↑↑	↑↑↑↑	■
Unemployment				↓↓↓	■	↑		■	↑↑	■
Aging / lone-person hh.								↑↑	↑↑	↑↑
Birth rate							■	■	↑↑	
<u>Urban form</u>										
Density	↓↓↓	↑	↑↑↑↑	↓↓↓	■	↑	■	■	↓	■
Natural capital							■	■		
Accessibility	↑	↓	■				↑↑↑↑	■		■
<u>Transports</u>										
Bus net density	↓	↑↑	↓	↓↓↓	↑↑↑↑	■				
<u>Economy</u>										
Economy	↓	■	↑↑	■	↓↓↓	↑↑		■		■
Agriculture				■	↓↓↓	■	↑	↓	■	■
Goodness of fit ³	R ² = 0,84	R ² = 0,27	R ² = 0,43	r ² = 0,94	r ² = 0,35	r ² = 0,66		R ² = 0,84	R ² = 0,73	Sc. dev. / df = 0,131

SEM: structural equation modeling; SVM: support vector machines.

¹ Some nonsignificant or less relevant variables are omitted, although they were tested.² Unlike the other models, results displayed for SEM are based on the total effects and not in direct effects only.³ For SEM, averaged values between 1991 and 2001 are presented; for support vector machines, values represent the squared correlation coefficients between the actual modal shares and predicted values.

■ These variables were tested but their effects were nonsignificant or very small; ↑ or ↓: small effects; ↑↑ or ↓↓: moderate effects; ↑↑↑ or ↓↓↓: very large effects.

Table 5.10-2: Total and partial correlations between the independent variable effects (left column) and dependent variables (top row).

Factor or single indicator	Modal shares*						Water		Electricity	
	Car		PT		Foot		consumption		consumption	
	sr^2	r^2	sr^2	r^2	sr^2	r^2	sr^2	r^2	sr^2	r^2
<u>Human capabilities</u>										
Education	9,9%	63%	1,3%	3,2%	0,3%	0,3%				
Wage	5,1%	64%	0,0%	6,4%	2,6%	0,1%	36%	50%	27%	47%
Unemployment									9,0%	14%
Aging / lone person hh.							16%	40%	2,2%	12%
Birth rate									6,0%	6,5%
<u>Urban form</u>										
Density	1,6%	9,0%	0,5%	4,1%	0,1%	11%			1,7%	3,8%
Accessibility	0,9%	32%	2,2%	4,1%	0,0%	1,2%				
<u>Transports</u>										
Bus net density	0,5%	6,3%	13%	7,4%	3,6%	2,5%				
<u>Economy</u>										
Economy	0,3%	1,4%	5,3%	1,2%	8,6%	18%				
Agriculture							2,4%	20%		
<u>Partial redundancy</u>	67%		-1,4%		15%		31%		27%	
<u>R^2</u>	85%		21%		30%		85%		75%	

Sr^2 : squared partial correlation coefficient between the independent and the dependent variables; r^2 : correlation coefficient between the independent and the dependent variables.

* Only for 1991.

6. Conclusions

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6. Conclusions

Research presented in this thesis aimed at providing a better understanding of urban processes, their dynamics, and linkages. Specifically, it aimed at clarifying the linkages between urban form and selected urban sustainability dimensions such as mobility patterns, water consumption, energy consumption, and urban growth. Based on a general human ecosystem framework, I assembled and grouped a large number of indicators in selected sustainability domains. In addition, I produced diverse cartography, namely land cover and population density maps, from where I was able to derive urban form metrics and accessibility indicators. From the statistical point of view, a number of methods were employed. The fact that I worked with cross-sectional and longitudinal datasets, normal and nonnormal data, counts and noncounts, etc., required methods adapted to each specific case. In the case of mobility patterns, and because of their importance for this thesis, I employed an advanced method – structural equation modeling – which provided further information regarding the causal mechanisms explaining the influence of territorial structure.

In the next two sections I present the conclusions of my work. The first section includes specific conclusions drawn from the statistical models which relate to issues of greater relevance for planning and policy. The second section involves more general conclusions dealing with urban sustainability and sustainable development, including some of their dilemmas. They are also related to the empirical work developed in this thesis, but they are of greater interest to the researcher than to the planner. I finish with indications for further research.

6.1 Conclusions drawn from the empirical models

6.1.1 The influence of urban form and human capabilities on mobility

- Human capabilities explain most of the variability and have higher effects on car shares, but the choice between commuting by public transports or by foot is essentially determined by the urban form

Human capabilities largely determine the level of car dependency of a borough, although urban form still plays a significant suppressing role. Urban form is particularly important in determining the relative balance of alternative mobility options. Specifically, higher densities and mixture of land uses stimulate walking, while a good bus transportation network favors commuting by public transports.

□ Urban form characteristics consistently appear as important factors towards sustainable mobility patterns

Urban form indicators are found to be significantly associated with environmental friendly travel behavior and electricity consumption patterns. Density is the most relevant urban form characteristic because it enables alternative transports besides the car, and also because it directly fosters commuting by foot and to a lesser degree by public transports. Although density is crucial in terms of sustainable mobility patterns, other urban form characteristics play a significant role: improving the level of bus service is an efficient promoter of public transport use, and stronger local economies favor walking. Accessibility is associated with higher car use and lower public transport shares, except for very high levels of accessibility, where the evidence is contradictory. The most probable explanations for this fact are twofold: firstly, data concerning modal shares were restricted to home-work commuting (if travel for recreation and shopping was used, the relationship between accessibility and use of public transports would probably be positive); and secondly, accessibility was also a measure of accessibility to highways.

Accessibility is also a strong stimulator of urban growth, which is consistent with theory. Interestingly, criminality is not positively associated with density (at least in the range the values show in the dataset), and the number of crimes seems to decouple from resident population at about 22000 inhabitants.

□ Mixture of land uses stimulates more sustainable mobility patterns

Structural equation modeling suggests that a causal relationship does exist between economy and density. It turns out that a stronger economy is also a result of higher densities, but their separate effect on mobility patterns can be estimated. Economy, which acts as a proxy of land use mix, has a significant indirect effect on not using the car for commuting (particularly, a significant effect on commuting by foot). In new urbanism and transit-oriented development literature, references abound to the importance of land use mix in promoting sustainable mobility patterns. My research gives credit to those claims and suggests that the main causal mechanism is through an increased propensity of people to walk instead of using their car. However, it must be reminded that these conclusions are valid only for home to work trips.

□ The direct effect of density on mobility patterns appears to stagnate at relatively high gross densities and is ambiguous when they are very low

Partial residuals plots suggest that the direct influence of density on modal shares starts to stagnate at around 1,5–2 standard deviations (ca. 60–70 inhabitants/ha at the borough level), similar to a *saturation effect*. However, the indirect effects of density on mobility through economy do not seem to suffer from this effect. At very low gross densities (below –0,5

standard deviations, ca. 10 inhabitants/ha) the effect of density is not significant. The influence of economy is also ambivalent at very low economic levels (below ca. 10 jobs/ha).

❑ Longitudinal changes in density are associated with higher car dependencies

In spite of the consistent suppressor influence that density has on car dependency, changes in densities from 1991 to 2001 do not show the same pattern. On the contrary: they were not significantly associated with changes in car shares. Most likely, this is related to the movement of population from denser and central boroughs to outer boroughs where housing is cheaper. These are precisely the kind of persons that have a predisposition to use their cars. Hence, results suggest the existence of a self-selection bias. It appears that the suppressor effect of increased density is largely nullified by the influence of car dependent movers. Interestingly enough, longitudinal increase in density is significantly associated with lower commuting by foot. This is probably because the stimulating effect of density on walking is lower than the suppressor effect of density on car shares. Moreover, indirect effects stemming from increased densities may take time to be visible, and this could not be tested in my model because longitudinal data for wage and economy were lacking. Similarly, even in dense areas people may need some time until they become less car dependent, perhaps after being acquainted with the public transportation system or finding a job nearer home.

6.1.2 The influence of urban form on urban growth and on the economy

❑ Higher densities save land from conversion into artificial uses and stimulate a vibrant local economy

From 1990 to 2006, the Metropolitan Area of Porto has converted about 8,5 thousand ha of land to urban uses. As the densities of newly built areas are lower than previous typical urban densities, a significant portion of that land could have been saved from urbanization if densities were higher. If derelict areas were prioritized to build and renew, even larger land savings could be achieved.

Higher densities are also strongly associated with more jobs as found in the results: they foster vibrant local economies. These are good news for those seeking a job, and also good news for those who enjoy the lively character of cities. I am not arguing for very high densities, as green areas are also an essential component of a sustainability-oriented city, but for high *net* densities. In any case, advocating specific urban design arrangements is beyond the scope of this thesis.

6.1.3 Understanding consumption patterns

- ❑ Human capabilities explain most of consumption patterns, but dense urban forms help reduce electricity consumption

Human capabilities, particularly wage, explained the largest variability in consumption patterns. The influence of urban form at the borough level was modest. Still, density fostered electricity savings.

- ❑ Larger households represent economies of scale in the consumption of water and electricity

The consumption of water and electricity – particularly the former – is significantly influenced by household size. Results support an effect of economy of scale as family size increases and on a *per capita* basis. Consequently, demographic trends, which have been towards smaller families and larger numbers of lone person households, run against savings in water and electricity.

6.1.4 Investigating sustainability in urban settings

- ❑ The human ecosystem framework provides an integrative framework to study the sustainability of societies in urban settings

I developed a general human ecosystem framework to guide me through this thesis. This framework highlights the main components of the human ecosystem, the flows between them, the services they provide, the impacts they originate, and the goals and options that guide their evolution and development. In this task I have credited sources originating from different branches of science, including the hierarchical sustainability pyramid proposed by Daly (1973) and Meadows (1998), the human capabilities approach developed by Sen (1999/2003), previous contributions on human development reviewed by Alkire (2002), and the concept of societal metabolism put forward by Fischer-Kowalski & Weisz (1999). The human ecosystem framework, although necessarily abstract and general, details some of the fundamental domains in terms of urban sustainability such as the urban form, transportation network, mobility patterns, and land use changes.

I derived from the human ecosystem framework a more specific model to analyze mobility patterns in 1991 and 2001. I used structural equation modeling to accommodate such complex causal relationships. When compared with previous research in the area (e.g., Abreu e Silva, 2007; Cao, et al., 2007; Lin & Yang, 2009), I have innovated in the research design by incorporating longitudinal data, and by explicitly modeling the influence of changes in density and in education levels.

❑ Novel urban form indicators did not show significant additional discriminatory capacity in distinguishing different urban forms when compared with traditional indicators such as population density

In trying to distinguish different urban forms with metrics, I decided to separate density (measured by indicators such as population density and compactness) and dispersion (as measured by indicators such as the Gini index and the standard distance) into distinct factors derived by factor analysis. However, density and dispersion were so highly correlated that they could not be introduced simultaneously in regression models. These results suggest that the added discriminant capacity of novel urban form indicators such as the Gini index or standard distance is low, contrary to what is suggested by Tsai (2005). It appears that, at the borough scale, these indicators are just different measures of population density and cannot by themselves differentiate between different levels of urban sprawl. From this I conclude that sprawl is not a distinctive attribute of urban form at the borough scale, although it may be at larger scales, and that traditional and widely used indicators such as population densities are able to capture the essential territorial information.

❑ At the borough scale of analysis, it is difficult to disentangle the importance of different urban form dimensions on consumption and mobility patterns

Just as sprawl seems to be measurable only at the city or metropolis level, different urban form dimensions cannot be adequately captured at the borough level. Indicators such as road density, dwellings per building and compactness, for instance, are too correlated with population density measures to be of utility in distinguishing different urban forms. Instead, at the borough scale, different characteristics seem to merge into one relevant territorial characteristic, which is very well captured by the population density of the territory.

❑ In urban settings, it is fundamental to access the synergic effects of groups of indicators

William Rees (1995) has called to the various effects stemming from urban concentration the *urban sustainability multiplier*. Cities are characterized by a complex interplay of people, economy, and the built environment at different scales. SEM makes it possible to access a simple model accounting for some of these relationships and to estimate the synergic effects between density, economy, accessibility, and public transportation network. When their combined effects are considered – instead of segregate impacts as obtained through multiple regression – the relevance of density in promoting more sustainable mobility patterns becomes more pronounced and, probably, closer to its real significance.

❑ Urban sustainability research requires a careful selection and processing of variables

Urban sustainability research deals with a large variety of issues. In order to avoid the possible lack of relevant information and model misspecification, a number of variables covering the

most relevant sustainability dimensions at the borough level were gathered. Moreover, data concerning confounding variables such as household size were added. As the amount of data grew, many indicators were highly correlated, which proved they were measuring the same underlying phenomena. Their amalgamation through factor analysis was performed not only to avoid multicollinearity in models, but also because it was theoretically sound. Factor analysis is thus of great utility in urban sustainability modeling in order to reduce into a manageable dataset the large number of redundant indicators widely presented in theoretical publications.

□ Archetypal configurations of human capabilities, urban forms and mobility patterns can be detected

Although the Metropolitan Area of Porto exhibits a large diversity of human capabilities, urban forms and mobility patterns, the cluster analysis revealed the existence of archetypal configurations of these urban sustainability dimensions. Although no causation may be inferred from this method, educated and wealthy communities are usually found together in the metropolis, and the youngest communities are also those with the lowest wealth.

Regarding the territorial structure, the region could be divided into several concentric rings around Porto: in the center, dense but declining territories are found; around, a number of urban boroughs whose urbanized areas have been growing faster than population; around this ring, there is a group of suburban boroughs characterized by lower densities and high growth rates both in population and in urban area; mainly in the upper west peripheral area (Vila do Conde) there is another group of boroughs with peri-urban characteristics because of their low densities, modest growth rates, higher than average share of forests, and accessibility to the metro; the outer layer is formed by forested territories with little real estate dynamics, while in Vila do Conde, and to a lesser degree in the southeast periphery (Gondomar), the agricultural activity is also significant (the typical patchwork of forests intermingled with forage crops called *bouças*; see Andresen, et al., 2004); agriculture, specially horticulture, dominates a last group of boroughs found in Póvoa de Varzim.

With respect to mobility patterns, four clusters were found: boroughs where commuting to work by foot is the preferred mode and car dependency is the lowest in the region; boroughs where the share of public transports is highest although car already dominates; boroughs whose car shares increased most dramatically from 1991 to 2001; and boroughs with the highest car dependencies. There are some obvious relationships between these groups of clusters. Educated and wealthy people, for instance, tend to live in urban or suburban territories and to be highly dependent on their cars; young communities with very low qualifications and wealth are also prone to rely on the car for their home-work trips; the highest walking shares are usually found in wealthy and aged communities situated in the

compact center of Porto; and the highest share of public transports are found among communities with low qualifications in Gondomar and parts of Vila Nova de Gaia.

□ A simple sustainability classification of the territorial structure shows that the highest sustainability levels are achieved in urban territories

I devised a very simple sustainability classification for territorial structures based on human capabilities and mobility patterns. When compared with sustainability indices, which aggregate incommensurable dimensions into a single number, this methodology has the advantage of portraying existing relationships between sustainability dimensions. As a result, it is much more transparent and subject to scrutiny. This is obtained, however, at the cost of having to severely limit the number of sustainability dimensions represented; otherwise, the classification would be very difficult to interpret.

Sustainable territorial structures, defined as those where human capabilities are equal or above metropolis average and whose mobility patterns are less car dependent, are mainly found in central urban areas or suburban territories around them; mixed performance territories, defined as those where human capabilities are high or average, and are in addition highly car dependent, are essentially localized in a ring of suburban areas around Porto; unsustainable territories, defined as those with low human qualifications, coincide with rural areas in large parts of the municipalities of Vila do Conde and Póvoa de Varzim, but also in parts of Gondomar, Valongo, Vila Nova de Gaia and Espinho.

6.2 Reflections and indications for further research

6.2.1 Reflections about urban sustainability

□ Human capabilities and urban form: is there a conflict?

Increased human capabilities are one of the constituents of sustainable development. In most countries, trends have been towards the expansion of those capabilities and to provide larger numbers of people with greater opportunities to develop their potential. At the same time, results show that these trends are also associated with higher consumption and emission levels that represent pressures on the Earth system. The emerging conflict is obvious, but the solution cannot involve the limitation of human capabilities lying at the center of sustainable development. In addition, the impacts of cities are usually exaggerated just because cities concentrate a large number of people in a relatively small area (the ecological footprint of cities are two to three orders of magnitude larger than the areas they occupy). On one side, it is fair to “blame” cities for the more intensive lifestyle of urbanites in terms of energy and resource consumption. On the other side, migration to cities and the acculturation to urban

behavior contribute to slow down natural population growth. It is difficult therefore to derive general conclusions about the environmental impact of cities. Meanwhile, and quoting William Rees, “we in the wealthiest cities must do what we can to create cities that are more ecologically benign” (Rees & Wackernagel, 1996, p. 245). In urban areas, a number of possible sustainability paths are worth being explored: decoupling higher human capabilities from unsustainable consumption levels by replacing a part of this consumption with strengthened cultural and informational services; decoupling economic development from resource intensity (Daly, 1996); implementing a coherent fiscal scheme geared to favor environmental friendly attitudes by citizens and firms; and profiting from the innovation spurred by cities in finding creative solutions to existing problems. Unfortunately, instead of trying to counteract the detrimental impacts of increased wealth with more sustainable urban forms, densities in Portuguese cities have been decreasing over time, i.e., accentuating the undesirable dynamics. Clearly, there is room for great improvements at the policy level.

□ Is there such a thing as a sustainable city? Radical changes are necessary in order to fully benefit from the role of cities in fostering sustainability

Cities are powerful engines of human and economic development. They concentrate resources and decision-making. The rate of urbanization is slowing down in the most developed countries, but, in most of the less developed world, people are still migrating in large numbers to cities where they hope to find better opportunities for their lives. Surely, the equilibrium between the rural and the urban world must be rethought so that rural lifestyles are adequately protected, but human concentration in cities is also a result of societal evolution. Such a defining characteristic of most human societies must be very difficult to counteract. As engines of development, cities are associated with increased pressures on the Earth system, most of them originating from the very intensive lifestyles – in terms of energy and materials – of urbanites. Most of the cities’ impacts take place in faraway regions of the planet (cities have even been considered “black holes” because of their voracious appetite for resources; see Rees & Wackernagel, 1996, p. 237). Because citizens, and particularly politicians, do not perceive the consequences of societal metabolism, they have no incentive to change the course. The question, however, is not whether cities are sustainable or not. A very precise definition of sustainability would be grounded on arbitrary assumptions such as administrative limits and the acceptable degree of substitutability between different forms of capital. An important issue like sustainable development must not rest on such fragile arguments. I evoke the known aphorism stating that “it’s better to be approximately right than precisely wrong.” Likewise, it is preferable to regard sustainability as a goal (a social construct) that can mobilize people, than as a probably useless and arbitrary mathematical formula. (At the end, sustainability is played at the global level; it is at the global level that humanity has to be

sustainable.) The relevant question is whether cities, accepting them as intrinsic to human societies, can be engines of worldwide sustainable development – and not engines of their own development but elsewhere destruction. I believe cities have also the capacity to regenerate themselves. As *loci* of creativity, knowledge and information, innovative solutions and paths towards sustainability may emerge there. The bottom line is that cities are needed because they support humankind development, but the environmental pressures they originate must be urgently counteracted. Results obtained in this thesis regarding mobility patterns fully support the role of high density urban form as a lever towards more environmental friendly cities.

❑ Scale considerations seem to be of great importance in understanding urban sustainability

The literature review about urban growth and travel behavior pointed to the need to consider scales in order to correctly interpret those phenomena. Some authors have already developed multi-level theories (Couch, et al., 2007; Lambin & Geist, 2006). At larger scales, slow variables seem to largely determine system's behavior. For urban growth, driving forces such as demographic changes, institutional dysfunctions, and fiscal incentives are the most relevant; for mobility patterns, urban form and, to a lesser extent, socioeconomic conditions, appear to be the critical factors. At lower scales, other variables play a role, but their influence is limited by the conditioning effect of the larger scale. This is why personal characteristics explain most of the intracity variations in travel behavior while density accounts for most of intercity's. Evidence suggests that urban sustainability can only be adequately understood and conceptualized through a multilevel approach.

6.2.2 Reflections about sustainable development

❑ Sustainable development must not be transformed into a cure for all

Sustainable development is a concept still embedded in ambiguity. One risk of relying on such a vague concept is that consensus between politicians, citizens and scientists may be apparent at the surface, just to hinder contradictory deep worldviews. One of the problems with sustainable development is that it has been transformed into something like a cure for every problem – from small issues to critical problems (see also Quental, 2006a). This is visible in sustainability plans, which have become interminable lists of probably unrealizable actions – at least in the proposed time horizon. The Portuguese strategy for sustainable development, for instance, contains more than one hundred actions. Instead, focusing on the cross-cutting issues of sustainable development might lead to better results for the Earth system and the human societies. To the possible extent, these sustainability goals should not attempt to incorporate every sectoral goal, but struggle to find those of greater relevance and urgency. The Millennium Development Goals are a meritorious step in this direction, but the environmental

dimension is still too generic. Further research and debate are necessary at different levels and *fora* to achieve more effective Sustainability Goals. Then sustainability could be better perceived by people.

❑ Sustainability assessments must encompass a wide range of goals and clarify the tradeoffs between them

Sustainability assessments must necessarily encompass a wide range of goals and domains. If in the academic circles sustainability is often restricted to the environmental domain – relegating social and economic issues to a secondary plan – decision-makers typically neglect environmental impacts and favor the economic pillar. A first requirement for sustainability assessments should be the capacity to include all the relevant domains with significant implications on sustainable development. This I would call the *wide* characteristic of sustainability. My thesis tried to comply with this demand by incorporating indicators concerning various sustainable urban development dimensions. In addition to being *wide*, sustainability assessments must also be *long*, meaning that they must evaluate the impact of current actions into the future and on other places and communities. One difficulty with sustainability assessments resides on the tradeoffs between conflicting goals that are usually masked behind technical documents and obscure formulas. Assessments should clarify these conflicts so that more conscious decisions can be made. In addition, sensitivity analysis with different assumptions should be routinely performed.

❑ A redefinition of sustainable development dimensions

Usually, sustainable development is understood as the interplay between the environmental, economic, and social pillars. However, this is a crude simplification of what sustainability is about. The path to sustainability requires concerted efforts in very different dimensions. It is useless to stipulate the goal of halving poverty if the improvement of the conditions supporting the achievement of that goal is not a goal in itself. The important question is to find the critical sustainability factors where human intervention should be concentrated. It is important to understand where the key issues lie. The *institutional* dimension of sustainability deals with the enabling instruments supporting policy implementation, with the procedural notions of equity and justice in decision-making, and the need to debate and clarify conflicting policy goals. The *substantive* dimension of sustainability deals with the ends that societies want to achieve (the traditional three-pillar approach could be inserted here). Lastly, the *scale* dimension of sustainability deals with importance of conceptualizing a system in its relationship with other systems (at larger and lower scales). Each of these three dimensions, if seen in isolation, is necessary but insufficient for a transition to sustainable development.

6.2.3 Indications for future research on sustainability

- ❑ Carefully designed research is duly needed, particularly longitudinal studies controlling for attitudinal factors, or quasi-experimental designs

Statistical literature cautions researchers to the very strong assumptions required to establish causal relationships. “Correlation is not causation.” But a number of difficulties is postponing the verification of causality between, for instance, density and car shares. In urban settings, there is a very large number of variables that can have influence on the object of study; it is often not possible to control all confounding variables; data is hard to collect and costly; and it is the complex behavior of human beings that is being studied. These difficulties highlight the importance of carefully designed research in solving limitations of previous research designs. The recent focus on longitudinal studies (e.g., Giles-Corti, et al., 2008), structural equation modeling (e.g., Van Acker, et al., 2007), and control for attitudinal factors and self-selection bias (e.g., Schwanen & Mokhtarian, 2005) applied to urban areas is promising (Mokhtarian & Cao, 2008). This thesis made use of such methods by relying on available longitudinal data for two waves. Handy (2006) recommends conducting quasi-experimental research taking advantage of the opportunity posed by urban projects and by relevant shifts in people’s life. For example, information gathered before and after the metro started to operate in the Metropolitan Area of Porto could be of great importance to understand the influence of a new transit system in the mobility patterns of citizens. Unfortunately, because of financial and other contextual constraints, researchers do not always fully profit from existing opportunities.

- ❑ Sustainability research should also strive to understand the implications of childhood lifestyle on the later behavior of those persons as adults

Contemporary literature studying mobility patterns, particularly walking, usually attempts to control for attitudinal factors whose absence would exacerbate the influence of land use factors such as density. Researchers caution against the self-selection bias, whereby a person tends to find a residence that better fits her lifestyle and allows her to behave according to her existing preferences. Although there is enough evidence of residential self-selection, the opposite effect may also be present: attitudes may also change, with time, as a consequence of the characteristics of the surrounding built environment. I am referring not to the visible behavior of people, which seems to be influenced by the built environment regardless of attitudes (e.g., Schwanen & Mokhtarian, 2005), but to deeper beliefs and attitudes that take time to build. Experiences in the childhood and youth are probably relevant to understand behavior of those persons as adults, but research in this area is lacking. If a long-lasting influence of urban form is confirmed, the argument for compact and lively urban areas is

greatly reinforced. A similar line of research should be pursued to elucidate consumption attitudes and behavior.

❑ Sustainability assessment should be based on sound scientific methodologies derived from theories

Most of the so-called sustainability indicators – either sets or indices – lack solid theoretical grounds and are usually created by intuition. This has led to excessively large sets of indicators or to obscure indices. Indicators may have many functions, and one of the most important is certainly to aid the public opinion in the proper monitoring of sustainability trends. I understand that indicators obtained through participatory processes may lack a strong scientific basis, but their increased saliency and legitimacy somehow serve as compensation. Still, the construction of indicator sets should be guided by important rules (for instance, the Bellagio principles), and the transformation of sustainability indicators into something like a collection of sectoral indicators should be critically avoided.

❑ Sustainability indices should be constructed to convey clear messages about sustainability goals, impacts, themes or risks

There is room for meaningful sustainability indices. While the rush to the perfect sustainability index goes on, it is important to understand that no meaningful messages can be communicated by indicators whose object is difficult to explain. We need indicators which convey relevant messages to politicians, scientists, and/or citizens, and are linked to sustainability goals. Different indices may, as such, have different objectives and target populations. Interesting examples include goal-based indices (e.g., carbon dioxide equivalent emissions), impact-based (e.g., Prescott-Allen's Well-being Index), thematic (e.g., the Living Planet Index or the Genuine Savings Index) or risk-based indices (e.g., the Environmental Vulnerability Index). All of them convey salient messages that can trigger action.

6.3 Synthesis

I performed throughout this thesis numerous tasks in order to provide a better understanding of urban processes and their relationship with sustainable development. Is urban form an important dimension that planners shall carefully consider in order to create livable and more environmental-friendly cities? The large array of data from the second largest metropolitan area in Portugal used in this thesis supports an affirmative answer. Dense, mixed-use urban forms, served by high levels of public transports were found associated with lower car dependencies. While previous research in other territorial areas already suggested this, the longitudinal research design employed in this thesis represents a further step in establishing the necessary and scientific cause-effect relationship. Moreover, it also brought light into the

complex paths through which urban form exerts its influence: not only density directly decreased car shares, it also stimulated vibrant local economies in the Metropolitan Area of Porto; these economies, in turn, favor walking; at the same time, frequent public transports attract users.

Higher densities were also associated with lower *per capita* electricity consumption. These conclusions were taken after controlling for socioeconomic characteristics such as wage and education, which consistently promoted automobile use and more intensive consumption patterns. Although the influence of socioeconomic characteristics on mobility and consumption patterns was more pronounced than the influence of urban form, I think this does not diminish the importance of this finding. First, because increasing human capabilities is, in principle, a desirable achievement. Second, because urban form can counteract the negative environmental consequences of higher wages and educational levels. And third, because decoupling wealth from resource use is certainly not impossible: it's just part of the sustainability challenge.

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A. Annexes

A.1. Most relevant references about sustainable development

The first 60 most relevant publications cited in papers containing sustainable development or sustainability science in their title, abstract or keywords.

Year	Authors	Title	Journal ¹	Type ²	Citations	Rank ³
1987	WCED	Our common future	(Book)	3.3	744	(1) 22,5%
2001	IPCC	IPCC: 3rd assessment (all reports)	(Book)	-	158	(2) 9,7%
2005	MEA	Ecosystems and human well-being (all reports)	(Book)	3.5	45	(3) 5,9%
1989	Pearce, D. et al.	Blueprint for a green economy	(Book)	3.3	140	(4) 4,3%
1972	Meadows, D. et al.	The limits to growth	(Book)	3.1	124	(5) 3,7%
2001	Kates, R. et al.	Sustainability science	Science	3.5	56	(6) 3,5%
1989	Daly, H. and Cobb, J.	For the common good	(Book)	3.2	113	(7) 3,4%
1995	IPCC	IPCC: 2nd assessment (all reports)	(Book)	-	95	(8) 3,4%
2003	Turner, B. et al.	A framework for vulnerability analysis in sustainability science	PNAS	3.5	34	(9) 3,2%
1997	Costanza, R. et al.	The value of the world's ecosystem and natural capital	Nature	3.3	65	(10) 2,6%
1992	United Nations	UNCED – Agenda 21	(Document)	3.3	81	(11) 2,6%
1980	IUCN et al.	The world conservation strategy	(Book)	-	83	(12) 2,5%
1968	Hardin, G.	The tragedy of the commons	Science	3.1	79	(13) 2,4%
1987	Redclift, M.	Sustainable development: exploring the contradictions	(Book)	-	74	(14) 2,2%
1991	Lele, S.	Sustainable development: a critical review	World Development	-	67	(15) 2,1%

Year	Authors	Title	Journal ¹	Type ²	Citations	Rank ³
1973	Daly, H.	Toward a steady-state economy	(Book)	3.2	65	(16) 2,0%
1990	Ostrom, E.	Governing the commons: the evolution of institutions for collective action	(Book)	3.4	60	(17) 1,8%
1996	Wackernagel, M. and Rees, W.	Our ecological footprint: reducing human impact on the earth	(Book)	3.1	49	(18) 1,8%
1999	Kaygusuz, K.	The viability of thermal energy storage	Energy Sources	-	37	(19) 1,7%
1992	Meadows, D. et al.	Beyond the limits	(Book)	3.1	55	(20) 1,7%
2003	Berkes, F. et al.	Navigating socioecological systems: building resilience for complexity and change	(Book)	3.4	17	(21) 1,6%
1999	National Academy of Sciences	Our common journey: a transition toward sustainability	(Book)	3.5	33	(22) 1,6%
1997	Daily, G. (Ed.)	Nature's services: societal dependence on natural ecosystems	(Book)	3.5	39	(23) 1,6%
1995	Hajer, M.	The politics of environmental discourse: ecological modernization and the policy process	(Book)	-	40	(24) 1,4%
1990	Pearce, D. and Turner, R.	Economics of natural resources and the environment	(Book)	3.3	46	(25) 1,4%
1977	Hartwick, J.	Intergenerational equity and the investing of rents from exhaustible resources	American Economic Review	-	46	(26) 1,4%
2002	Gunderson, L. and Holling, C.	Panarchy: understanding transformations in human and natural systems	(Book)	3.4	18	(27) 1,3%
2004	Walker, B. et al.	Resilience, adaptability and transformability in socioecological systems	Ecology and Society	3.4	10	(28) 1,3%
1993	Pearce, D. and Atkinson, G.	Capital theory and the measurement of sustainable development: an indicator of "weak" sustainability	Ecological Economics	3.2	40	(29) 1,3%
1991	IUCN et al.	Caring for the Earth: a strategy for sustainable living	(Book)	-	41	(30) 1,3%

Year	Authors	Title	Journal ¹	Type ²	Citations	Rank ³
1991	Costanza, R. (Ed.)	Ecological economics: the science and management of sustainability	(Book)	3.5	40	(31) 1,2%
1986	Holling, C.	The resilience of terrestrial ecosystems: local surprise and global change (in sustainable development of the biosphere)	(Book chapter)	3.4	41	(32) 1,2%
2003	Cash, D. et al.	Knowledge systems for sustainable development	PNAS	3.5	13	(33) 1,2%
1999	Hawken, P. et al.	Natural capitalism: creating the next industrial revolution	(Book)	3.3	25	(34) 1,2%
1997	Dryzek, J.	Environmental discourses: the politics of the earth	(Book)	-	29	(35) 1,2%
1997	Vitousek, P. et al.	Human domination of earth's ecosystems	Science	-	29	(36) 1,2%
1987	Barbier, E.	The concept of sustainable economic development	Environmental Conservation	3.3	37	(37) 1,1%
1992	Costanza, R. and Daly, H.	Natural capital and sustainable development	Conservation Biology	3.2	35	(38) 1,1%
1987	Blaikie, P. and Brookfield, H.	Land degradation and society	(Book)	-	36	(39) 1,1%
1971	Georgescu-Roegen, N.	The entropy law and the economic progress	(Book)	3.1	36	(40) 1,1%
1990	Adams, W.	Green development: environment and development in the third world	(Book)	-	35	(41) 1,1%
1991	Jacobs, M.	The green economy	(Book)	3.2	34	(42) 1,1%
1992	United Nations	UNCED – Rio Declaration	(Document)	3.3	33	(43) 1,0%
1993	Ludwig, D. et al.	Uncertainty, resource exploitation, and conservation: lessons from history	Science	3.4	32	(44) 1,0%
1995	Porter, M. and van der Linde, C.	Green and competitive – ending the stalemate	Harvard Business Review	-	29	(45) 1,0%
1990	IPCC	IPCC: 1st assessment (all reports)		-	33	(46) 1,0%
1997	Von Weizsäcker, E. et al.	Factor four: doubling wealth, halving resource use	(Book)	3.1	25	(47) 1,0%

Year	Authors	Title	Journal ¹	Type ²	Citations	Rank ³
1992	Beck, U.	Risk society: towards a new modernity	(Book)	-	31	(48) 1,0%
1994	Norgaard, R.	Development betrayed: the end of progress and a coevolutionary revisioning of the future	(Book)	3.5	29	(49) 1,0%
1973	Holling, C.	Resilience and stability of ecological systems	Annual Reviews in Ecology and Systematics	3.4	32	(50) 1,0%
1998	Lubchenco, J.	Entering the century of the environment: a new social contract for science	Science	-	21	(51) 0,9%
1986	Vitousek, P. et al.	Human appropriation of the products of photosynthesis	Bioscience	-	30	(52) 0,9%
2002	Eissen, M. et al.	10 years after rio-concepts on the contribution of chemistry to a sustainable development	Angewandte Chemie	-	12	(53) 0,9%
2002	Raskin, P. et al.	Great transition: the promise and lure of the times ahead	(Book)	3.3	12	(54) 0,9%
2002	Wackernagel, M. et al.	Tracking the ecological overshoot of the human economy	PNAS	3.1	12	(55) 0,9%
1973	Schumacher, E.	Small is beautiful: a study of economics as if people mattered	(Book)	3.2	29	(56) 0,9%
1998	Berkes, F. and Folke, C. (Eds.)	Linking social and ecological systems	(Book)	3.4	20	(57) 0,9%
2001	Scheffer, M. et al.	Catastrophic regime shifts in ecosystems	(Book)	3.4	14	(58) 0,9%
1992	Breheny, M. (Ed.)	Sustainable development and urban form	(Book)	-	27	(59) 0,9%
1979	Dasgupta, P. and Heal, G.	Economic theory and exhaustible resources	(Book)	3.3	28	(60) 0,8%

Note: shaded publications were also identified by Ma & Stern (2006) or by Costanza, et al. (2004) as influential.

¹ If applicable.

² This column refers to the section number of this paper where the publication in question could be included as an example of the approach it portrays.

³ Ranking criterion is the percentage of citing papers published after the publication in question. Only references with 10 or more citations are included.

A.2. Selected references dealing with the relationship between urban form and travel behavior

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
<u>Literature reviews</u>					
Arrington & Cervero, 2008 S: neighborhood P: TOD neighborhoods, United States G: literature review A: literature review D: literature review	.Car .PT	.Travel time .Car ownership	.Public transport .Accessibility to jobs	.Residential preferences	Between 1970 and 2000, public transport ridership for work trips increased in transit oriented development (TOD) zones but declined markedly in the surrounding areas. Compared with commuters in the region, TOD commuters: used transit 2 to 5 times more; owned roughly half as many cars. Households placed high value on neighborhood design, home prices and perceived value, and proximity to public transport. Travel times of transit compared with those of car, and accessibility to jobs by public transport were important in predicting modal choice.
Rickwood, et al., 2007 S: multilevel P: various G: literature review A: literature review D: literature review					For in-house consumption, appliances and building design seemed to be at least as important as urban form. High-rise buildings have high operational and embodied energy costs. For transport consumption, urban form is critical. Density reduces vehicle travel. The conclusion is supported when city size is controlled for, and by evidence from intercountry, interstate, intercity, and intracity comparisons. However, not even approximate estimates of combined in-house/transport energy can be made, although significant total energy savings are possible through a combination of different measures.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
Handy, 2006 S: multilevel P: various G: literature review A: literature review D: literature review	.Foot (active travel and physical activity)	(Depend on the study)	(Depend on the study)	(Depend on the study)	Accessibility is a strong correlate of away-from-home physical activity. The importance of design variables is somewhat more ambiguous. Design may prove more important for other physical activity than for active travel, and distance more important than design for active travel. Individual factors are potentially more important than the built environment in explaining physical activity. Considerable progress has been made in showing the significant connection between the built environment and physical activity, but evidence on what aspects of the built environment affect what types of physical activity to what degree is slim.
<u>Aggregated models at the city level or greater based on longitudinal data</u>					
Geurs & van Wee, 2006 S: multilevel (national, regional and 25 ha pixels) P: Netherlands G: statistics, modeling A: land use and transport model; cellular automata; simulation of two scenarios D: longitudinal, 1970–2000	.Car .PT	.Travel speed .Congestion levels .CO ₂ emissions .Habitat fragmentation .Noise	.Land use characteristics .Green areas .Accessibility to jobs		Without compact the urban development policies implemented in the Netherlands between 1970 and 2000, urban sprawl would likely have been greater, car use would have been higher at the cost of alternative modes and increased emission and noise levels in residential and natural environments, and the fragmentation of wildlife habitats would have been higher.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
Muñiz & Galindo, 2005 S: municipal and homogeneous zones (center, rings, satellite cities, etc.) P: Barcelona Metropolitan Region G: $n = 163$ municipalities A: comparison of averages and multiple regression D: longitudinal, 1986–1991		.Transportation ecological footprint	.Density .Accessibility	.Income .Job ratio	Net population density and accessibility had a greater capacity to explain transportation ecological footprint than factors such as family income and the job ratio. However, the relevance of job ratio and income spatial distribution in explaining eco-footprint differentials increased with time. Municipalities with low-density levels located in the outer periphery had a higher <i>per capita</i> ecological footprint of commuting than denser central areas. Ecological footprint also increased with income and decreased with job ratio.
Cameron, et al., 2003 S: city P: all continents G: statistics, $n = 46$ (training) and 49 (test) A: specific model D: longitudinal, 1960–1990	.Car .PT .PT demand	.Travel distance .Number of trips .Car ownership	.Population .Jobs .Land use characteristics .Public transport .Road density	.Gross domestic product	Private motorized mobility was largely determined by the structure of the city. An equation containing only population density and a traffic saturation factor, despite its simplicity, explained between 85% and 92% of the variance in private motorized mobility. Its functional form was consistent over four decades and across different all geographic and cultural regions. Aggregate urban system behavior was determined by the physical characteristics of the city.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
Webster and Bly (1987), as cited in Anderson, Kanaroglou, & Miller (1996) S: city P: 16 countries G: statistics, $n = 100$ A: multiple regression D: longitudinal, ca. 1950–1985	.PT	.Car ownership	.Density	.Travel costs	There was a consistent pattern of declining transit use due largely to increased car ownership in most cities. Except where there were heavy subsidies, average fares have been increasing in real terms, while average transit travel speeds have been declining. By contrast, automobile costs have been relatively stable. As for urban form, dispersion of employment created difficulties in transit provision. The form of suburbanization mattered: cities like Paris and Stockholm with a radial pattern of growth along rail transit lines were better able to maintain public transport shares. The model had a low explanatory power.
<u>Aggregated models at the city level or greater based on cross-sectional data</u>					
Shim, Rhee, Ahn, & Chung, 2006 S: city P: Korea G: $n = 61$ A: simple regression D: cross-sectional, 1999		.Transportation energy consumption	.Density		Transportation energy consumption decreased as the density increases. Energy inefficiency could increase due to congestion if the density increases further.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
van de Coevering & Schwanen, 2006 S: city P: Europe, Canada and United States G: statistics, $n = 31$ A: multiple regression D: cross-sectional, 1990	.Car .PT .Foot .Bike	.Travel distance .Travel time .Car ownership	.Population .Density .Population centrality .Job density .Road density .Public transport .Housing size .Building age	.Gender .Education .Age .Household size .Unemployment .Gross-domestic product	Various sociodemographic, land use, and history-related variables were associated with intermetropolitan differences in travel patterns. Characteristics of urban form however remained relevant to all dimensions of travel patterns when other factors were taken into consideration. The magnitude (and sometimes the sign) of the effects of one or more determinants varied significantly between European and United States cities. Share of car and public transport in Canadian cities resembled those in Europe, but with respect to walking and cycling they took an intermediate position between Europe and the USA.
Bento, et al., 2003 S: city P: United States G: questionnaires, $n = 114$ cities A: multiple regression D: cross-sectional, 1990	.Car .PT	.Travel distance	.Population centrality .City shape .Road density .Public transport (rail)	.Job ratio	Jobs-housing balance, population centrality, and rail service significantly reduced the probability of driving to work in cities with some rail transit. Population centrality, jobs-housing balance, city shape, road density, and (in rail cities) rail service level had a significant impact on annual household travel distances. The elasticity of travel distance with respect to each land use variable was small (around 0,10–0,20 in absolute value) but their combined effect could be significant.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
Ewing, et al., 2002 S: metropolitan area P: United States G: statistics, $n = 83$ (regions with population > 500000) A: multiple regression D: cross-sectional	.Car .PT .Foot	.Travel distance .Traffic fatalities .Air quality	.Density .Land use mix .Population centrality .Road density		Travel distances were longer in sprawling metropolitan areas than in areas with a lower sprawling index. In the ten most sprawling areas there were on average 180 cars to every 100 households; in the least sprawling areas (excluding New York City and Jersey City), there were 162 cars to every 100 households. Even controlling for income, households were more likely to own more vehicles in more sprawling areas. In these places, people were significantly less likely to commute by public transport or walking than in more compact areas. Twice the proportion of residents took public transit to work in relatively nonsprawling metropolitan areas against those sprawling more.
Banister, et al., 1997 S: city P: United Kingdom and Netherlands G: statistics, $n = 6$ A: case study D: cross-sectional		.Transportation energy use	.City size .Density .Open space	.Social structure	Significant relationships have been found principally between energy use in transport and the physical characteristics of the city, such as density, size, and amount of open space. Comparability problems between cities hindered the establishment of definitive causal relationships.
<u>Aggregated models at subcity levels based on cross-sectional data</u>					
Lin & Yang, 2009 S: traffic analysis zone P: Taipei, Taiwan G: statistics, $n = 173$ A: SEM D: cross-sectional, 2000	.Car + motorcyc.	.Number of trips .Car ownership	.Density .Land use mix .Accessibility .Public transport .Road density	.Income	Density was positively related to trip generation and negatively associated with private mode transports. Diversity of land uses reduced trip generation, but its total effect on private modes was positive. Pedestrian-friendly road design had a negative influence on private transport use.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
Bhat & Guo, 2007 S: transport analysis zone P: Alameda, San Francisco, United States G: statistics, $n = 233$ A: joint mixed multinomial logit-ordered response structure D: cross-sectional, 2000		.Travel time .Car ownership	.Density .Job density .Land use .Accessibility to recreation facilities .Public transport .Urban design	.Travel cost .Income .Household size .Housing value .Ethnicity .Residential location	Household demographics had a more prominent effect than building environment in influencing residential choice and car ownership. Household income was the dominant factor in residential sorting. Specifically, low-income households consciously chosen to (or were constrained to) locate in neighborhoods with low commute costs, long commute times, and high employment density compared to their high-income counterparts. Such low-income households also owned fewer cars.
Nicolas, et al., 2003 S: subcity P: Lyons conurbation G: questionnaire A: simple comparison D: cross-sectional, 1994		.Travel distance .Transportation CO ₂ emissions .Car ownership	.Distance from the center (center, 1 st ring and 2 nd ring)	.Income	Carbon emissions <i>per capita</i> rise with increasing distances from the center. Suburban residents emitted 2,5 times as much atmospheric pollutants as city centre residents. Similarly, suburbs performed consistently worse in the other considered indicators. Car ownership increased with higher household income.
Holtzclaw, et al., 2002 S: neighborhood P: Chicago, Los Angeles and San Francisco regions, United States G: statistics, $n \approx 3000$ A: multiple regression D: cross-sectional		.Travel distance .Car ownership	.Density .Urban design .Public transport	.Income .Household size	Car ownership and travel distance per car varied with neighborhood urban design and socioeconomic characteristics. Average car ownership was primarily a function of the residential density, <i>per capita</i> income, family size and the availability of public transport. Similarly, average annual distance driven per car was a strong function of density, income, household size and public transit, and a weaker function of the pedestrian and bicycle friendliness of the community. Results were valid for the three regions analyzed.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
Camagni, et al., 2002 S: borough P: Milan G: statistics, $n = 184$ A: multiple regression D: cross-sectional, 1991		.Mobility impact	.Density .Population change .Typology of urban .expansion .Distance from Milan .Housing age	.Job ratio	Net density and housing age had a strong negative influence on mobility impact. Jobs to residents ratio also had a negative, although less pronounced, influence. On the contrary, increased growth rate of residents implied higher mobility impacts.
<u>Aggregated models based on comparisons between groups or on case studies</u>					
Newman & Jennings, 2008 S: neighborhood P: BedZED neighborhood, United Kingdom G: statistics A: simple comparison D: cross-sectional		.Transportation ecological footprint			Ecological footprint in BedZED neighborhood was 4,35 ha <i>per capita</i> , below the average United Kingdom footprint of 6,19 ha <i>per capita</i> .
Rickwood, et al., 2007 S: borough P: Sydney and Melbourne, Australia A: bivariate scatter plots D: cross-sectional	.PT		.Density		There was a clear and nonlinear association between higher density and greater public transport use. The largest effects took place at up to 70 people/ha, beyond which marginal returns decrease. However, given that population densities typically decrease with distance from the central business district, the true underlying effect could be also related to this.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
Newman, 2006; Newman & Kenworthy, 1999 S: city P: all continents G: statistics, $n = 46$ A: correlations and bivariate scatter plots D: cross-sectional, 1990	.Car .PT .Foot + bike	.Travel distance .Travel time .Energy use .Car ownership .Transport deaths (variables below account only for the transportation share) .CO ₂ emissions .NO _x emissions .SO ₂ emissions	.Density .Road density	.Commuting costs	Total <i>per capita</i> use of transportation energy in United States cities was five times higher than in Asian cities. Compared with wealthier European cities, United States cities were 2,5 times as inefficient. There was a strong statistical link between transport energy use <i>per capita</i> and urban density. Similarly, the length of travel to work followed very closely the density of a city. There seemed to be a critical point (about 20 to 30 persons per ha) below which car-dependent land use patterns were an inherent characteristic of the city. Total mobility varied considerably but was not related to wealth. When energy consumption was plotted against urbanized land area, a straight line was achieved. Transport energy use <i>per capita</i> generally declined as city size increase. On average, the economic factors explained, at most, about half the differences in gasoline use.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
<u>Disaggregated models controlling for travel attitudes and/or residential preferences based on quasi-longitudinal data</u>					
Cao, et al., 2007 S: individual P: California, Unites States (four traditional and four suburban neighborhoods) G: questionnaire, $n = 547$ movers A: SEM D: quasi-longitudinal, 2003	.Changes in driving behavior	.Changes in car ownership	.Accessibility .Urban design (also change in these attributes)	.Education .Income .Age .Household size (also change or perceived change in these attributes) .Residential preferences .Travel attitudes	Residential self-selection had significant direct and indirect impacts on travel behavior. Neighborhood preferences, travel-related attitudes, and sociodemographic variables exerted direct influences on the choice of residential neighborhood, which then influenced travel behavior, and exerted direct influences on car ownership, driving behavior, and walking behavior (even controlling for after built environment influences). Changes in the built environment significantly changed travel behavior. Models suggested that increases in accessibility were the most important factor in reducing driving. Enhancements to the design quality of the built environment also increased walking. Effects of the built environment on travel behavior were similar to or larger than those of sociodemographics.
Handy, Cao, & Mokhtarian, 2005 S: individual P: four neighborhoods in California, United States G: questionnaire, $n = 1682$ A: multiple regression and multinomial logistic regressions D: cross-sectional and quasi-longitudinal, 2003		.Change in travel distance	.Accessibility .Urban design .Public transport (rail) (also change in these attributes)	.Education .Income .Age .Household size .Street life .Safety (also change or perceived change in the above attributes) .Travel attitudes	In the cross-sectional study, differences in travel distance were largely explained by attitudes and the effect of the built environment mostly disappeared when attitudes and sociodemographic factors were been accounted for. However, the quasi-longitudinal analysis showed significant associations between changes in driving and changes in the built environment, even when attitudes were accounted for, providing support for a causal relationship.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
<u>Disaggregated models controlling for travel attitudes and/or residential preferences based on cross-sectional data</u>					
Schwanen & Mokhtarian, 2005 S: individual P: one traditional neighborhood and two suburban neighborhoods in the San Francisco Bay, United States G: questionnaire, $n = 1358$ A: multinomial logistic regression D: cross-sectional, 1998	.Car	.Car ownership	.Neighborhood type	.Age .Income .Job classification .Personality type .Lifestyle type .Residential preferences (dissonant residents live in a neighborhood different from their stated preferences) .Travel attitudes	Dissonant residents of the traditional neighborhood were far more likely to commute by private vehicle than consonant urbanites but not quite as likely as suburbanites. In the suburban neighborhoods, the conditioning influence of the environment prevailed over travelers' preferences regarding their residential environment. In the urban neighborhood, the relative contributions of preferences toward and constraints imposed by the physical structure to the explanation of travel patterns were more balanced. The difference between these two outcomes may lie in the degree of choice available to the residents of each type of neighborhood. Although mismatched suburban residents might be more inclined to use transit than their matched neighbors, they might feel they have no choice. In the traditional neighborhood, by contrast, mismatched urban residents might be more inclined than their matched neighbors to commute by car, but the relatively good transit service increased their options and many took advantage of that. Results suggested that residential self-selection processes play a significant role in explaining travel patterns. Nevertheless, neighborhood structure appears to have an autonomous influence.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
Holden, 2004 S: household P: Greater Oslo and Førde, Norway G: questionnaire, $n = 537$ A: no specific statistical testing D: cross-sectional, 1998		.Ecological footprint .Car ownership	.Density .Accessibility .Housing type .Housing size	.Consumer behavior .Household size .Income .Environmental attitudes	The first and most important factor influencing ecological footprint was household size: larger households had a lower <i>per capita</i> footprint. The second factor was car ownership, and the third one was income. Planning factors also had a strong influence on the household's footprint. In spite of the additional income of people living in dense areas, their ecological footprint was lower. The ecological footprint of people living in detached houses was almost 20% higher than the footprint of people living in more concentrated types of housing.
<u>Other disaggregated models based on longitudinal data</u>					
Vance & Hedel, 2007 S: individual (car owners) P: Germany G: questionnaire, $n = 4328$ A: two-part model (probit and multiple regression) D: longitudinal, 1996–2003	.Car	.Travel distance .Car ownership	.Density .Land use mix .Accessibility .Road density	.Age .Income (zip code average) .Gender .Household size	Results suggested that urban form has a causative impact on car use, a finding that was robust to alternative econometric specifications. 1979, 1986, 1991, 1993
Stead, 2001 S: individual P: United Kingdom G: questionnaire, $n \approx 24000$ A: multiple regression D: longitudinal		.Travel distance .Car ownership	.Density .Accessibility .Public transport .City size	.Age .Employment .Household size .Education	Socioeconomic characteristics explained about half the variation in travel distance per person across different boroughs, whereas land-use characteristics often explain up to one third of the variation in travel distance per person.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
<u>Disaggregated structural equation models based on cross-sectional data</u>					
Van Acker, et al., 2007 S: individual P: Flanders, Belgium G: statistics, $n = 3905$ people and 39712 trips A: SEM D: cross-sectional, 2000		.Travel distance .Travel time	.Land use characteristics	.Social status .Household responsibility	Travel behavior was mainly influenced by the respondent's social status: a high social status was associated with higher distances and travel times. Significant indirect effects stemmed from individual's role within the household. The effect of land use was limited. Indirect effects were of great importance in understanding travel behavior.
Abreu e Silva, 2007 S: individual P: Metropolitan Area of Lisbon, Portugal G: questionnaire, $n = 7849$ A: SEM D: cross-sectional, 1994	.Car .PT .Foot	.Number of trips .Travel distance .Car ownership	.Traditional urban .Highway accessibility .Land use diversity (all variables above for the residential and employment locations) .Road density	.Age .Gender .Youth in the family .Household size	Residents in dense, central and compact areas with a reasonable land use mix were more likely to use public transport, cycle or walk, and less likely to own a car. Employment location significantly influenced mode choice: people with jobs in central and dense areas commuted by public transport more frequently.
Næss, 2005; Næss, 2006 S: household P: 29 residential areas in Copenhagen G: questionnaire, $n = 1932$ A: multiple regression and SEM D: cross-sectional	.Car .PT .Foot .Bike	.Travel distance .Car ownership	.Distance to the city center .Distance to the rail station	.Gender .Education .Household size .Income .Age .Travel attitudes	Residential location influenced travel behavior, even when controlling for socioeconomic and attitudinal differences among the inhabitants. Respondents living in a dense area close to downtown Copenhagen traveled shorter distances, less by car, and opted more frequently for cycling and walking. On the contrary, people living far from the center reported a lower share of public transport. For most travel purposes, respondents emphasized the possibility to choose among facilities rather than proximity.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
<u>Other disaggregated models based on cross-sectional data</u>					
Frank, et al., 2008 S: individual P: Central Puget Sound, Seattle G: questionnaire A: logistic regression, $n = 14487$ people and 130339 trips D: cross-sectional, 1999	.Car .Carpool .PT .Foot .Bike	.Travel time .Car ownership	.Density .Street connectivity .Land use mix .Retail density (all variables for the origin and destination of trips)	.Travel cost .Socioeconomic characteristics .Demographic characteristics	Travel time was an extremely important predictor of public transport use. The analysis showed transit users to be more sensitive to changes in travel time than to cost, with wait time much more relevant than in-vehicle time. The results suggested that a considerable growth in transit ridership could be achieved through more competitive travel times on public transport. Land use mix, residential density, street connectivity and retail density at the place of residence and employment significantly increased walking, cycling, and use of public transport. The degree to which participants chained trips together into tours was also highly correlated to the land use characteristics near where residents live and work.
Forsyth, et al., 2007 S: individual P: Twin Cities, Minnesota, United States G: questionnaire, $n = 715$ A: negative binomial and logistic regressions D: cross-sectional	.Foot	.Travel distance .Travel reason	.Density .Building density .Job density	.Age .Income .Health .Race	Few associations were detected, except for of a modest correlation for nonWhites between density and overall physical activity. Higher-density environments promoted travel walking and lower density environments promoted leisure walking, but overall physical activity and total walking did not change. However, higher densities alone did not appear to be determinant for a public health campaign aiming to increase physical activity.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
Holden & Norland, 2005 S: individual P: Greater Oslo Region, Norway G: questionnaire, 591 < n < 778 A: multiple regression D: cross-sectional, 2003		.Everyday travel .Leisure travel by plane .Leisure travel by car .Residential energy .Car ownership	.Density .Land use mix .Distance from the city center .Housing type	.Gender .Age .Education .Household size .Income	Low energy use correlated with high-density housing located near a centre and offering a range of private and public services. There was an apparent reduction in leisure time travel when residents had access to a private garden. Residents having access to a private garden used on average 1000 fewer kWh annually for long leisure-time travel by car and plane than did residents without such access. The annual energy use for housing differed substantially with housing type. Residents in single-family housing used about 50 per cent more energy than residents in multifamily housing. However, the difference in energy consumption between the two types of housing has reduced in recent decades. Total energy use decreased as density reached a certain level beyond which the total energy use increased.
Lawrence Frank & Co., 2005 S: household P: King County, Washington G: questionnaire, n = 3259 A: multiple regression and logistic regression D: cross-sectional, 1999	.Car .PT .Foot	.Travel distance .Physical activity .CO ₂ emissions .Air quality	.Land use characteristics .Road density	.Socioeconomic characteristics .Demographic characteristics	Results showed a 20% increase in the likelihood that someone walked for each additional institutional and recreational facility within one km from his place of residence. Distance to transit from home and work was also a significant predictor of public transport use. Each additional km from home and from work was associated with a 40 and 80% reduction in transit use respectively. The study also showed a 42% reduction in the likelihood a respondent used transit for each additional household vehicle.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
Moudon, et al., 2005 S: household P: King County, Washington G: questionnaire, $n = 608$ A: logistical regression D: cross-sectional, 2002	.Bike		.Land use characteristics .Road density	.Socioeconomic characteristics .Demographic characteristics	One-fifth of the respondents reported cycling at least once a week in their neighborhood, and more often for recreation or exercise than for transportation. Both perceived and objective environmental conditions contributed to the likelihood of cycling. Proximity to trails and the presence of agglomerations of offices, hospitals, and fast food restaurants were significant environmental variables. The presence of bicycle lanes, traffic speed and volume, slope, block size, and the presence of parks, were found not significant. A nonlinear relationship was found between the odds of cycling and the perception of traffic problems and car-oriented facilities. Overall, cycling was only moderately associated with the neighborhood environment.
Cervero, 2002 S: individual P: Montgomery County, Maryland, United States G: questionnaire, $n = 5167$ trips A: binomial and multinomial logistic regression D: cross-sectional, 1994	.Car .Carpool .PT	.Travel time .Car ownership	.Density .Land use mix .Urban design (all variables above for the origin and destination of trips) .Job accessibility .Labor-force accessibility	.Gender .Household size .Full-time employment .Travel cost	Land use factors significantly influenced mode choice, even upon controlling for modal travel times and costs. Higher densities and land-use mixtures consistently worked in favor of public transport use and against drive-alone automobile travel. The influences of urban design factors on mode choice were generally weaker. Transit usage was found to be most sensitive to changes in land use attributes. The dimensions of density and diversity exerted the strongest influences on the probability of selecting a mode. The influences of design factors on mode choice were more modest, as were the affects of accessibility and transit-oriented housing.

Research characteristics ¹	Modal shares ²	Travel behavior and others ³	Urban form ⁴	Socio-demography	Results
Meurs & Haaijer, 2001 S: individual P: Netherlands G: questionnaire, $n = 713$ A: multiple regression D: cross-sectional, 1999	.Car .PT .Foot	.Travel reason (shopping, social or recreational and commuting) .Car ownership	.Housing type .Accessibility .Urban design .Urbanity (urban, suburban or rural)	.Education .Household size .Employment	About 40% of the total number of trips was related to personal, location, and environmental characteristics. The influence of the residential environmental characteristics differed by mode of transport: from about 10% for car trips to 40% for journeys on foot. The effect of the residential environment characteristics was greatest for shopping trips (more than 30%). Commuter traffic was essentially related to personal characteristics.
Hibbers et al. (1999), as cited in van Wee (2002) S: individual P: Netherlands G: questionnaire, $n = 1,1$ million individuals and 3,8 million trips) A: multiple regression D: cross-sectional, 1998–2002	.Car .PT .Foot + bike		.Density .Public transport .Accessibility .Neighborhood type	.Socioeconomic characteristics	Car use by people living in new residential areas built within an existing city or town is about one-third below the level of car use by people living in new residential areas built at the edge of town. Differences in travel behavior between several types of residential areas built at the edge of town are very limited.

Note: variable names were simplified and aggregated (for instance, several sociodemographic measures are sometimes grouped as *socioeconomic characteristics*; different age groups, often dummy-coded, are reported as *age*; etc.).

¹ S: scale; P: place; G: data gathering method, number of cases; A: data analysis method; D: research design, year.

² PT: public transport.

³ Travel behavior indicators are usually disaggregated by mode; car ownership was used in some models as an independent variable; in aggregated models, consumption indicators should be understood as normalized (e.g., on a *per capita* basis).

⁴ In disaggregated models, urban form indicators refer to the residential neighborhood of the individual or household, except when stated otherwise.

A.3. Bellagio principles

Bellagio principles concerning the selection of sustainability indicators (Hardi & Zdan, 1997, as published in McCool & Stankey, 2004).

1. Guiding vision and goals

Assessment of progress toward sustainable development should:

be guided by a clear vision of sustainable development and goals that define that vision

2. Holistic perspective

Assessment of progress toward sustainable development should:

include review of the whole system as well as its parts

consider the well-being of social, ecological, and economic subsystems, their state as well as the direction and rate of change of that state, of their component parts, and the interaction between parts

consider both positive and negative consequences of human activity, in a way that reflects the costs and benefits for human and ecological systems, in monetary and nonmonetary terms

3. Essential elements

Assessment of progress toward sustainable development should:

consider equity and disparity within the current population and between present and future generations, dealing with such concerns as resource use, overconsumption and poverty, human rights, and access to services, as appropriate

consider the ecological conditions on which life depends

consider economic development and other, nonmarket activities that contribute to human/social well-being

4. Adequate scope

Assessment of progress toward sustainable development should:

adopt a time horizon long enough to capture both human and ecosystem time scales, thus responding to needs of future generations as well as those current to short-term decision-making

define the space of study large enough to include not only local but also long distance impacts on people and ecosystems

build on historic and current conditions to anticipate future conditions where we want to go, where we could go

5. Practical focus

Assessment of progress toward sustainable development should be based on:

an explicit set of categories or an organizing framework that links vision and goals to indicators and assessment criteria

a limited number of key issues for analysis

a limited number of indicators or indicator combinations to provide a clearer signal of progress

standardizing measurement wherever possible to permit comparison, comparing indicator values to targets, reference

values, ranges, thresholds, or direction of trends, as appropriate

6. Openness

Assessment of progress toward sustainable development should:

make the methods and data that are used accessible to all

make explicit all judgments, assumptions, and uncertainties in data and interpretations

7. Effective communication

Assessment of progress toward sustainable development should:

be designed to address the needs of the audience and set of users

draw from indicators and other tools that are stimulating and serve to engage decision-makers

aim, from the outset, for simplicity in structure and use of clear and plain language

8. Broad participation

Assessment of progress toward sustainable development should:

obtain broad representation of key grass-roots, professional, technical, and social groups, including youth, women, and indigenous people — to ensure recognition of diverse and changing values

ensure the participation of decision-makers to secure a firm link to adopted policies and resulting action

9. Ongoing assessment

Assessment of progress toward sustainable development should:

develop a capacity for repeated measurement to determine trends

be iterative, adaptive, and responsive to change and uncertainty because systems are complex and change frequently

adjust goals, frameworks, and indicators as new insights are gained

promote development of collective learning and feedback to decision-making

10. Institutional capacity

Continuity of assessing progress toward sustainable development should be assured by:

clearly assigning responsibility and providing ongoing support in the decision-making process

providing institutional capacity for data collection, maintenance, and documentation

supporting development of local assessment capacity

A.4. Raw datasets

Datasets from where raw variables were queried or calculated.

Dataset	Date ¹	Institution in charge	Remarks	Code ²
<u>Socioeconomic data</u>				
Agriculture census	1989, 1999	INE – Statistics Portugal		AC
FUE – Statistical units database	2003, 2005	INE – Statistics Portugal	Mainly economic data	FUE
Local elections results	1997, 2001, 2005	CNE – National Elections Commission		CNE
Municipal inventories	2002	INE – Statistics Portugal	Inventory about available public equipments and services at the borough level	Inventories
Nongovernmental youth organizations registry	2008	IPJ – Portuguese Youth Institute		IPJ
Population and housing census	2001, 1991	INE – Statistics Portugal		Census
Taxpayers' contributions and means-tested benefits	2008	Social Security		SS
Volunteering database	2008	Entrajuda		Entrajuda
<u>Cartography</u>				
BGRI – Geographic Base of Information Reference	2008	INE – Statistics Portugal	1:25000; Database of territorial units for statistics covering the entire country; Includes data from the population and housing census at the statistical subsection level	BGRI

Dataset	Date ¹	Institution in charge	Remarks	Code ²
Bus routes	2008	Several private bus operators Municipality of Vila do Conde	1:25000	Bus
Bus routes and stops	2001, 2008	STCP – Porto Society of Collective Transports	1:25000	STCP
CAOP – Administrative Map of Portugal	1991–2006	IGP – Portuguese Geographic Institute	1:25000	CAOP
Localization of health centers	2008	ARS Norte – Northern Regional Health Authority	1:25000	ARS
Localization of schools	2008	GEPE – Office of Education Statistics	1:25000	GEPE
Metro routes and stops	2007	Metro do Porto	1:25000	Metro
SNIT – National Territorial Information System	2008	DGOTDU – Directorate General for Spatial Planning and Urban Development	1:25000; Includes the cartography of municipal master plans	SNIT
<u>Land use and land cover cartography³</u>				
Corine Land Cover	~1987, 2000	IGP – Portuguese Geographic Institute and EEA – EEA		CLC
COS – Land use map	1990	IGP – Portuguese Geographic Institute		COS
Metropolitan Area of Porto ecological structure	2005	CIBIO – Research Center in Biodiversity and Genetic Resources		CIBIO
Orthophotographs	2000	IFAP – Financing Institute for Agriculture and Fisheries		IFAP
Orthophotographs	2008	Google Maps		Google
Soil sealing	2006	IGP – Portuguese Geographic Institute and EEA – EEA		Sealing
Satellite images	1990	APA – Portuguese Environmental Agency		Satellite

Dataset	Date ¹	Institution in charge	Remarks	Code ²
Satellite images (Image 2000)	2000	APA – Portuguese Environmental Agency		Satellite
Satellite images (Image 2006)	2006	ESA – European Space Agency		Satellite
Topographic maps – series M888	~ 1997	IGeoE – Army Geographic Institute		IGeoE
<u>Other environmental and transportation data</u>				
Air quality index	2008	Fernando Pessoa University	Results were derived from modeling	UFP
Crimes against people	2007	PSP – Police for the Public Safety		PSP
Crimes against people	2007	GNR – National Guard		GNR
Electricity consumption	2007	EDP – Portuguese Energy		EDP
Mobility survey	2000	INE – Statistics Portugal		Mobility
Pedestrian and cycling routes	2005	Catholic University - College of Biotechnology and LIPOR – Regional Waste Management Service		ESB
Pedestrian crashes	2006	ANSR – National Authority for Road Security		ANSR
Public transportation demand	2008	TRENMO	Results were derived from modeling	TRENMO
Structural accessibility	2008	Cecília Silva (University of Porto – Engineering Faculty)	Results were derived from modeling	FEUP
Water consumption	2007	Several municipal water companies		Water

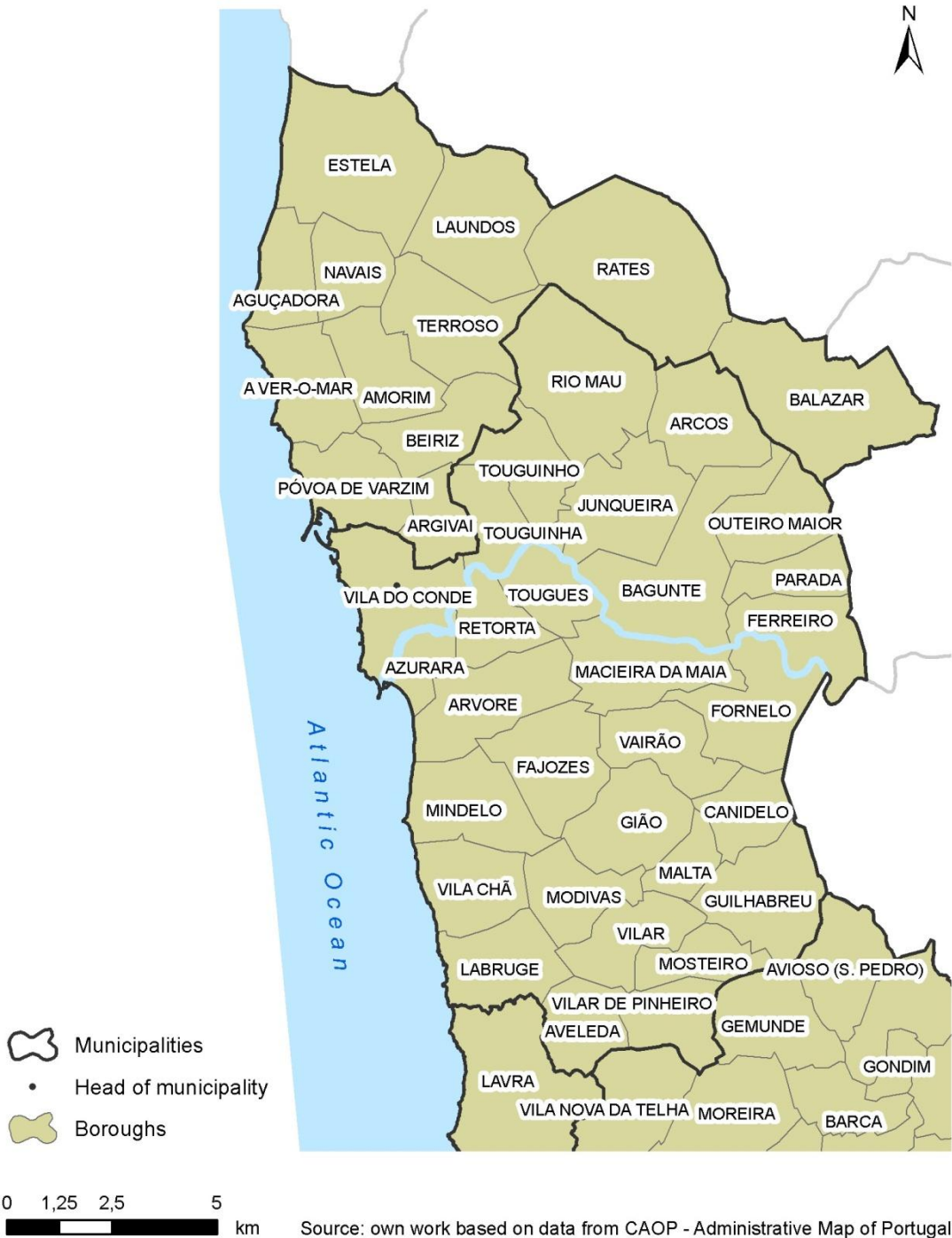
¹ Refers to the specific dates used in this thesis.

² Code used in Table 4.5-2.

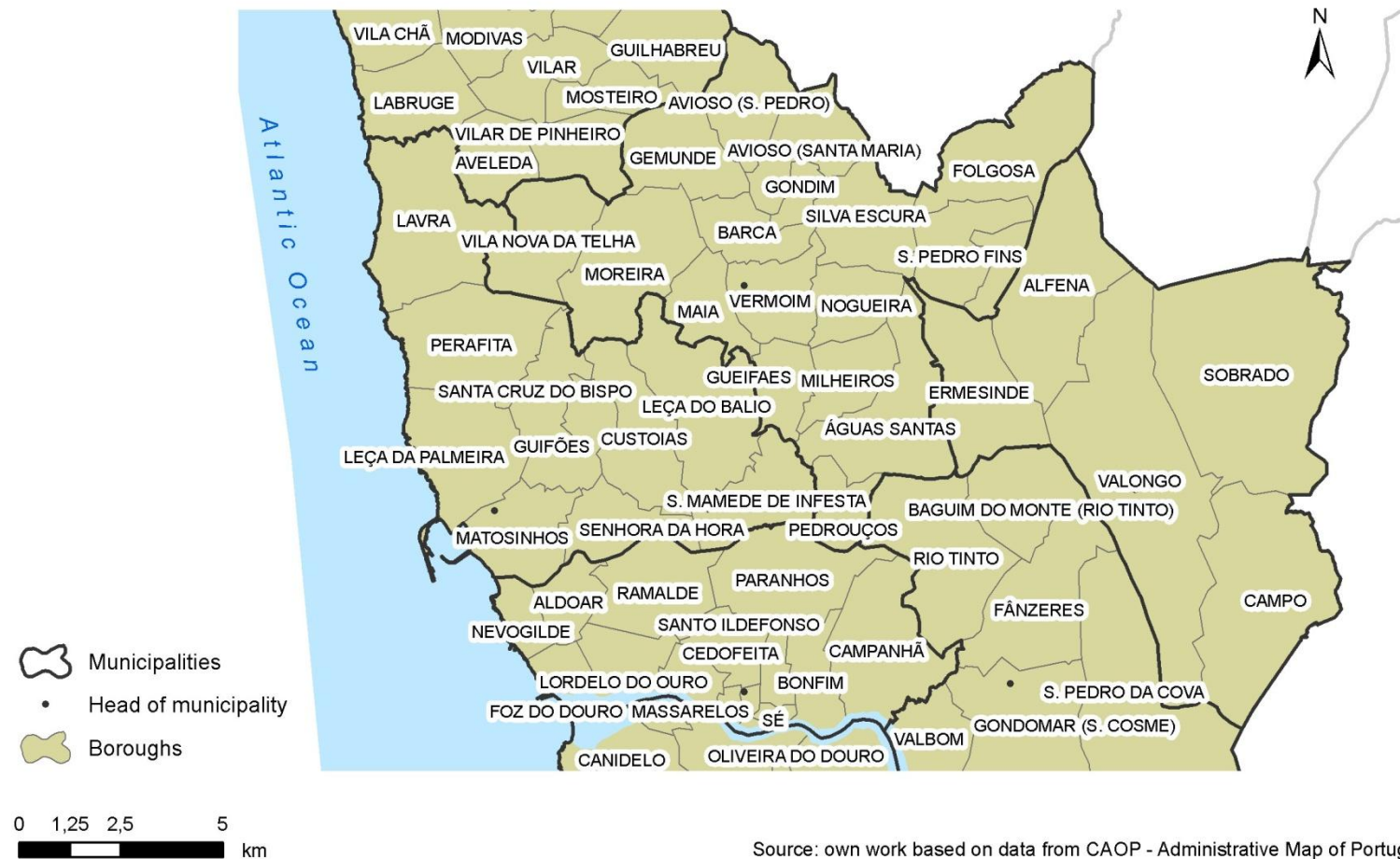
³ See below for further explanations.

A.5. Boroughs of the Metropolitan Area of Porto

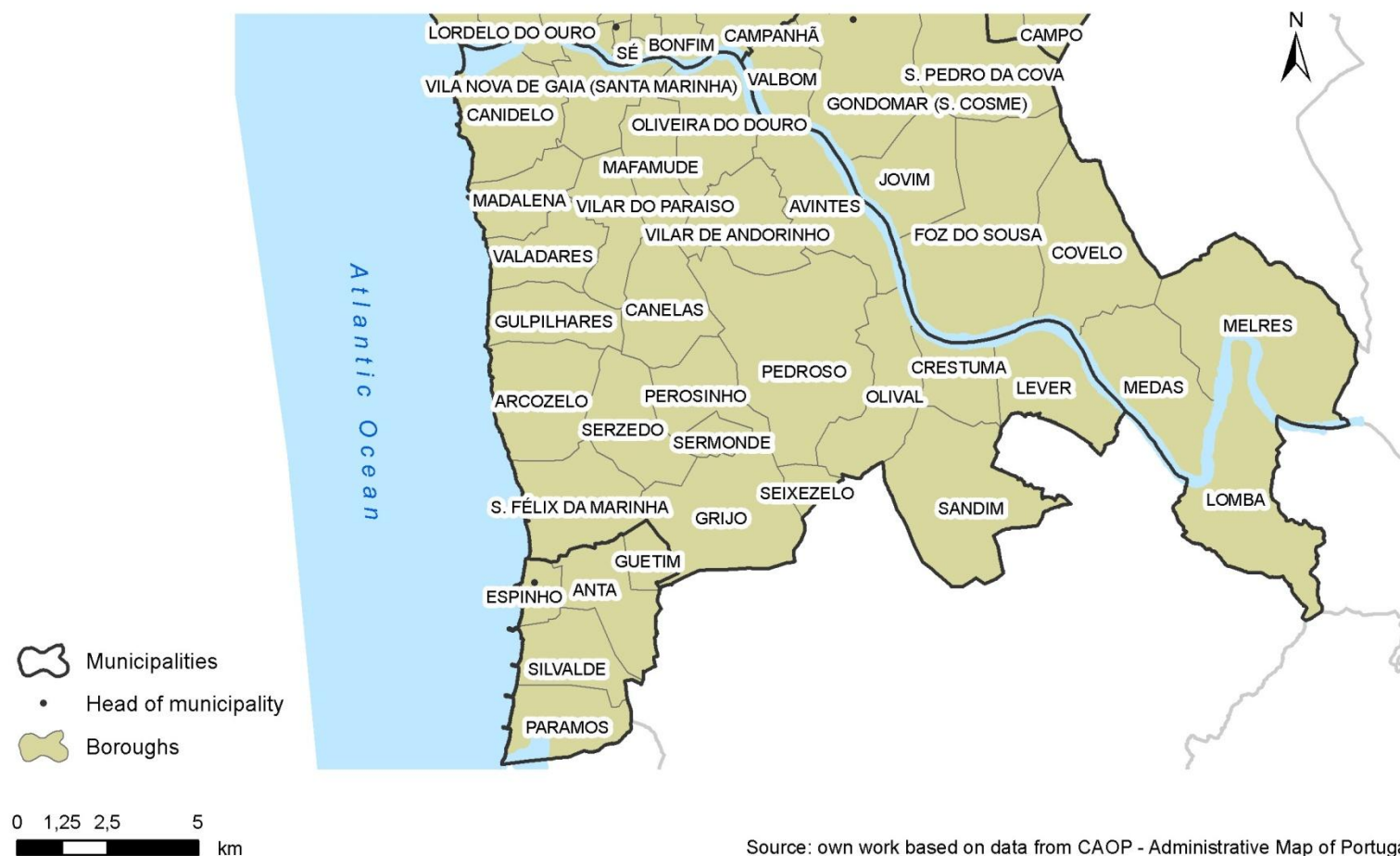
Boroughs of Metropolitan Area of Porto (North)



Boroughs of Metropolitan Area of Porto (Center)



Boroughs of Metropolitan Area of Porto (South)



A.6. Factor loadings

Cross-sectional dataset (2006)

Human capabilities

Variable	Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
	Education 1	
Illiteracy_2001	-0,803850	
Higher_education_2001	0,828125	
Secondary_education_2001	0,777434	
Students_2001	0,891516	
Expl.Var	2,731171	
Prp.Totl	0,682793	

Variable	Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
	Aging/Lone hh. 1	
Family_size_2001	-0,807948	
Lone_person_households_2001	0,956036	
Dwelling_occupancy_2006	-0,696986	
Aging_2001	0,892803	
Expl.Var	2,849671	
Prp.Totl	0,712418	

Territorial structure

Variable	Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
	Density 1	
Population_density_2006	1,00798	
Population_net_density_2006	0,87784	
Dwellings_building_2001	0,87354	
Moran_2006	0,58813	
Urban_mosaic_area_2006	0,60068	
Compactness_2006	0,59734	
Building_net_density_2007	0,66592	
Urban_fabric_proportion_2006	0,92061	
Expl.Var	4,90420	
Prp.Totl	0,61303	

Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
Variable	Dispersion 1
Urban_fabric_proportion_2006	-0,971743
Gini_2006	0,980398
SD_2006	0,742949
Expl.Var	2,457436
Prp.Totl	0,819145

Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
Variable	Accessibility 1
Kindergarten_distance_2007	-0,539349
Primary_school_distance_2007	-0,599261
Junior_school_distance_2007	-0,826305
Secondary_school_distance_2007	-0,927576
Healthcare_distance_2007	-0,611739
Sports_facilities_2002	-0,577460
Highway_distance_2007	-0,641626
Expl.Var	3,312556
Prp.Totl	0,473222

Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
Variable	Basic services 1
Dwellings_drinking_water_2001	0,974114
Dwellings_sewerage_system_2001	0,974114
Expl.Var	1,897795
Prp.Totl	0,948898

Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
Variable	Natural capital 1
Forest_proportion_2006	0,894449
Forest_proportion_non_urbanized_2006	0,894449
Expl.Var	1,600078
Prp.Totl	0,800039

Economy

		Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)
Variable	Economy 1	
Jobs_2005	0,761908	
Job_net_density_2005	0,892692	
Street_trade_2006	0,748485	
H_R_2006	0,766410	
Street_trade_net_density_2006	0,867803	
H_R_net_density_2006	0,711854	
Trade_services_jobs_2005	0,803449	
Trade_services_job_net_density_2005	0,898956	
Trade_services_location_quotient_2005	0,715594	
Office_residential_buildings_2001	0,683534	
Expl.Var	6,217780	
Prp.Totl	0,621778	

		Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)
Variable	Agriculture 1	
Agricultural_fishing_jobs_2001	0,633300	
Agricultural_fishing_labour_force_1999	0,839223	
Agricultural_fishing_job_density_2001	0,488893	
Agricultural_fishing_labour_force_density_1999	0,451605	
UAA_1999	0,620169	
UAA_proportion_1999	0,516092	
Expl.Var	2,199290	
Prp.Totl	0,366548	

		Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)
Variable	Occupation regularity 1	
Seasonally_vacant_dwellings_2001	-0,900457	
Occupied_dwellings_2001	0,900457	
Expl.Var	1,621646	
Prp.Totl	0,810823	

Longitudinal dataset (2001–1991)

Human capabilities

Variable	Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
	Education 1	
Resident_job_diversity_2001	0,877498	
Illiteracy_2001	-0,687423	
Higher_education_2001	0,797000	
Secondary_education_2001	0,967218	
School_desistance_2001	-0,769918	
Expl.Var	3,406049	
Prp.Totl	0,681210	

Variable	Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
	Aging/Lone hh. 1	
Family_size_2001	-0,937982	
Dwelling_occupancy_2001	-0,905600	
Aging_2001	0,809954	
Lone_person_households_2001	0,850472	
Expl.Var	3,079249	
Prp.Totl	0,769812	

Territorial structure

Variable	Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
	Density 1	
Population_density_2001	0,972837	
Population_net_density_2001	0,690321	
Dwellings_building_2001	0,866252	
Moran_2000	0,594976	
Urban_mosaic_density_2000	-0,512424	
Urban_mosaic_area_2000	0,722378	
Building_age_2001	0,672954	
Expl.Var	3,764619	
Prp.Totl	0,537803	

Variable	Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
	Dispersion 1	
Urban_fabric_proportion_2000	-0,978257	
Gini_2000	0,988539	
SD_2000	0,733722	
Expl.Var	2,472544	
Prp.Totl	0,824181	

Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
Variable	Accessibility 1
Highway_distance_2001	-0,673093
Junior_school_distance_2007	-0,871786
Secondary_school_distance_2007	-0,891871
Healthcare_distance_2007	-0,621095
Sports_facilities_2002	-0,602536
Expl.Var	2,757307
Prp.Totl	0,551461

Economy

Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
Variable	Economy 1
Job_net_density	0,919765
Companies_net_density	0,987660
Street_trade_net_density	0,956184
H_R_net_density	0,929587
Trade_services_job_net_density	0,937111
Trade_services_companies_net_density	0,990174
Expl.Var	5,458481
Prp.Totl	0,909747

Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
Variable	Agriculture 1
Agricultural_fishing_jobs_2001	0,719044
Agricultural_fishing_labour_force_1999	0,782924
Agricultural_fishing_job_density_2001	0,620501
Agricultural_fishing_labour_force_density_1999	0,547884
UAA_1999	0,543693
UAA_proportion_1999	0,486495
Expl.Var	2,347472
Prp.Totl	0,391245

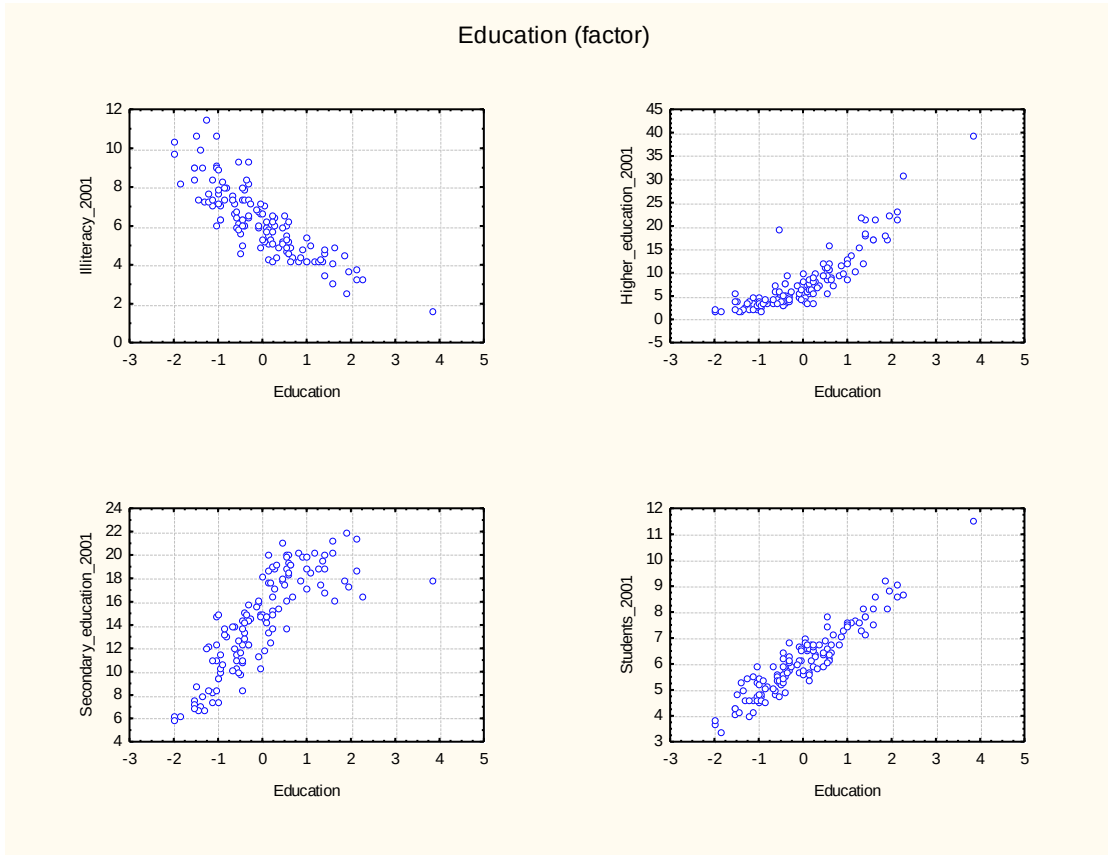
Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
Variable	Occupation regularity 1
Seasonally_vacant_dwellings_2001	-0,922611
Occupied_dwellings_2001	0,922611
Expl.Var	1,702421
Prp.Totl	0,851210

Interactions

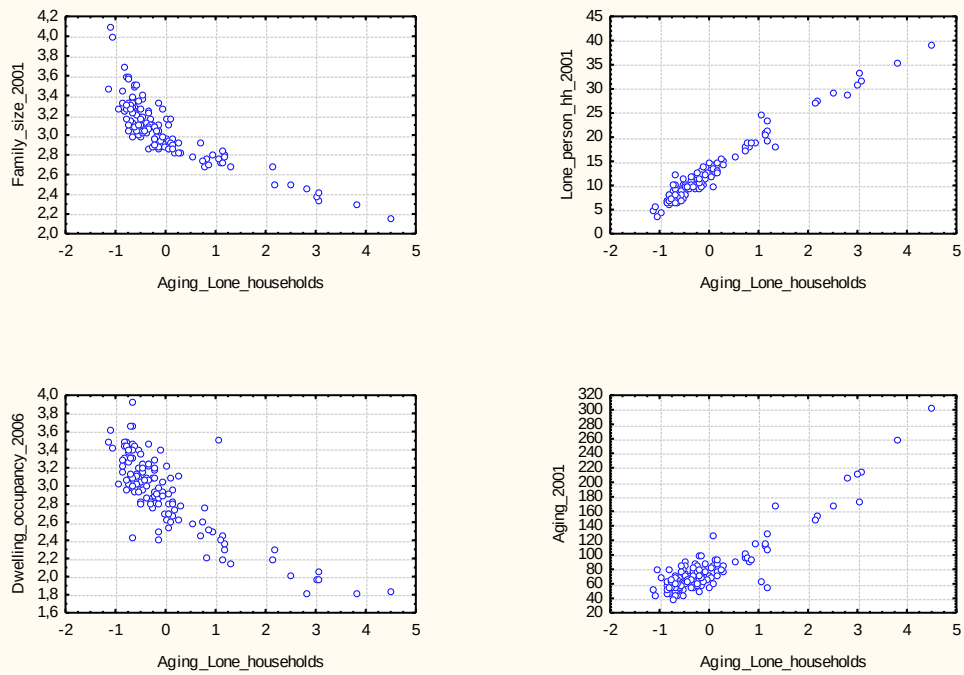
Variable	Factor Loadings (Unrotated) Extraction: Principal axis factoring (Marked loadings are >,700000)	
	Urban growth 1	
New_buildings	0,470420	
New_dwellings	0,689151	
Urban_expansion	0,697136	
Expl.Var	1,182223	

A.7. Relation between factors and their constituent variables

Human capabilities

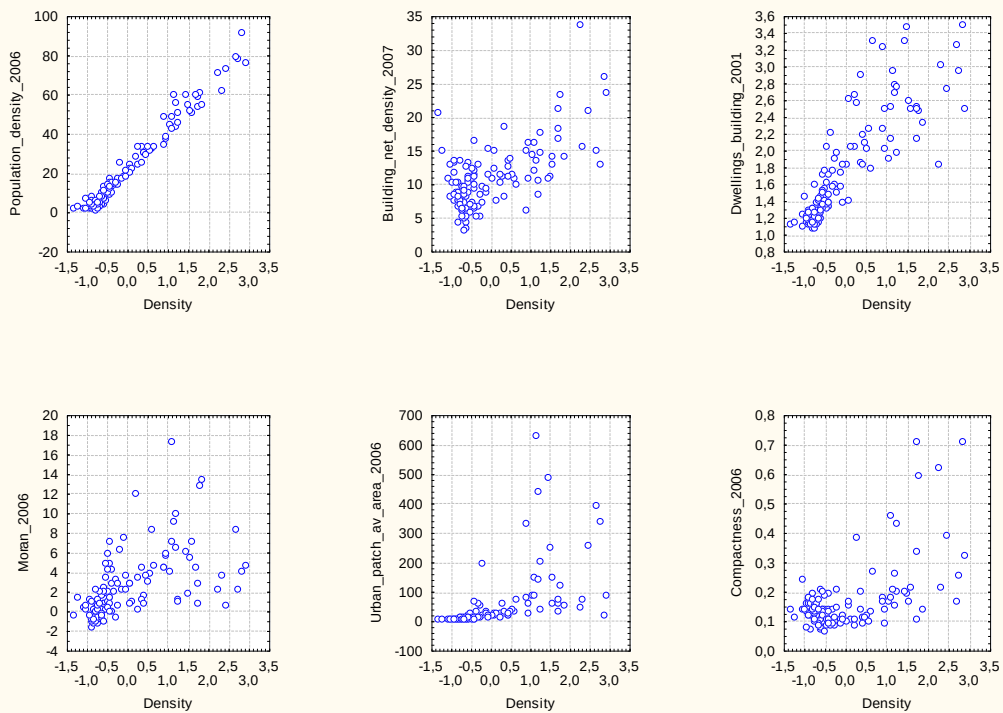


Aging / Lone person households (factor)

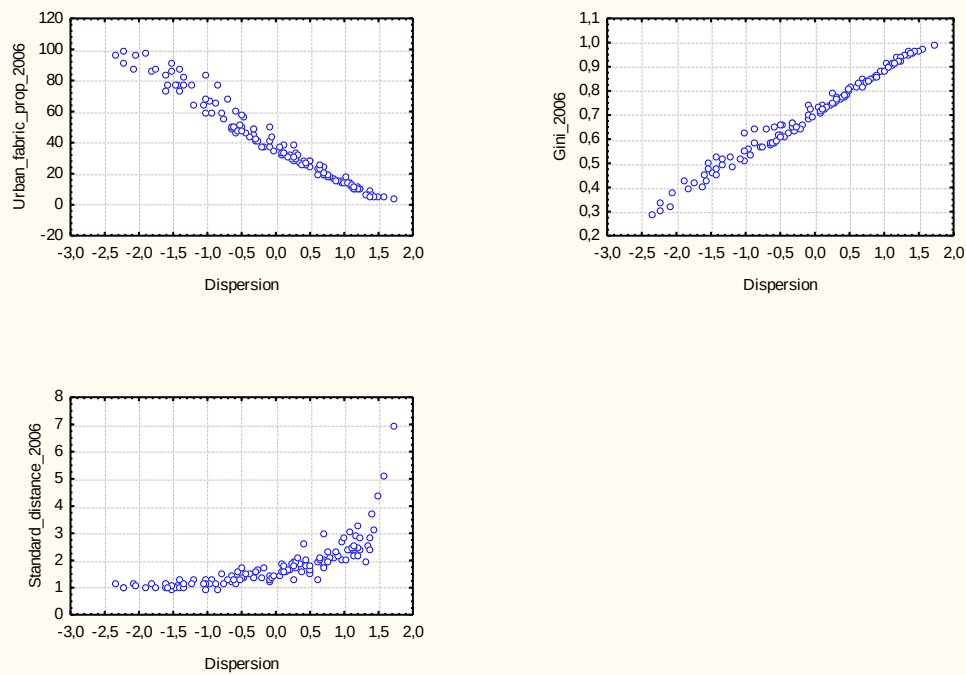


Territorial structure

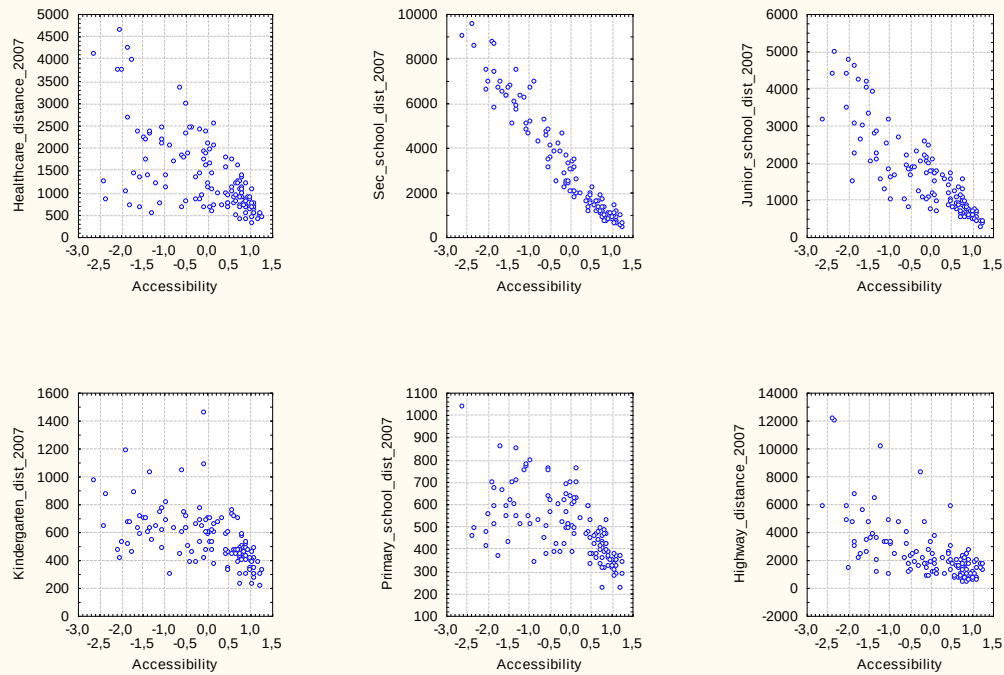
Density (factor)



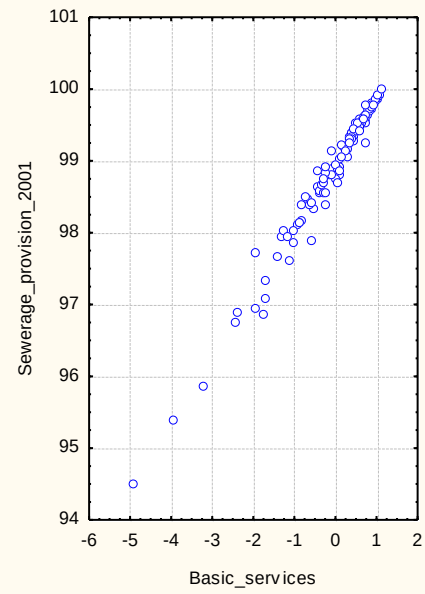
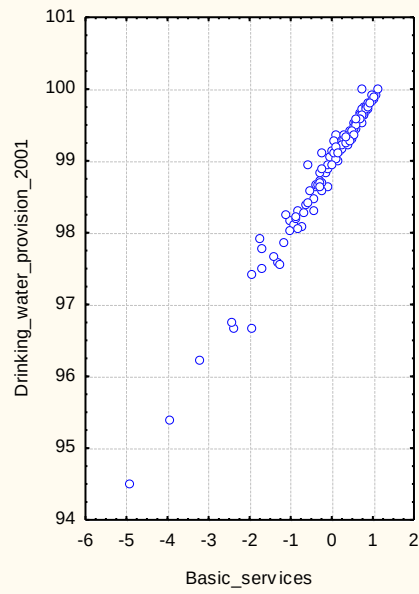
Dispersion (factor)



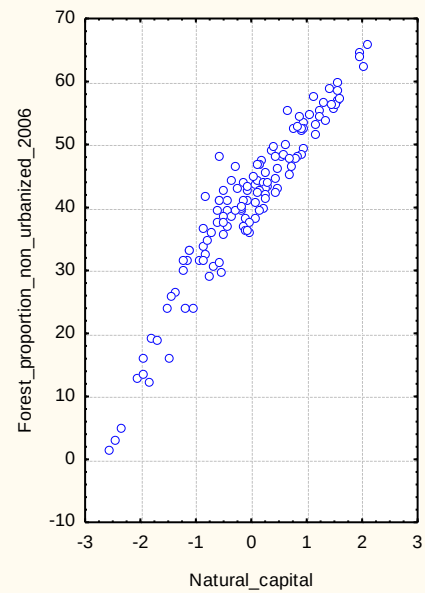
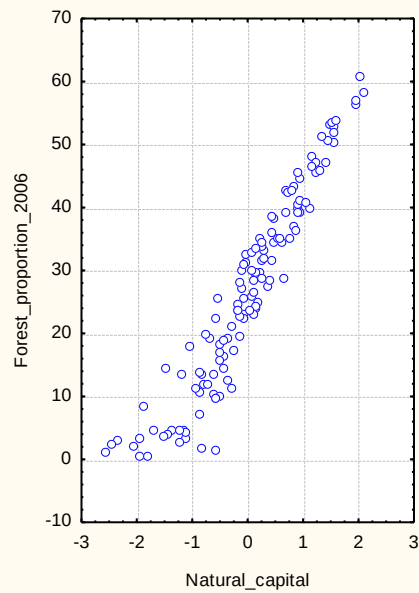
Accessibility (factor)



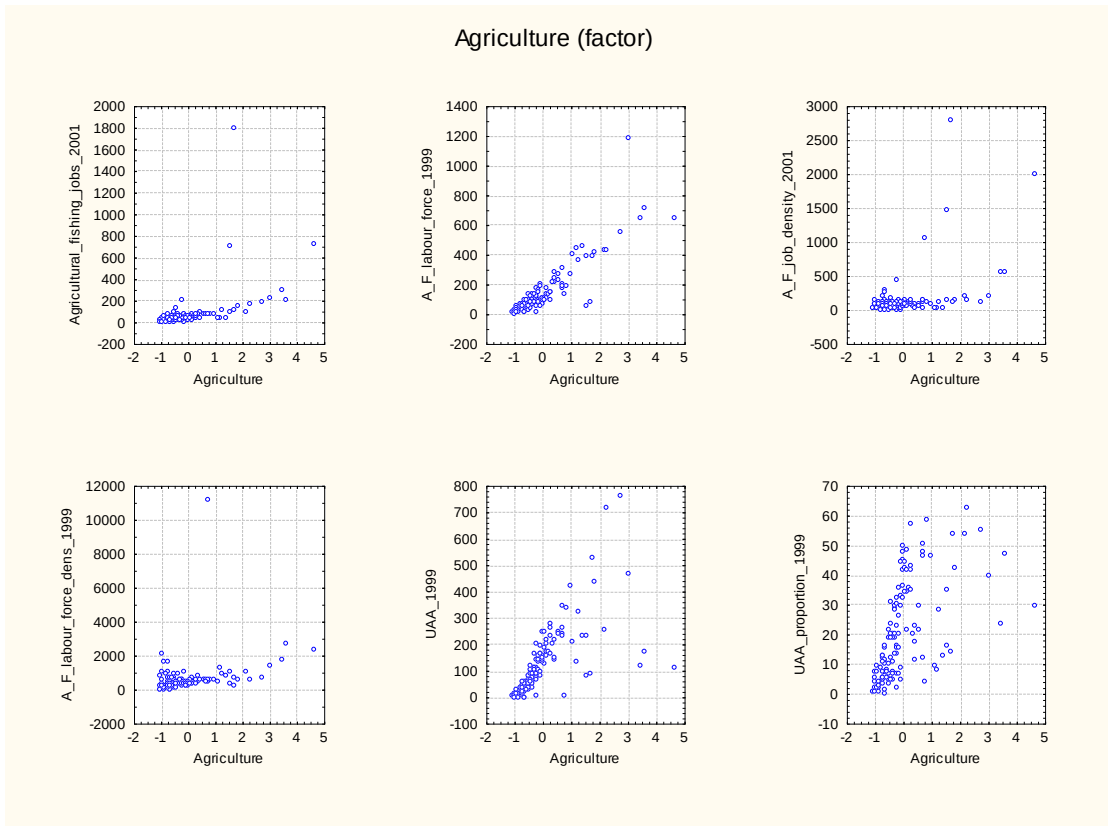
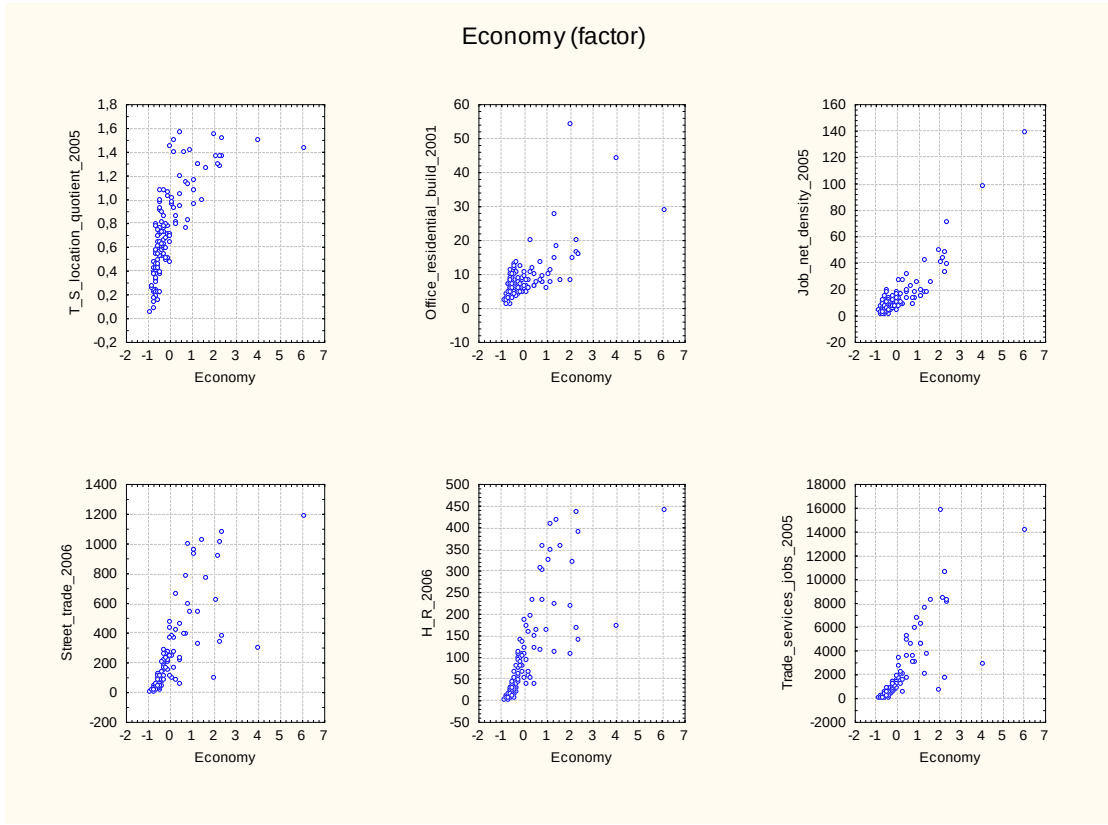
Basic services (factors)



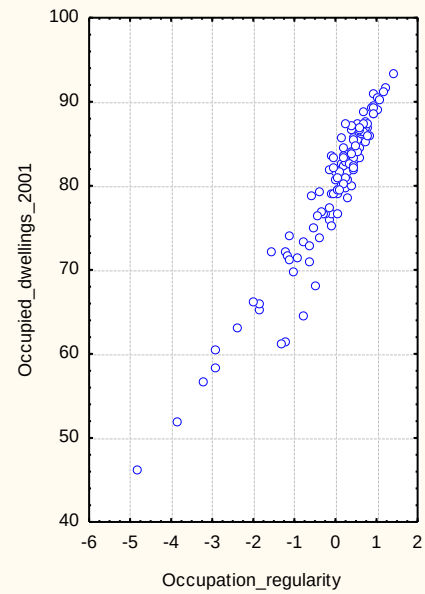
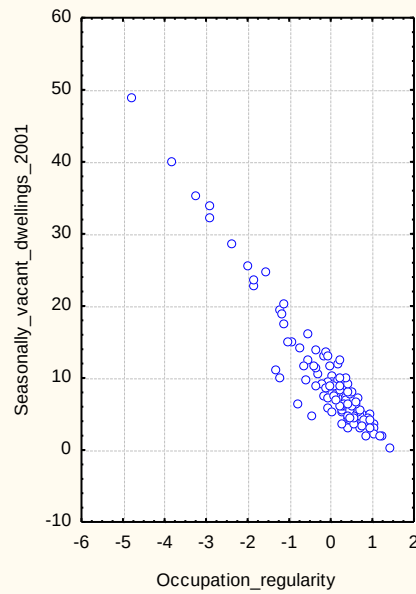
Natural capital (factor)



Economy

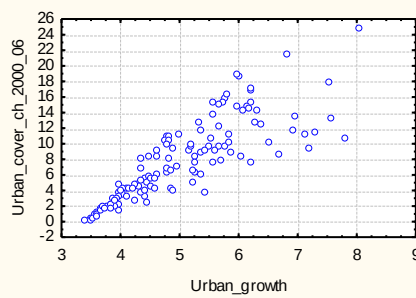
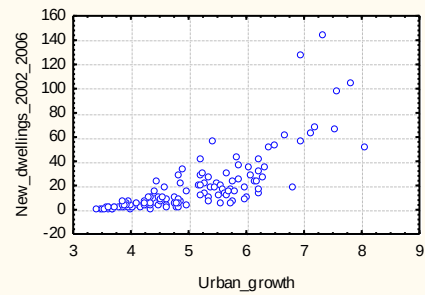
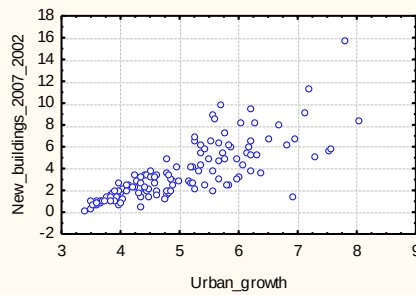


Occupation regularity of dwellings (factor)



Interactions

Urban growth (factor)



A.8. Descriptive statistics and correlation matrices

Basic statistics

Cross-sectional dataset

Variable	Descriptive Statistics					
	Mean	Median	Minimum	Maximum	Std.Dev.	Units
Education	0,000	-0,043	-1,9684	3,875	1,0000	n.a
Aging_Lone_households	0,000	-0,299	-1,1071	4,511	1,0000	n.a
Abstention	0,000	0,054	-2,1379	2,207	1,0000	n.a
Birth_rate	0,000	-0,161	-2,3974	2,698	1,0000	n.a
Child_mortality	0,000	-0,087	-1,0791	3,295	1,0000	n.a
Resident_job_diversity	0,000	0,137	-2,9868	1,161	1,0000	n.a
Income_support	0,000	-0,120	-1,4707	3,338	1,0000	n.a
Unemployment	0,000	-0,153	-1,9819	4,181	1,0000	n.a
Wage	0,000	-0,224	-1,3778	5,796	1,0000	n.a
Youth_NGO	0,000	-0,264	-0,2645	9,585	1,0000	n.a
Density	0,000	-0,446	-1,2826	2,941	1,0000	n.a
Dispersion	0,000	0,145	-2,3401	1,742	1,0000	n.a
Building_age	0,000	-0,299	-1,4800	4,579	1,0000	n.a
Natural_capital	0,000	0,063	-2,5542	2,093	1,0000	n.a
Accessibility	0,000	0,210	-2,6062	1,250	1,0000	n.a
Green_areas	0,000	-0,380	-0,3954	6,017	1,0000	n.a
Basic_services	0,000	0,340	-4,9107	1,137	1,0000	n.a
Native_forests	0,000	-0,500	-0,6006	4,408	1,0000	n.a
Bus_net_density	0,000	-0,305	-1,4004	3,857	1,0000	n.a
Metro_stop_distance	0,000	-0,327	-1,0505	3,278	1,0000	n.a
Train_stop_distance	0,000	-0,312	-1,1538	2,613	1,0000	n.a
Economy	0,000	-0,368	-0,8749	6,088	1,0000	n.a
Economic_diversity	0,000	0,207	-3,6844	1,580	1,0000	n.a
Agriculture	0,000	-0,268	-1,0708	4,643	1,0000	n.a
Occupation_regularity	0,000	0,244	-4,8161	1,429	1,0000	n.a
Urban_expansion_area_permitted	0,000	-0,082	-2,5721	2,309	1,0000	n.a
Air_quality	2,261	2,084	1,8883	3,032	0,3302	n.a
Crimes_against_people	112,302	90,304	21,9841	953,563	102,6211	(Count)
Electricity_consumption	1329,794	1281,791	354,4498	2679,754	322,5342	kWh per capita / year
Water_consumption	40,220	38,699	25,3957	69,795	8,8853	m3 per capita / year
Modal_share_PT	26,017	25,338	10,9573	49,875	7,7685	%
Modal_share_car	47,875	48,610	17,1900	73,680	9,5044	%
Modal_share_foot	22,286	20,044	12,0879	47,204	7,6145	%
Pedestrian_crashes	0,496	0,000	0,0000	6,341	1,0700	(Count) per inhabitant
Urban_growth	5,012	4,833	3,4211	8,059	1,0793	n.a

Longitudinal dataset in the long format

Variable	Descriptive Statistics					
	Mean	Median	Minimum	Maximum	Std.Dev.	Units
Education	0,00000	-0,04855	-1,96337	2,06116	1,00000	n.a.
Aging_Lone_households	-0,00000	-0,05534	-2,48821	3,10953	1,00000	n.a.
Unemployment	0,00000	-0,07085	-2,12028	3,19621	1,00000	n.a.
Income_support	-0,00000	-0,16496	-1,10767	9,93522	1,00000	n.a.
Students	-0,00000	-0,20673	-1,82308	4,12424	1,00000	n.a.
Wage	0,00000	-0,22450	-1,38051	5,80676	1,00000	n.a.
Density	-0,00000	-0,41750	-1,10306	3,10502	1,00000	n.a.
Dispersion	0,00000	0,27396	-2,93769	1,20995	1,00000	n.a.
Accessibility	-0,00000	0,30387	-2,63118	1,17848	1,00000	n.a.
Green_areas	0,00000	-0,43779	-0,43779	4,74422	1,00000	n.a.
Bus_net_density	0,00000	-0,30608	-1,45723	3,16114	1,00000	n.a.
Train_stop_distance	0,00000	-0,29382	-1,40238	1,59945	1,00000	n.a.
Economy	0,00000	-0,37054	-0,70327	4,32578	1,00000	n.a.
Economic_diversity	-0,00000	0,20430	-3,11923	1,62964	1,00000	n.a.
Agriculture	-0,00000	-0,24740	-1,20215	5,56346	1,00000	n.a.
Occupation_regularity	0,00000	0,26120	-5,09188	1,24367	1,00000	n.a.
Urban_expansion_area_permitted	0,00000	-0,08189	-2,57708	2,31387	1,00000	n.a.
Modal_share_PT	28,90584	27,58963	10,80702	56,31825	9,56552	%
Modal_share_car	33,05162	32,04500	5,98000	73,68000	17,09093	%
Modal_share_foot	28,98800	27,67740	12,08791	63,92545	10,70183	%
Urban_growth	5,00000	4,79750	3,42111	8,11182	1,00000	n.a.

Correlation matrices*Cross-sectional dataset*

Variable	Correlations Marked correlations are significant at $p < ,01000$																	
	Educational	Aging_Lone_households	Abstention	Birth_rate	Child_mortality	Resident_job_diversity	Income_support	Unemployment	Wage	Youth_NGO	Density	Dispersion	Building_age	Natural_capital	Accessibility	Green_areas	Basic_services	Native_forests
Education	1,00	0,40	0,45	-0,16	0,04	0,70	0,04	-0,12	0,85	0,02	0,62	-0,67	0,24	-0,36	0,62	0,29	0,48	-0,12
Aging_Lone_households	0,40	1,00	0,53	-0,22	0,02	0,33	0,39	0,38	0,44	0,44	0,68	-0,71	0,86	-0,42	0,46	0,11	0,14	-0,20
Abstention	0,45	0,53	1,00	-0,04	0,19	0,54	0,46	0,07	0,37	0,16	0,74	-0,81	0,54	-0,62	0,69	0,08	0,21	-0,17
Birth_rate	-0,16	-0,22	-0,04	1,00	0,16	-0,16	-0,09	0,02	-0,08	-0,12	-0,13	0,12	-0,23	-0,03	-0,10	0,05	-0,08	0,22
Child_mortality	0,04	0,02	0,19	0,16	1,00	0,10	0,09	0,01	0,08	-0,12	0,10	-0,18	-0,00	-0,25	0,22	-0,06	-0,19	0,12
Resident_job_diversity	0,70	0,33	0,54	-0,16	0,10	1,00	0,26	0,00	0,56	0,07	0,55	-0,67	0,26	-0,28	0,68	-0,03	0,36	-0,12
Income_support	0,04	0,39	0,46	-0,09	0,09	0,26	1,00	0,50	0,50	0,03	0,30	0,36	-0,39	0,57	-0,06	0,47	0,13	-0,06
Unemployment	-0,12	0,38	0,07	0,02	0,01	0,00	0,50	1,00	-0,14	0,34	0,05	-0,08	0,46	0,20	0,13	-0,00	-0,02	0,11
Wage	0,85	0,44	0,37	-0,08	0,08	0,56	0,03	-0,14	1,00	0,03	0,53	-0,61	0,27	-0,37	0,49	0,36	0,31	-0,13
Youth_NGO	0,02	0,44	0,16	-0,12	-0,12	0,07	0,30	0,34	0,03	1,00	0,20	-0,21	0,39	-0,04	0,11	0,06	-0,04	-0,07
Density	0,62	0,68	0,74	-0,13	0,10	0,55	0,36	0,05	0,53	0,20	1,00	-0,91	0,70	-0,61	0,70	0,06	0,37	-0,22
Dispersion	-0,67	-0,71	-0,81	0,12	-0,18	-0,67	-0,39	-0,08	-0,61	-0,21	-0,91	1,00	-0,67	0,70	-0,80	-0,08	-0,35	0,24
Building_age	0,24	0,86	0,54	-0,23	-0,00	0,26	0,57	0,46	0,27	0,39	0,70	-0,67	1,00	-0,35	0,46	0,00	0,14	-0,15
Natural_capital	-0,36	-0,42	-0,62	-0,03	-0,25	-0,28	-0,06	0,20	-0,37	-0,04	-0,61	0,70	-0,35	1,00	-0,47	-0,10	-0,11	0,29
Accessibility	0,62	0,46	0,69	-0,10	0,22	0,68	0,47	0,13	0,49	0,11	0,70	-0,80	0,46	-0,47	1,00	0,08	0,33	-0,15
Green_areas	0,29	0,11	0,08	0,05	-0,06	-0,03	-0,04	-0,00	0,36	0,06	0,06	-0,08	0,00	-0,10	0,08	1,00	0,05	-0,10
Basic_services	0,48	0,14	0,21	-0,08	-0,19	0,36	0,13	-0,02	0,31	-0,04	0,37	-0,35	0,14	-0,11	0,33	0,05	1,00	-0,11
Native_forests	-0,12	-0,20	-0,17	0,22	0,12	-0,12	-0,06	0,11	-0,13	-0,07	-0,22	0,24	-0,15	0,29	-0,15	-0,10	-0,11	1,00
Bus_net_density	-0,02	0,55	0,12	-0,12	-0,12	-0,05	0,31	0,37	0,01	0,34	0,31	-0,20	0,64	-0,01	0,02	0,01	0,06	-0,00
Metro_stop_distance	-0,37	-0,37	-0,50	0,03	-0,33	-0,39	-0,05	0,03	-0,40	-0,11	-0,48	0,56	-0,27	0,49	-0,39	-0,16	-0,09	0,06
Train_stop_distance	-0,46	-0,38	-0,33	0,20	0,07	-0,65	-0,49	-0,29	-0,42	-0,15	-0,44	0,49	-0,42	-0,06	-0,58	0,03	-0,25	0,08
Economy	0,47	0,83	0,64	-0,07	0,02	0,41	0,40	0,28	0,38	0,39	0,77	-0,77	0,74	-0,47	0,55	0,04	0,26	-0,12
Economic_diversity	0,27	-0,08	0,29	0,03	0,15	0,28	0,05	-0,08	0,11	-0,20	0,16	-0,19	-0,08	-0,13	0,25	0,00	0,18	-0,00
Agriculture	-0,40	-0,34	-0,08	0,22	0,11	-0,49	-0,30	-0,39	-0,39	-0,10	-0,29	0,32	-0,34	-0,26	-0,41	-0,04	-0,25	-0,05
Occupation_regularity	-0,10	-0,21	-0,28	-0,13	-0,18	-0,07	0,10	0,03	-0,07	-0,06	-0,16	0,21	-0,10	0,45	-0,06	-0,01	-0,09	0,14
Urban_expansion_area_perr	-0,01	-0,48	-0,10	-0,00	0,13	0,16	-0,07	-0,17	-0,11	-0,25	-0,31	0,18	-0,45	0,22	0,12	-0,06	-0,07	0,02
Air_quality	0,48	0,67	0,56	-0,26	0,08	0,36	0,45	0,20	0,47	0,29	0,71	-0,67	0,71	-0,32	0,57	0,18	0,30	-0,11
Crimes_against_people	-0,02	0,42	0,12	-0,08	-0,09	0,01	0,18	0,44	0,01	0,33	0,19	-0,20	0,46	-0,14	0,05	0,03	0,05	-0,12
Electricity_consumption	0,48	0,45	0,20	0,15	0,08	0,48	0,13	0,23	0,57	0,05	0,25	-0,37	0,22	-0,07	0,27	0,08	0,19	-0,05
Modal_share_PT	-0,10	0,17	0,03	-0,32	-0,21	-0,02	0,43	0,37	-0,17	0,18	0,10	0,03	0,39	0,30	-0,05	-0,11	0,08	0,05
Modal_share_car	0,46	-0,37	-0,00	0,10	0,10	0,40	-0,32	-0,43	0,49	-0,33	-0,12	-0,03	-0,52	-0,01	0,16	0,14	0,10	-0,01
Modal_share_foot	-0,08	0,53	0,29	0,10	-0,01	-0,04	0,32	0,31	-0,12	0,30	0,40	-0,36	0,54	-0,32	0,23	-0,05	0,11	-0,09
Pedestrian_crashes	0,10	0,09	0,08	0,08	0,15	-0,04	-0,03	0,05	0,10	-0,05	0,07	-0,08	0,05	-0,16	0,14	-0,00	-0,22	0,18
Urban_growth	0,58	0,04	0,55	0,10	0,23	0,61	0,03	-0,29	0,47	-0,11	0,51	-0,62	-0,02	-0,53	0,59	0,07	0,32	-0,08
Water_consumption	0,75	0,56	0,22	-0,04	-0,03	0,06	0,01	-0,05	0,80	0,15	0,55	-0,57	0,36	-0,54	0,57	0,46	0,44	-0,21

Variable	Correlations Marked correlations are significant at $p < .01000$																
	Bus_net_density	Metro_stop_distance	Train_stop_distance	Economy	Economic_diversity	Agriculture	Occupation_regularity	Urban_expansion_area_permitted	Air_quality	Crimes_against_people	Electricity_consumption	Modal_share_PT	Modal_share_car	Modal_share_foot	Pedestrian_crashes	Urban_growth	Water_consumption
Education	-0,02	-0,37	-0,46	0,47	0,27	-0,40	-0,10	-0,01	0,48	-0,02	0,48	-0,10	0,46	-0,08	0,10	0,58	0,75
Aging_Lone_households	0,55	-0,37	-0,38	0,83	-0,08	-0,34	-0,21	-0,48	0,67	0,42	0,45	0,17	-0,37	0,53	0,09	0,04	0,56
Abstention	0,12	-0,50	-0,33	0,64	0,29	-0,08	-0,28	-0,10	0,56	0,12	0,20	0,03	-0,00	0,29	0,08	0,55	0,22
Birth_rate	-0,12	0,03	0,20	-0,07	0,03	0,22	-0,13	-0,00	-0,26	-0,08	0,15	-0,32	0,10	0,10	0,08	0,10	-0,04
Child_mortality	-0,12	-0,33	0,07	0,02	0,15	0,11	-0,18	0,13	0,08	-0,09	0,08	-0,21	0,10	-0,01	0,15	0,23	-0,03
Resident_job_diversity	-0,05	-0,39	-0,65	0,41	0,28	-0,49	-0,07	0,16	0,36	0,01	0,48	-0,02	0,40	-0,04	-0,04	0,61	0,06
Income_support	0,31	-0,05	-0,49	0,40	0,05	-0,30	0,10	-0,07	0,45	0,18	0,13	0,43	-0,32	0,32	-0,03	0,03	0,01
Unemployment	0,37	0,03	-0,29	0,28	-0,08	-0,39	0,03	-0,17	0,20	0,44	0,23	0,37	-0,43	0,31	0,05	-0,29	-0,05
Wage	0,01	-0,40	-0,42	0,38	0,11	-0,39	-0,07	-0,11	0,47	0,01	0,57	-0,17	0,49	-0,12	0,10	0,47	0,80
Youth_NGO	0,34	-0,11	-0,15	0,39	-0,20	-0,10	-0,06	-0,25	0,29	0,33	0,05	0,18	-0,33	0,30	-0,05	-0,11	0,15
Density	0,31	-0,48	-0,44	0,77	0,16	-0,29	-0,16	-0,31	0,71	0,19	0,25	0,10	-0,12	0,40	0,07	0,51	0,55
Dispersion	-0,20	0,56	0,49	-0,77	-0,19	0,32	0,21	0,18	-0,67	-0,20	-0,37	0,03	-0,03	-0,36	-0,08	-0,62	-0,57
Building_age	0,64	-0,27	-0,42	0,74	-0,08	-0,34	-0,10	-0,45	0,71	0,46	0,22	0,39	-0,52	0,54	0,05	-0,02	0,36
Natural_capital	-0,01	0,49	-0,06	-0,47	-0,13	-0,26	0,45	0,22	-0,32	-0,14	-0,07	0,30	-0,01	-0,32	-0,16	-0,53	-0,54
Accessibility	0,02	-0,39	-0,58	0,55	0,25	-0,41	-0,06	0,12	0,57	0,05	0,27	-0,05	0,16	0,23	0,14	0,59	0,57
Green_areas	0,01	-0,16	0,03	0,04	0,00	-0,04	-0,01	-0,06	0,18	0,03	0,08	-0,11	0,14	-0,05	-0,00	0,07	0,46
Basic_services	0,06	-0,09	-0,25	0,26	0,18	-0,25	-0,09	-0,07	0,30	0,05	0,19	0,08	0,10	0,11	-0,22	0,32	0,44
Native_forests	-0,00	0,06	0,08	-0,12	-0,00	-0,05	0,14	0,02	-0,11	-0,12	-0,05	0,05	-0,01	-0,09	0,18	-0,08	-0,21
Bus_net_density	1,00	-0,05	-0,14	0,49	-0,04	-0,16	-0,02	-0,58	0,44	0,40	-0,08	0,52	-0,63	0,36	-0,03	-0,30	0,34
Metro_stop_distance	-0,05	1,00	0,04	-0,38	-0,11	0,10	0,16	0,08	-0,44	-0,27	-0,15	0,26	-0,18	-0,01	-0,00	-0,45	-0,32
Train_stop_distance	-0,14	0,04	1,00	-0,36	-0,07	0,69	-0,30	-0,11	-0,44	-0,11	-0,37	-0,25	-0,13	-0,04	0,05	-0,23	-0,16
Economy	0,49	-0,38	-0,36	1,00	0,09	-0,24	-0,20	-0,47	0,64	0,36	0,35	0,12	-0,31	0,55	0,12	0,23	0,46
Economic_diversity	-0,04	-0,11	-0,07	0,09	1,00	-0,01	0,01	0,17	0,05	-0,13	-0,06	0,01	0,22	-0,17	0,04	0,35	-0,15
Agriculture	-0,16	0,10	0,69	-0,24	-0,01	1,00	-0,29	-0,07	-0,27	-0,22	-0,30	-0,19	-0,11	-0,00	0,13	-0,06	-0,41
Occupation_regularity	-0,02	0,16	-0,30	-0,20	0,01	-0,29	1,00	0,12	0,03	-0,07	-0,12	0,24	0,02	-0,24	-0,02	-0,18	-0,35
Urban_expansion_area_permitted	-0,58	0,08	-0,11	-0,47	0,17	-0,07	0,12	1,00	-0,35	-0,25	0,08	-0,28	0,53	-0,42	-0,00	0,24	-0,53
Air_quality	0,44	-0,44	-0,44	0,64	0,05	-0,27	0,03	-0,35	1,00	0,25	0,14	0,35	-0,25	0,28	0,08	0,19	0,69
Crimes_against_people	0,40	-0,27	-0,11	0,36	-0,13	-0,22	-0,07	-0,25	0,25	1,00	0,04	0,15	-0,33	0,24	-0,04	-0,19	0,25
Electricity_consumption	-0,08	-0,15	-0,37	0,35	-0,06	-0,30	-0,12	0,08	0,14	0,04	1,00	-0,12	0,41	-0,06	0,01	0,30	0,49
Modal_share_PT	0,52	0,26	-0,25	0,12	0,01	-0,19	0,24	-0,28	0,35	0,15	-0,12	1,00	-0,50	-0,10	-0,03	-0,24	-0,05
Modal_share_car	-0,63	-0,18	-0,13	-0,31	0,22	-0,11	0,02	0,53	-0,25	-0,33	0,41	-0,50	1,00	-0,66	0,01	0,49	0,01
Modal_share_foot	0,36	-0,01	-0,04	0,55	-0,17	-0,00	-0,24	-0,42	0,28	0,24	-0,06	-0,10	-0,66	1,00	0,03	-0,11	0,14
Pedestrian_crashes	-0,03	-0,00	0,05	0,12	0,04	0,13	-0,02	-0,00	0,08	-0,04	0,01	-0,03	0,01	0,03	1,00	0,10	0,30
Urban_growth	-0,30	-0,45	-0,23	0,23	0,35	-0,06	-0,18	0,24	0,19	-0,19	0,30	-0,24	0,49	-0,11	0,10	1,00	0,06
Water_consumption	0,34	-0,32	-0,16	0,46	-0,15	-0,41	-0,35	-0,53	0,69	0,25	0,49	-0,05	0,01	0,14	0,30	0,06	1,00

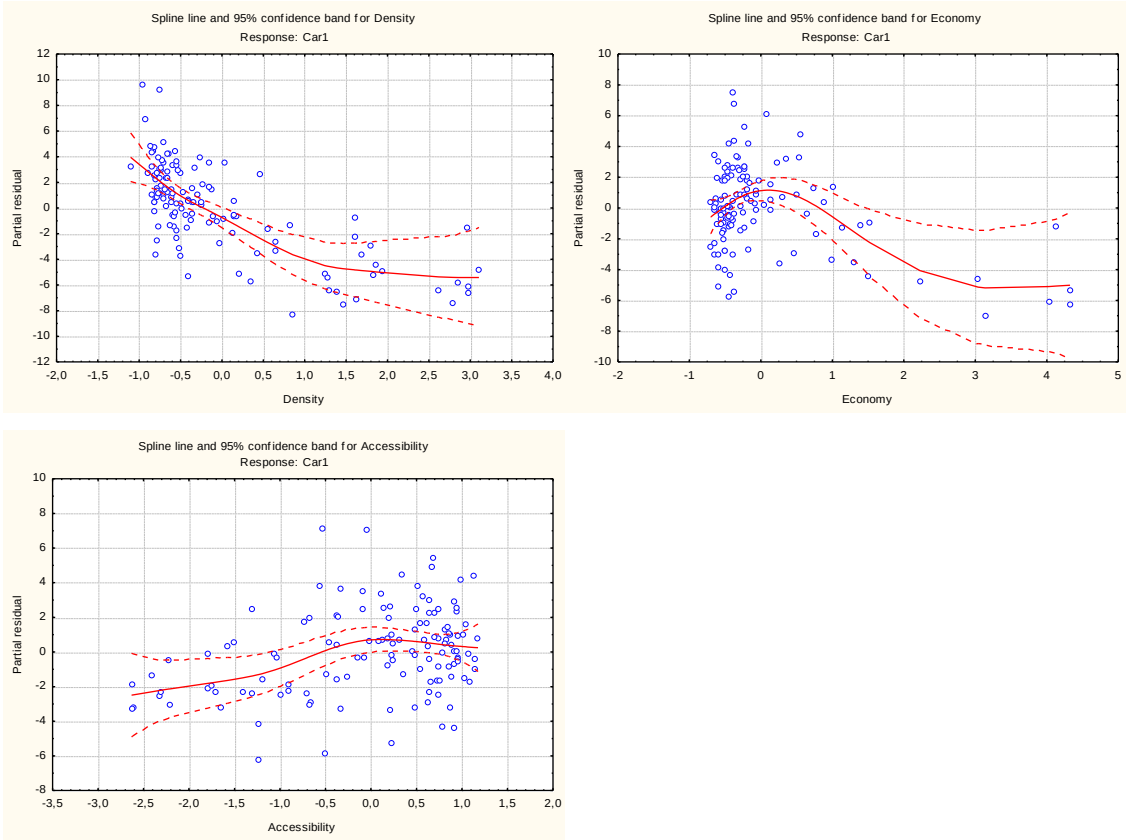
Longitudinal dataset

Variable	Correlations Marked correlations are significant at p < ,01000																				
	Educ ation	Aging_ Lone_ house holds	Unemp loymen t	Incom e_sup port	Studen ts	Wage	Densit y	Disper sion	Acces sibility	Green _areas	Bus_n et_den sity	Train_ stop_di stance	Econo my	Econo mic_di versity	Agricul ture	Occup ation regular ity	Urban_ expan sion_a rea_pe rmitted	Modal_ share_ PT	Modal_ share_ car	Modal_ share_ foot	Urban_ growt h
Education	1,00	0,76	0,53	0,15	0,16	0,60	0,57	-0,61	0,57	0,10	0,01	-0,34	0,37	0,23	-0,46	-0,12	0,01	-0,09	0,75	-0,40	0,50
Aging_Lone_households	0,76	1,00	0,62	0,35	0,03	0,45	0,72	-0,74	0,55	0,11	0,30	-0,34	0,67	0,04	-0,46	-0,12	-0,22	-0,01	0,51	-0,15	0,24
Unemployment	0,53	0,62	1,00	0,40	-0,03	0,23	0,56	-0,57	0,50	0,07	0,21	-0,32	0,49	0,12	-0,32	-0,00	-0,12	0,20	0,23	-0,02	0,23
Income_support	0,15	0,35	0,40	1,00	-0,12	0,03	0,30	-0,30	0,20	0,07	0,30	-0,09	0,37	-0,08	-0,21	0,02	-0,08	0,11	-0,01	0,08	-0,05
Students	0,16	0,03	-0,03	-0,12	1,00	0,60	0,38	-0,42	0,44	0,09	-0,01	-0,30	0,30	0,20	-0,07	0,04	-0,00	0,29	-0,31	0,35	0,37
Wage	0,60	0,45	0,23	0,03	0,60	1,00	0,54	-0,59	0,49	0,24	0,02	-0,32	0,40	0,11	-0,29	-0,03	-0,11	0,01	0,31	-0,10	0,46
Density	0,57	0,72	0,56	0,30	0,38	0,54	1,00	-0,95	0,62	0,15	0,41	-0,45	0,85	0,08	-0,26	-0,11	-0,45	0,15	0,08	0,24	0,39
Dispersion	-0,61	-0,74	-0,57	-0,30	-0,42	-0,59	-0,95	1,00	-0,70	-0,12	-0,31	0,50	-0,83	-0,10	0,28	0,11	0,34	-0,10	-0,12	-0,24	-0,49
Accessibility	0,57	0,55	0,50	0,20	0,44	0,49	0,62	-0,70	1,00	0,04	-0,02	-0,47	0,47	0,29	-0,25	-0,01	0,16	0,06	0,18	0,11	0,61
Green_areas	0,10	0,11	0,07	0,07	0,09	0,24	0,15	-0,12	0,04	1,00	0,08	0,03	0,17	-0,07	-0,09	-0,05	-0,14	-0,02	0,06	0,02	-0,03
Bus_net_density	0,01	0,30	0,21	0,30	-0,01	0,02	0,41	-0,31	-0,02	0,08	1,00	0,13	0,56	-0,03	-0,20	0,07	-0,57	0,36	-0,22	0,20	-0,23
Train_stop_distance	-0,34	-0,34	-0,32	-0,09	-0,30	-0,32	-0,45	0,50	-0,47	0,03	0,13	1,00	-0,37	-0,09	0,17	0,18	0,04	0,10	-0,01	-0,18	-0,41
Economy	0,37	0,67	0,49	0,37	0,30	0,40	0,85	-0,83	0,47	0,17	0,56	-0,37	1,00	-0,05	-0,27	-0,06	-0,50	0,12	-0,08	0,39	0,13
Economic_diversity	0,23	0,04	0,12	-0,08	0,20	0,11	0,08	-0,10	0,29	-0,07	-0,03	-0,09	-0,05	1,00	0,03	0,04	0,16	0,06	0,12	-0,11	0,29
Agriculture	-0,46	-0,46	-0,32	-0,21	-0,07	-0,29	-0,26	0,28	-0,25	-0,09	-0,20	0,17	-0,27	0,03	1,00	-0,29	0,02	-0,15	-0,32	0,22	-0,02
Occupation regularity	-0,12	-0,12	-0,00	0,02	0,04	-0,03	-0,11	0,11	-0,01	-0,05	0,07	0,18	-0,06	0,04	-0,29	1,00	0,05	0,31	-0,10	-0,06	-0,10
Urban_expansion_area_pe	0,01	-0,22	-0,12	-0,08	-0,00	-0,11	-0,45	0,34	0,16	-0,14	-0,57	0,04	-0,50	0,16	0,02	0,05	1,00	-0,16	0,20	-0,26	0,20
Modal_share_PT	-0,09	-0,01	0,20	0,11	0,29	0,01	0,15	-0,10	0,06	-0,02	0,36	0,10	0,12	0,06	-0,15	0,31	-0,16	1,00	-0,36	-0,02	-0,01
Modal_share_car	0,75	0,51	0,23	-0,01	-0,31	0,31	0,08	-0,12	0,18	0,06	-0,22	-0,01	-0,08	0,12	-0,32	-0,10	0,20	-0,36	1,00	-0,73	0,26
Modal_share_foot	-0,40	-0,15	-0,02	0,08	0,35	-0,10	0,24	-0,24	0,11	0,02	0,20	-0,18	0,39	-0,11	0,22	-0,06	-0,26	-0,02	-0,73	1,00	-0,05
Urban_growth	0,50	0,24	0,23	-0,05	0,37	0,46	0,39	-0,49	0,61	-0,03	-0,23	-0,41	0,13	0,29	-0,02	-0,10	0,20	-0,01	0,26	-0,05	1,00

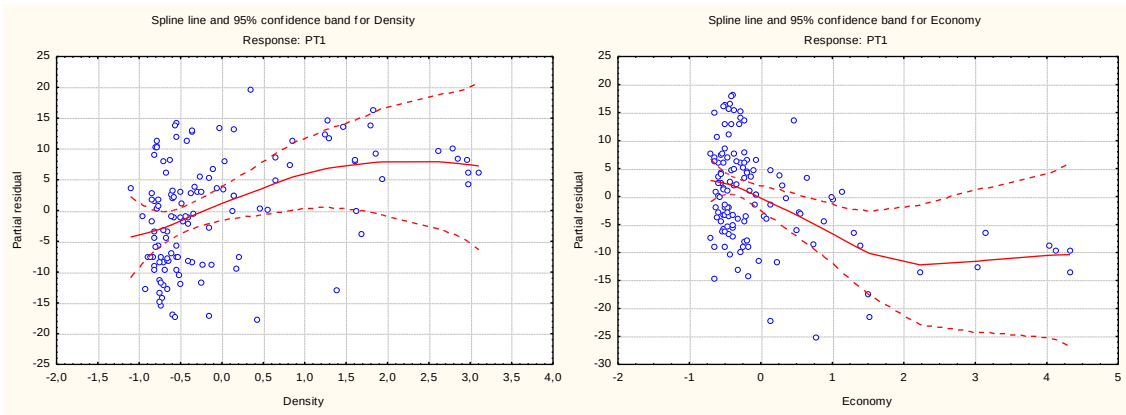
A.9. Partial residual plots

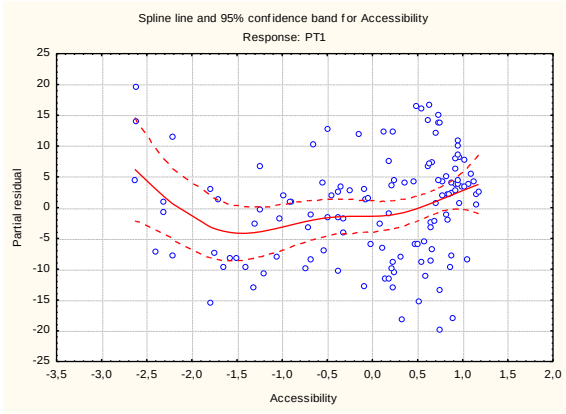
Modeling mobility patterns

Modal share: car

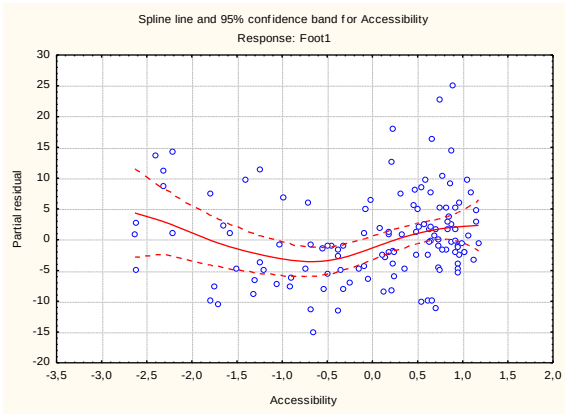
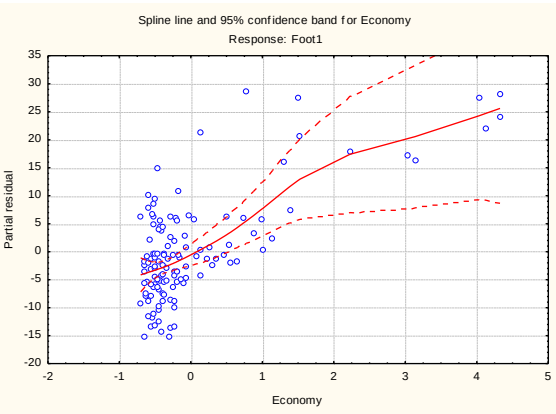
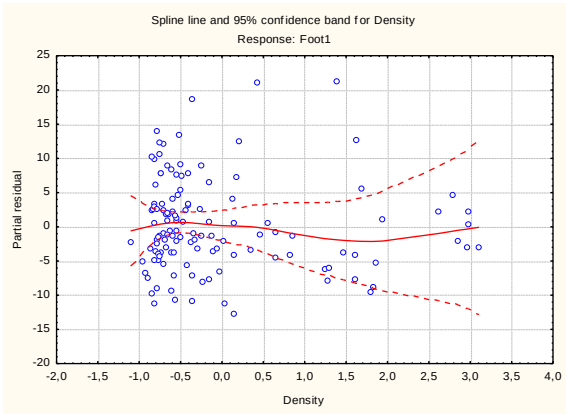


Modal share: public transports

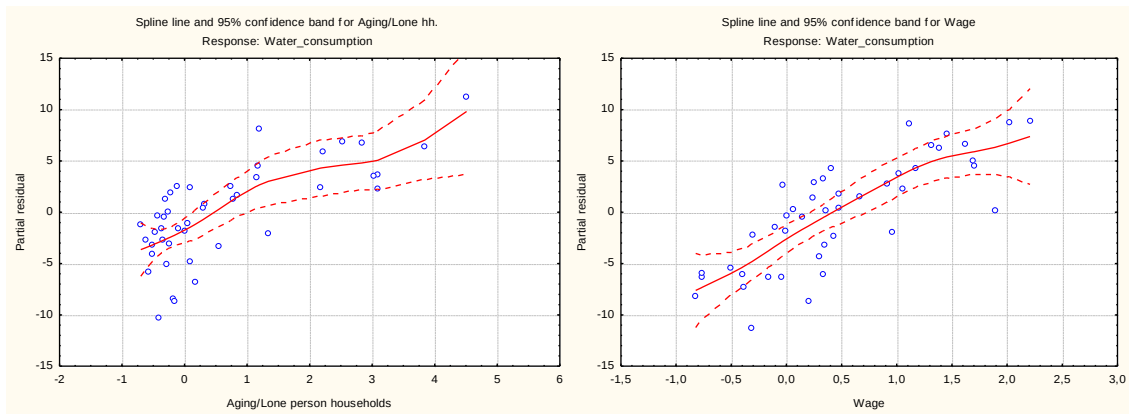




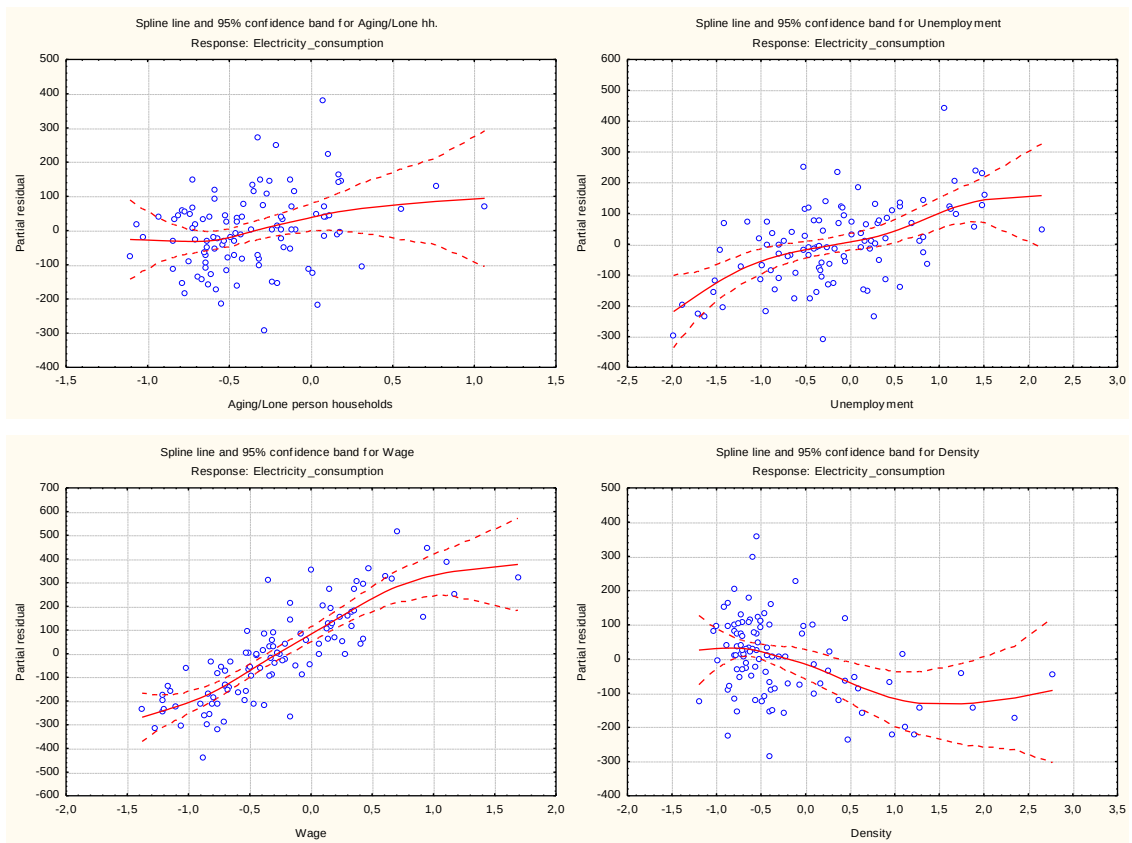
Modal share: foot



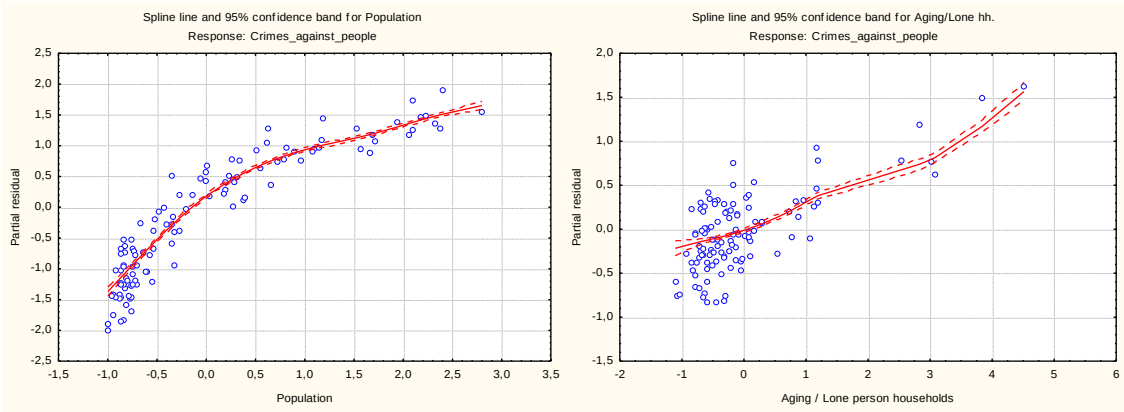
Modeling water consumption



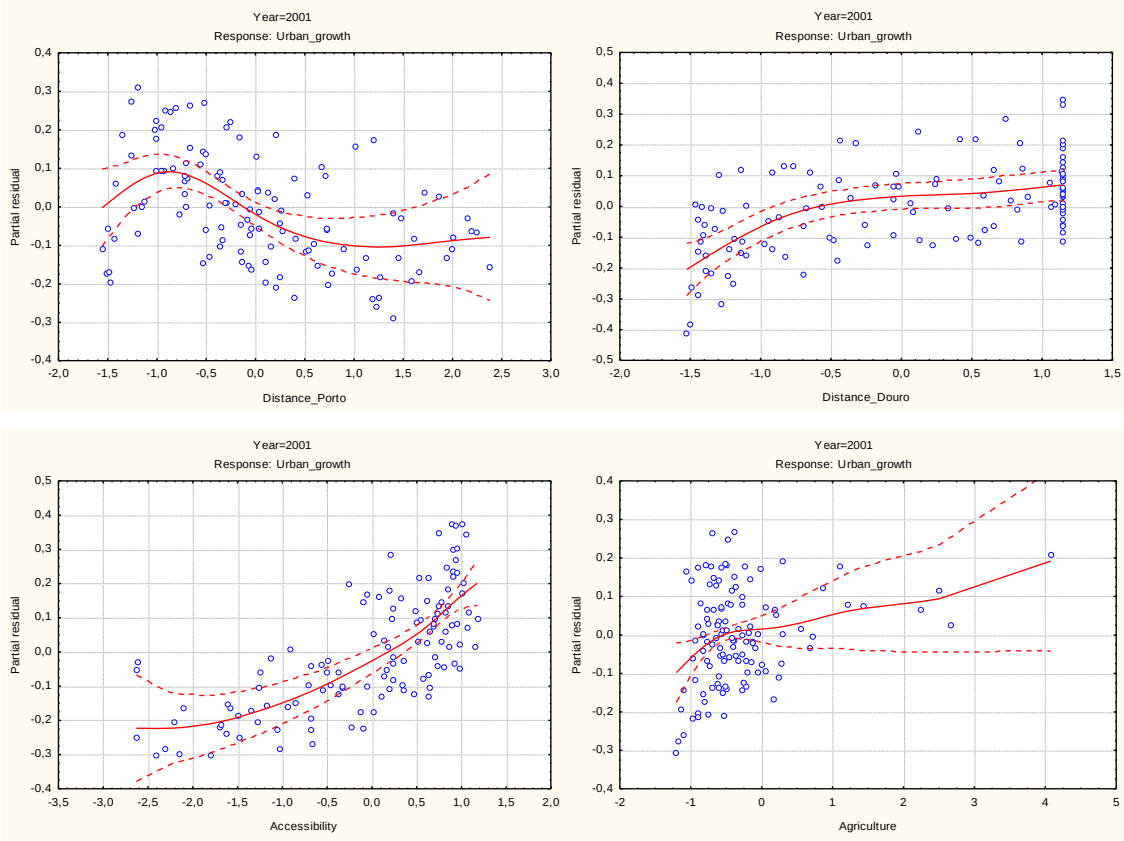
Modeling electricity consumption



Modeling crimes against people



Modeling urban growth



A.10. Modeling mobility patterns with structural equation

Measurement equations in the matrix form and variance explained

Endogenous variable	R ²	Causal variable							
		Education (1991)	Education ch. (1991–2001)	Wage (2008)	Density (1991)	Density ch. (1991–2001)	Economy (2005)	Bus net density (2008)	Accessibility (2001)
Wage (2008)	0,69	0,838* (0,057) 14,656							
Education (1991–2001)	0,44	-0,245* (0,064) -3,858		0,216* (0,066) 3,261	-0,232* (0,036) -6,381				0,267* (0,034) 7,823
Economy (2005)	0,79	-0,238* (0,114) -2,098			1,023* (0,115) 8,869				
Bus net density (2008)	0,43	-0,196 (0,119) -1,645			0,150 (0,137) 1,096		0,650* (0,099) 6,559		-0,320* (0,120) -2,672
Density (1991)	0,49	0,898* (0,086) 10,417							
Density (1991–2001)	0,37	0,171 (0,041) 4,215	0,215* (0,056) 3,861		-0,128* (0,041) -3,110				0,018 (0,028) 0,738
Accessibility (2001)	0,46	0,650* (0,108) 6,003			0,243* (0,061) 3,961				

Endogenous variable	R ²	Causal variable							
		Education (1991)	Education ch. (1991–2001)	Wage (2008)	Density (1991)	Density ch. (1991–2001)	Economy (2005)	Bus net density (2008)	Accessibility (2001)
Modal share: car (1991)	0,85	5,992* (0,713) 8,400		3,556* (0,520) 6,835	-2,252* (0,667) -3,374		-0,911 (0,612) -1,488	-0,626* (0,251) -2,497	0,884* (0,264) 3,351
Modal share: car (2001)	0,82	2,558* (0,969) 2,640	3,581* (1,250) 2,864	6,550* (0,614) 10,676	-4,849 (0,961) -5,046	1,394* (1,424) 0,979	-1,458 (0,842) -1,732	-2,444* (0,491) -4,974	0,737 (0,534) 1,380
Modal share: PT (1991)	0,21	3,342 (2,838) 1,178		-0,367 (2,163) -0,170	2,028 (1,944) 1,043		-5,643* (1,518) -3,717	5,042* (1,085) 4,646	2,198 (1,331) 1,651
Modal share: PT (2001)	0,33	1,163 (1,468) 0,792	-1,881* (0,846) -2,223	-1,458 (1,196) -1,219	2,276 (1,383) 1,646	1,500 (1,270) 1,181	-3,555* (1,120) -3,175	4,907* (0,831) 5,904	-0,243 (0,979) -0,248
Modal share: foot (1991)	0,30	-1,382 (1,782) -0,776		-3,378* (1,020) -0,252	0,841 (1,603) 0,525		6,185* (1,053) 5,874	-2,281* (0,840) -2,716	-0,258 (1,020) -0,252
Modal share: foot (2001)	0,56	-1,362 (1,133) -1,202	-1,586 (1,161) -1,366	-3,800* (0,883) -4,305	2,408* (1,054) 2,285	-3,215* (1,353) -2,377	4,668* (0,712) 6,552	-1,502* (0,569) -2,641	0,565 (0,765) 0,738

This table is in an equation-like format: each row represents one structural equation with the dependent variable on the first column and the explanatory variables on the remainder columns. Parameter estimates are presented in the first line of each row (robust standard errors in parenthesis); robust test statistics are presented in the second line. Statistics significant at the 5% level are marked with *.

EQS command file used for the modal of car shares

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Model built by EQS 6 for Windows

/SPECIFICATIONS
DATA='widezdif.ESS';
VARIABLES=23; CASES=130;
METHOD=ML,ROBUST; ANALYSIS=COVARIANCE; MATRIX=RAW;
OUT=HTML;
DELETE=53,49,52;

/LABELS
V1=DICOFRE; V2=CONCELHO; V3=FREGUESI; V4=WAGE; V5=UNEMPL1;
V6=UNEMPL2; V7=EDUCAT1; V8=EDUCAT2; V9=STUDEN1; V10=STUDEN2;
V11=ECONOMY; V12=BUS; V13=DENS1; V14=DENS2; V15=ACCESS1;
V16=ACCESS2; V17=INHAB2; V18=PT1; V19=PT2; V20=CAR1;
V21=CAR2; V22=FOOT1; V23=FOOT2; V24=EDUCBUS1; V25=EDUCBUS2;

/EQUATIONS
V4 = *V7 + E4;
V8 = *V7 + *V13 + *V15 + E8;
V11 = *V7 + *V13 + E11;
V12 = *V7 + *V11 + *V13 + *V15 + E12;
V13 = *V7 + E13;
V14 = *V7 + *V8 + *V13 + *V15 + E14;
V15 = *V7 + *V13 + E15;
V20 = *V4 + *V7 + *V11 + *V12 + *V13 + *V15 + E20;
V21 = *V4 + *V7 + *V8 + *V11 + *V12 + *V13 + *V14 + *V15 + E21;

/VARIANCES
V7 = *;
E4 = *;
E8 = *;
E11 = *;
E12 = *;
E13 = *;
E14 = *;
E15 = *;
E20 = *;
E21 = *;

/COVARIANCES
E21,E20 = *;

```

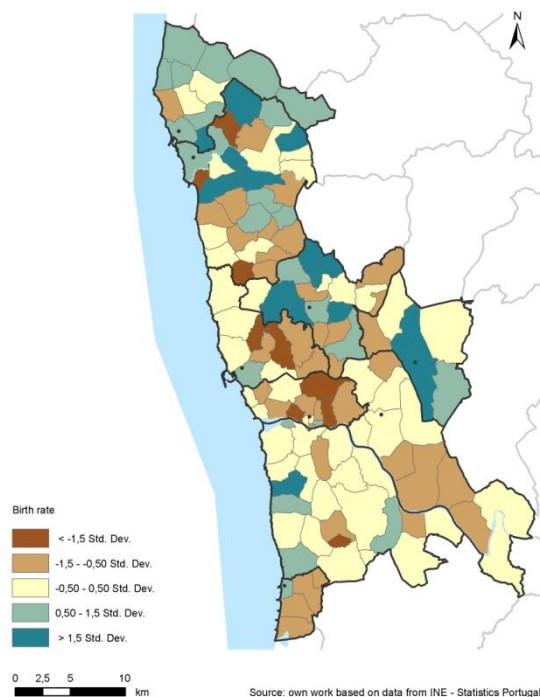
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FIT=ALL;
EFFECT=YES;
TABLE=EQUATION;
/OUTPUT
Parameters;
Standard Errors;
RSquare;
Codebook;
Listing;
DATA='EQSOUT.ETS';
/TECHNICAL
ITER=1000;
EITER=1000;
RELIABILITY = NO;
/LMTEST
PROCESS=SIMULTANEOUS;
SET=PVV, PFV, PFF, PEE, PDD, GVV, GVF, GFV,
GFF, BVF, BFF;
/WTEST
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COMPARE=YES;
/END
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A.11. Other thematic maps

Human capabilities

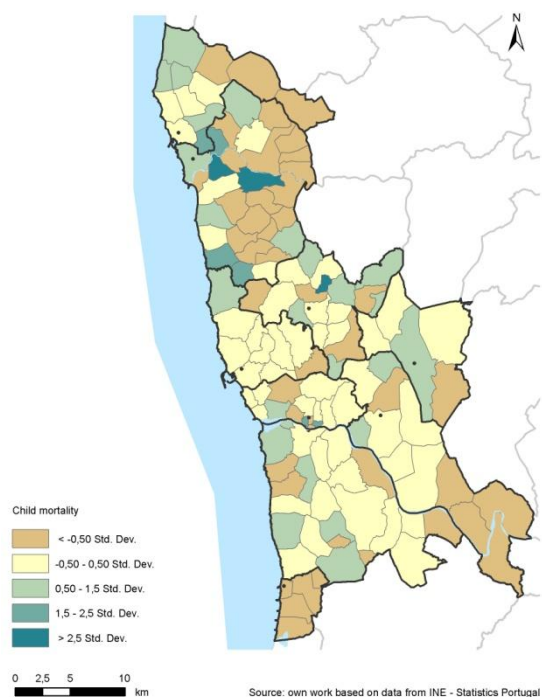
Birth rate

Average 2001 - 2006



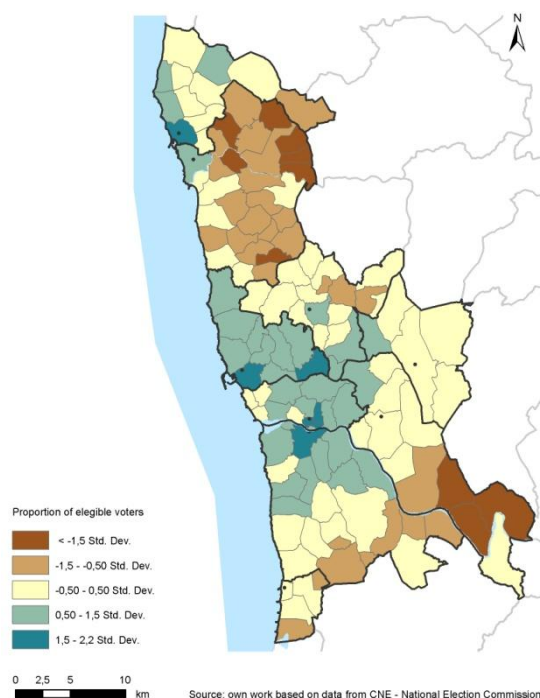
Child mortality

Average 2001 - 2005



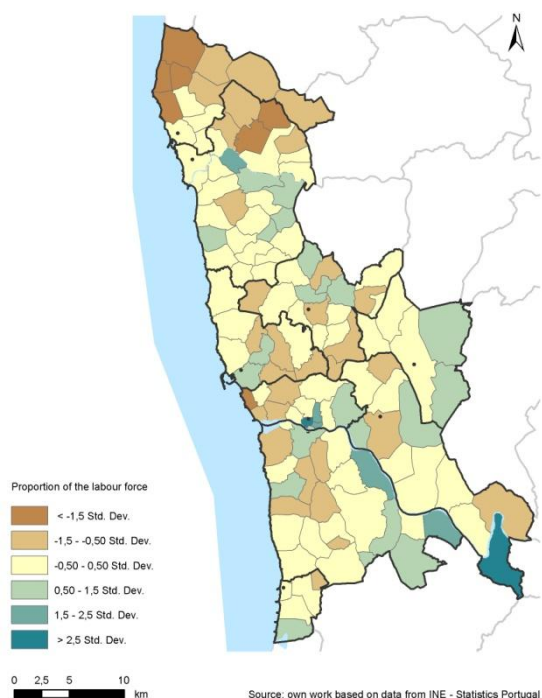
Abstention

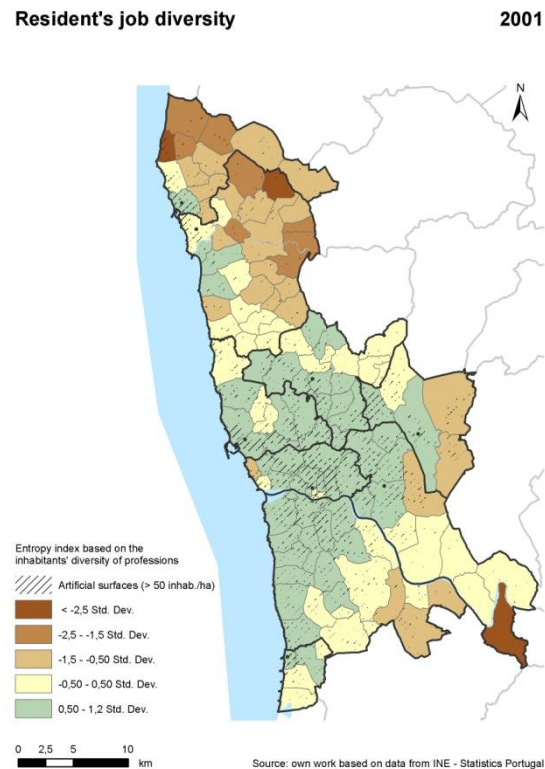
2005



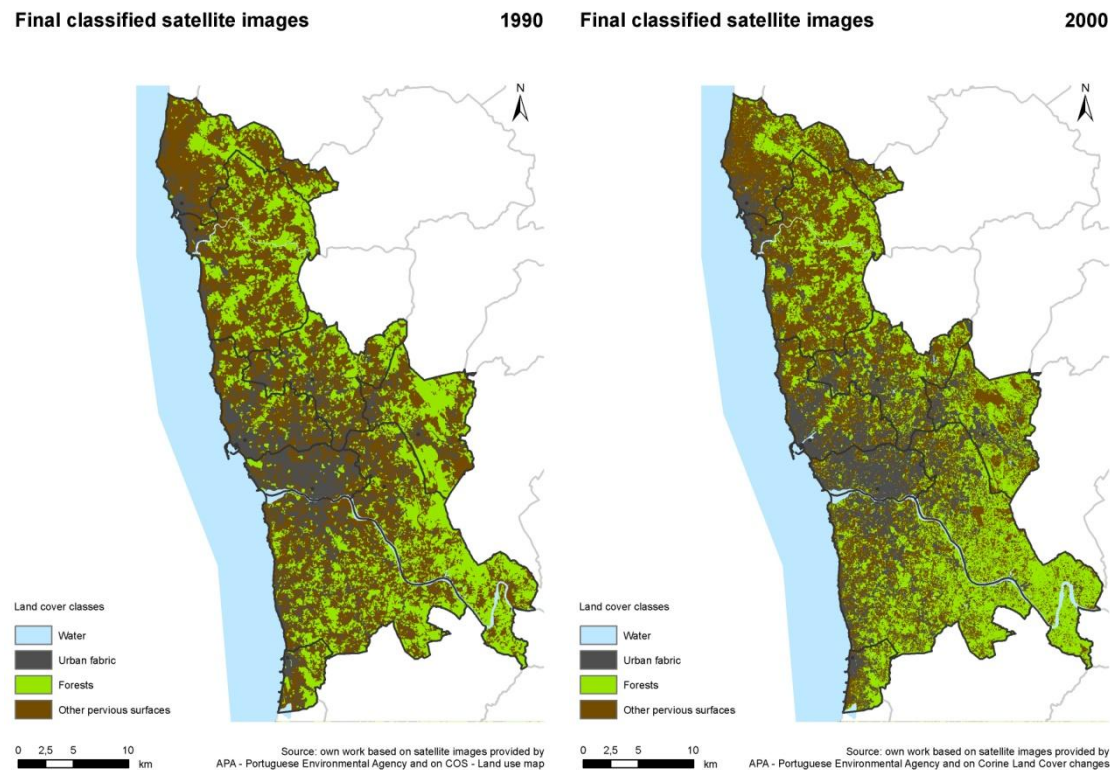
Unemployment

2008





Territorial structure

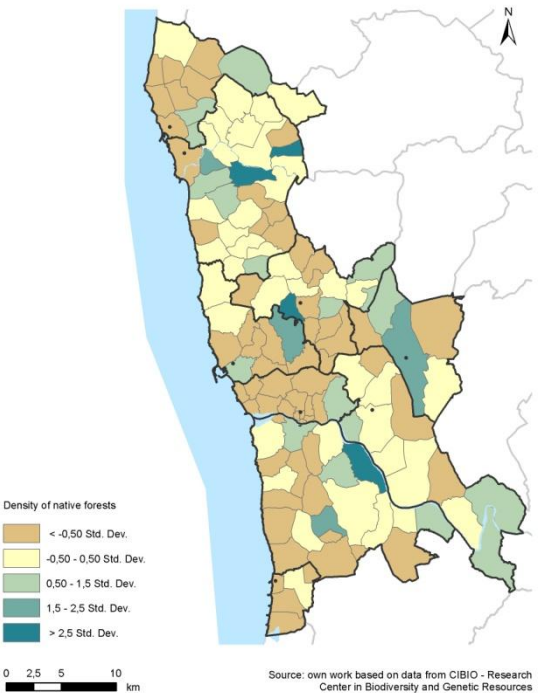
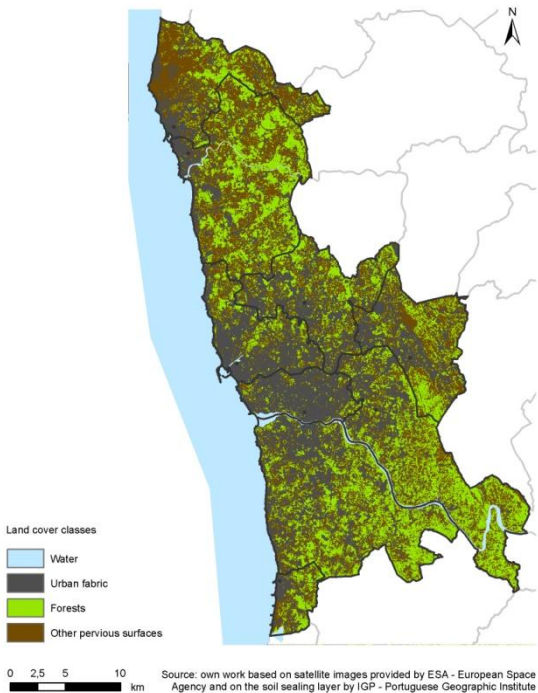


Final classified satellite images

2006

Native forests

2004

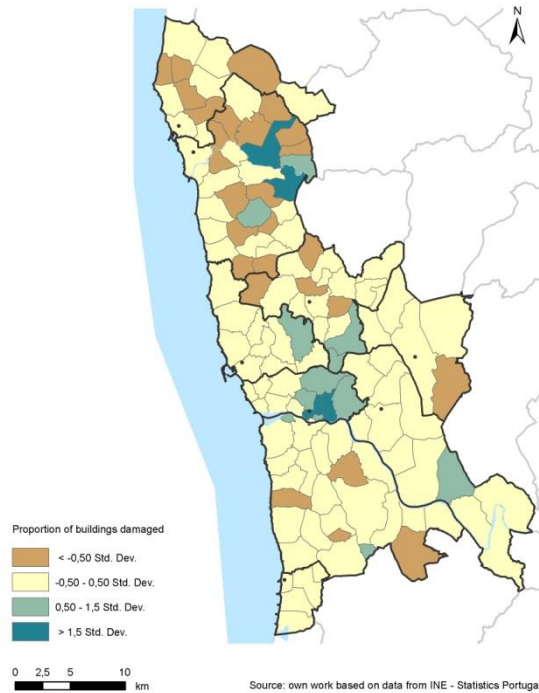
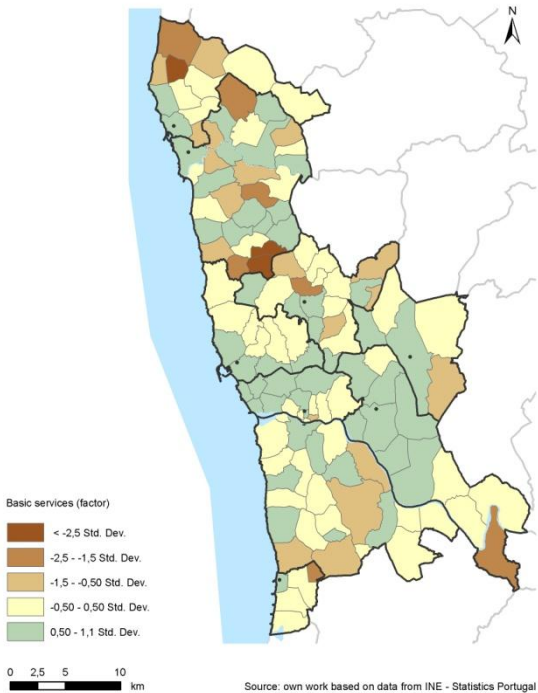


Basic services

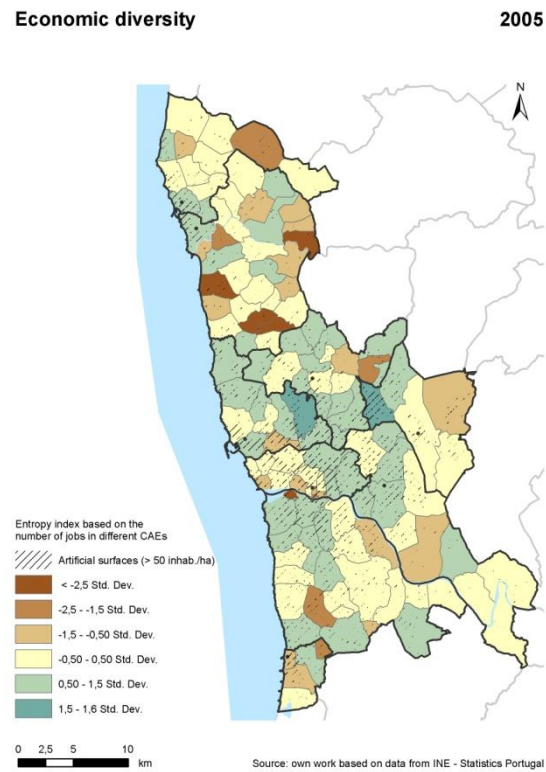
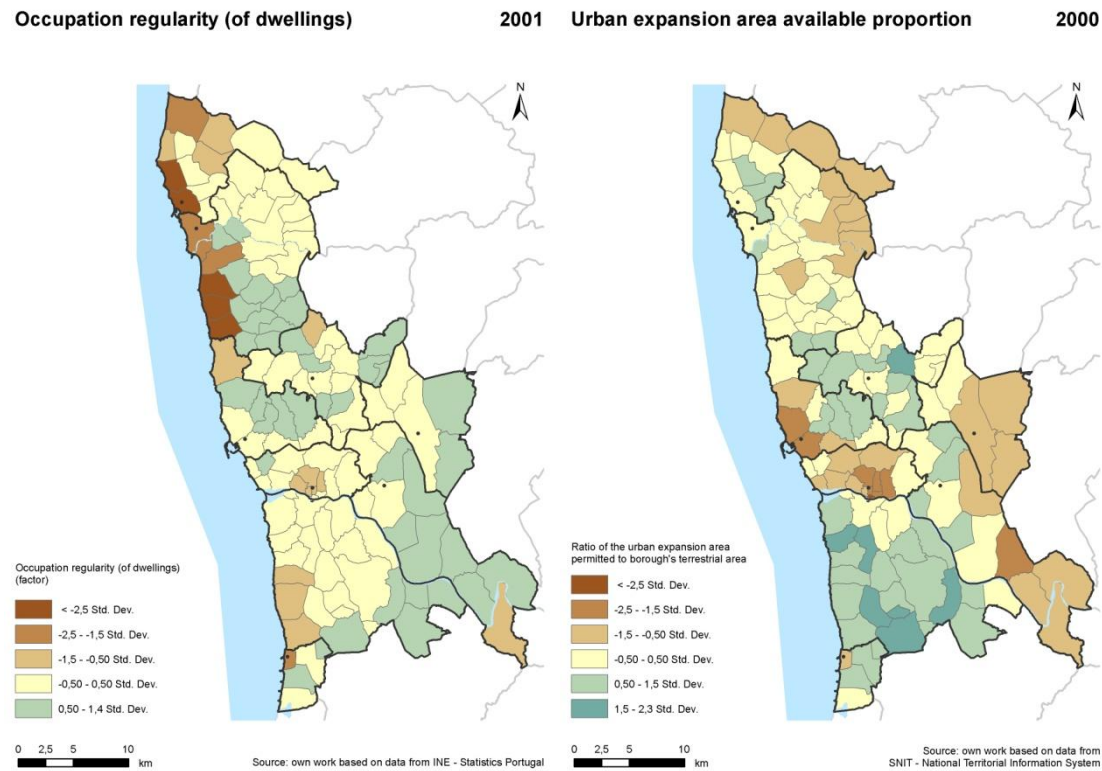
2001

Damaged buildings

2001



Economy



Interactions

