Department of Surveying and Planning

# The Impacts of Urban Structure and the Related Consumption Patterns on the Carbon Emissions of an Average Consumer

Jukka Heinonen

Aalto University

DOCTORAL DISSERTATIONS

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# The Impacts of Urban Structure and the Related Consumption Patterns on the Carbon Emissions of an Average Consumer

**Jukka Heinonen**

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**Aalto University**
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**Department of Surveying and Planning**
**Real Estate Business**

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# Abstract

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**Abstract**

Climate change, in the form of global warming, has been a hot topic throughout the present millennium, and is currently becoming a more and more widely accepted phenomenon. Urban areas hold a central position in the search for feasible climate change mitigation opportunities as a significant share of all the global greenhouse gas (GHG) emissions is closely related to urban structures. Embracing the situation, cities worldwide are setting ambitious GHG reduction targets. However, the strategies to attain these are still evolving. One explanation is that the cities and urban areas in developed countries are demand and consumption centers where the majority of all consumed goods are imported from outside of the city boundaries. Thus, the traditional geographically restricted assessment methods cannot produce sufficient information for effective carbon management.

The dissertation argues that in order to create city level carbon mitigation strategies, which would materialize the potential related to urban areas, it is necessary to identify and understand the emissions caused by the consumers. Derived from this, the dissertation strived to account for all the carbon emissions caused by the inhabitants in different types of urban structures, i.e. their carbon consumption, including the upstream emissions of production and supply chains. To create a clear understanding of the issue, a multiple case study approach was chosen in the Finnish context with each of the individual studies reported in academic journals or conference publications.

The studies employ a method based on hybrid life cycle assessment, along with an assessment model developed to calculate city and sub-city level carbon consumption. The main argument of the dissertation is that in the context of the study, the urban structure of an area per se seems to have little effect on the carbon emissions of an average consumer of the area. Rather, the overall consumption volume seems to affect the carbon consumption so strongly that a higher consumption volume indicates higher carbon consumption regardless of the type of the urban structure. The urban structure has a direct impact only on the emissions related to private driving, whereas the emissions from other consumption activities closely follow the overall consumption. Thus, while the environmental, social and functional importance of high urban density and the building type have been demonstrated in a number of studies, from the climate change perspective these factors are not decisive and they are not sufficient measures for effective city level carbon management.

**Keywords** life cycle assessment, LCA, urban structure, city, climate change, consumption, carbon emissions, GHG

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**Tekijä**
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**Tiivistelmä**

Ilmastonmuutos, tarkemmin ilmaston lämpeneminen, on ollut kuuma puheenaihe läpi kuluvan vuosituhannen, ja ilmiön olemassaolo hyväksytään yhä laajemmin. Kaupunkialueilla on keskeinen asema etsittäessä tehokkaita ja kannattavia ratkaisuja ilmastonmuutoksen hillitsemiseksi, koska merkittävä osuus maailman kasvihuonekaasupäästöistä liittyy tiiviisti kaupunkirakenteisiin. Myös tämä tilanne on laajasti tunnustettu, ja kaupungit ympäri maailmaa asettavat kunnianhimoisia vähennystavoitteita päästöilleen. Strategiat tavoitteiden saavuttamiseksi ovat usein kuitenkin puutteellisia. Yksi selittävä tekijä on kaupunkien ja kaupunkialueiden asema kulutuskeskuksina, joihin kulutettavat hyödykkeet tuodaan muualta. Perinteiset kaupunkien ja kaupunkialueiden sisällä syntyviä päästöjä tarkastelevat arviointimenetelmät eivät tällaisessa tilanteessa kykene tuottamaan riittävää pohjaa tehokkaalle kaupunkitason hiilijohtamiselle.

Tässä väitöskirjassa pyritään näyttämään, että kaupunkirakenteisiin liittyvän kasvihuonekaasujen vähennyspotentiaalin tehokas hyödyntäminen vaatii asukkaiden kulutuksesta aiheutuvien päästöjen tunnistamista ja ymmärtämistä. Tältä pohjalta väitöskirjassa rakennetaan kuva asukkaiden kulutuksen aiheuttamista päästöistä erityyppisissä aluerakenteissa, ts. heidän hiilikulutuksestaan, huomioiden tuotannon ja kuljetusten päästöt elinkaarinäkökulmasta globaalilla tasolla. Kattavan ymmärryksen saavuttamiseksi väitöskirja rakentuu useille samaa aihepiiriä eri näkökulmista tarkasteleville tapaustutkimuksille Suomen aluekontekstissa. Kaikkien viiden väitöskirjaan kuuluvan tutkimuksen tulokset on julkaistu artikkeleina akateemisissa julkaisuissa vuosina 2010-2011.

Väitöskirjan tutkimuksissa rakennettiin hybridi-elinkaarilaskentamenetelmää hyödyntävä arviointimalli kaupunkien ja kaupunkialueiden asukkaiden hiilikulutuksen laskemiseksi. Tuloksista nouseva väitöskirjan pääväite on, ettei aluerakenne tai aluetyyppi itsessään vaikuta merkittävästi keskimääräisen asukkaan kasvihuonekaasupäästöihin. Ratkaiseva tekijä näyttäisi olevan tämän sijaan kulutuksen volyymi, joka vaikuttaa niin merkittävästi, että korkeampi kulutustaso viittaa korkeampiin kasvihuonekaasupäästöihin aluerakenteista riippumatta. Aluerakenne vaikuttaa suoraan ainoastaan yksityisautoilun päästöihin, kun taas kaikkeen muuhun kulutukseen liittyvät päästöt seuraavat tiiviisti kulutustasoa. Näin ollen, vaikka aluerakenteiden tiiviyden ympäristö-, sosiaaliset ja toiminnalliset hyödyt ovat monesta näkökulmasta merkittäviä, ilmastonmuutoksen suhteen tämä ei ole riittävä eikä edes merkittävä tekijä, eikä se voi ohjata kaupunkien hiilijohtamista.

**Avainsanat** elinkaarianalyysi, LCA, aluerakenne, kaupunki, ilmastonmuutos, kulutus, hiilidioksidi, kasvihuonekaasu

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When I first applied for a position as a doctoral candidate in 2005, Professor Tuula Pohjola was the brave one who believed in my ability to accomplish the task. Thank you, Tuula. Since then many things changed in my life and around me, and in 2008, when I had planned to get my doctorate, I was doing something totally different with just as little of my dissertation completed as when I started in 2005. Still, getting a doctorate had been in my thoughts for a long time, and after a period of some hard thinking I decided to put other things aside and do what it would take.

Occasionally coincidences lead to good things. In the winter of 2009 I was sitting in a class and thinking what would be the right way to proceed with my doctorate plans. The lecture was given by Dr. Antti Tuomela whom I knew distantly. After a brief discussion with Antti he advised me to contact a newly appointed Professor Seppo Junnila, who might be the person to talk to about my PhD plans. Antti probably didn't understand the value of the advice for me back then, but I definitely owe him very warm thanks, which he hopefully someday reads from here. Thank you, Antti.

The most important person (besides maybe myself) behind my dissertation has since then undoubtedly been my instructor and supervisor Seppo Junnila. When I first went to talk to Seppo, he was concerned about my motivation for the doctoral studies. Was I serious or just "in between jobs" with nothing better to do? I then managed to convince him and now I can deliver the promise as a whole. I am hugely grateful for Seppo for the time he has allocated for guiding my work during the last 2.5 years. But I've also gained a lot more. Seppo has shown me how to do high quality research and given me confidence to aim high with my research. The gain from this school won't end with this thesis, and I truly hope that neither will our productive and fluent co-operation. Thank you, Seppo.

I have also been privileged to have a very supporting workplace. While the physical place mainly did all but stop me from accomplishing my task, my colleagues were the ones who made it so much fun. During my time in the academia I have been asked many times how I can cope with the

atmosphere of keeping secrets and not sharing information. Apparently I have been in a better position in this respect than many others. This also applies beyond my own team members; to administration as well as other research teams in our department. Thank you, all my colleagues.

Even from within this group of wonderful colleagues, three names merit special thanks. Dr. Matti Kuronen was the first one from our team to cross the finish line. He shaped the way for me and made things a lot easier by doing them right before me. Matti was also one of the first ones to ponder over the initial findings of my research, acting as the representative of YIT Group in my first project, Carbon Off, where it all got started. Since then, Matti has been an important discussion partner along the way. Thank you, Matti.

For Ms. Riikka Kyrö I will always be grateful for her support. After she shaped a crappy conference paper into a wonderful journal paper that received more positive review comments than I've ever seen, I've little by little carried all my mediocre conference papers for her to get the same treatment. However, that is only a fraction of the support she has given to me. Especially during the long days of writing the summary section of this dissertation, she was always ready to discuss my ideas and proposals. Hopefully I can be of similar help when Riikka soon reaches the final stages of her dissertation work. Thank you, Riikka.

Mr. Antti Säynäjoki will also soon follow in the footsteps of Matti, me and Riikka in getting his doctorate. He has been a valuable co-worker for me all the way since joining our team and I believe there is a lot we can achieve in the coming years. Notwithstanding, Antti has been primarily my friend instead of just a colleague, which I hope to last regardless of where life takes us in the future. Thank you, Antti.

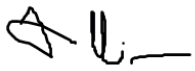
While this is and has been as much a hobby as a job for me, I don't try to claim that money wouldn't matter. Money unarguably has some practical value for me, but there is another side to money that may sometimes be forgotten. Those who have funded my research have also told me that they see my work as having significance for them. Especially as an inexperienced new researcher that truly has value beyond the monetary figure. The list is not in any order, but hopefully I remembered all my supporters: Aalto University, YIT Group, Tekes – the Finnish Funding Agency for Technology and Innovation, Confederation of Finnish Construction Industries RT, KIINKO Real Estate Education, City of Tampere, City of Helsinki, Sitra - The Finnish Innovation Fund, RYM Oy, The Research Foundation of Helsinki University of Technology, and all the partners in my current research projects who have indirectly supported my work, thank you all.

All the reviewers of the different parts of this dissertation have also earned a special acknowledgement for their contributions, especially the pre-examiners of this dissertation, Professor Holger Wallbaum and Dr. Robert Crawford for the valuable comments on the summary part. The comments and suggestions have unarguably greatly increased the quality of this piece of work. For Professor Arpad Horvath I will always be grateful; the credibility of my work took a leap upwards with him agreeing to act as the opponent. Thank you all.

At least for me research is not a regular day-job at the office. I like to think whenever and wherever, write notes on my cellphone – or for example on a napkin – and translate my notes and thoughts into papers and reports during the night. Sometimes this has not been exactly what my family would have hoped for. Hopefully the occasional days off and rare but short vacations have been enough to make up for all the hours spent working. Thank you Anna-Mari, Onni and Olga-Eedit.

Finally, behind all the studying and desire to achieve something like a doctorate is probably something that I've learned already way before any of this dissertation stuff took place. I don't remember ever being pushed or even guided to educate myself, but I certainly have an inherent respect for high education, which undoubtedly has affected my choices. Thank you, Mom, Dad and my brother Mikko.

Mainly in H and R trains between Helsinki and Hyvinkää in February 2012,



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# Papers of the dissertation

Paper I: Heinonen, Jukka; Junnila, Seppo; Kuronen, Matti (2010): A Life Cycle Assessment of Carbon Mitigation Possibilities in Metropolitan Areas, SB10 Finland, Sustainable Community - BuildingSMART, Espoo, 22.-24.9.2010, Finnish Association of Civil Engineers RIL, Conference Proceedings.

Paper II: Heinonen, Jukka; Junnila, Seppo (2011): Case study on the carbon consumption of two metropolitan cities, International Journal of Life Cycle Assessment, 16, 569-579.

Paper III: Heinonen, Jukka; Junnila, Seppo (2011): Implications of urban structure on carbon consumption in metropolitan areas, Environmental Research Letters, 6, 014018.

Paper IV: Heinonen Jukka; Junnila Seppo (2011): Carbon Consumption Comparison of Rural and Urban Lifestyles, Sustainability, 3 (8), 1234-1249.

Paper V: Heinonen, Jukka; Kyrö, Riikka; Junnila, Seppo (2011): Dense downtown living more carbon intense due to higher consumption: a case study of Helsinki, Environmental Research Letters, 6, 034034.

**Journal impact factors (2010)**

| | Provider | ISI | SCOPUS |
|---|---|---|---|
| Journal | | IF+ | SJR* |
| The International Journal of Life Cycle Assessment | | 3.148 | 0.228 |
| Environmental Research Letters | | 3.049 | 0.108 |
| Sustainability | | not listed | 0.026 |

+IF: Journal Citation Report Impact Factor

*SJR: SCImago Journal Rank

# The author's contribution in the papers

Paper I: The author is responsible for writing the paper.

Paper II: The author is responsible for writing the paper.

Paper III: The author is responsible for writing the paper.

Paper IV: The author is responsible for writing the paper.

Paper V: The author is responsible for initiating the paper, conducting the assessments and writing the first manuscript of the paper as well as several parts of the final paper.

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# 1 Introduction

Climate change, in the form of global warming, has been a hot topic throughout the present millennium. Despite some counterarguments [e.g. 1, 2], the phenomenon has been widely accepted [3, 4] and it is often stated as the most severe global environmental problem of our age. Embracing this paradigm set the course for this dissertation.

The overall leading purpose of the dissertation is to analyze the climate change implications of different types of communities living in different types of urban structures. In other words, the aim is to integrate inhabitants into the analysis of the emissions of buildings and urban structures, with the idea that buildings are necessary goods for living, and the building, the urban structure and the location may all affect the lifestyle of the inhabitant. Based on these factors, the dissertation aims to account for all the emissions from consumption, including the upstream emissions of production and supply chains.

The need for this type of consumption-based greenhouse gas (GHG) assessment approach, accounting for all life cycle emissions from consumption, has been recently expressed by several authors [5, 6, 7, 8]. While some such approaches have also been reported in academic journals in the past years [5, 8, 9], space for new contributions is still ample. Within the field, this dissertation contributes especially to the area of city and sub-city level GHG assessments, where the academic research tradition is thin [10]. However, the topic is important, as both cities and urban areas appear to be accountable for the majority of all GHG emissions in developed countries [8, 11] and are important contributors in reaching carbon mitigation targets if willing to reduce their emissions [10-12].

While a variety of different calculation tools have been developed by academics and consultants, especially the techniques for a consistent consumption-based GHG assessment on a city or sub-city level are still insufficient. Cities worldwide are setting ambitious GHG reduction targets, but the ways to attain these, and even to assess whether they are reached or not, are still under development. Cities and urban areas in developed countries are demand and consumption centers [5, 8, 13] where the

majority of all consumed goods are imported from outside of the geographical city area. Thus, the traditional geographically restricted assessment methods cannot produce sufficient information for effective carbon management, mainly because the results depend heavily on the presence or absence of heavy industries [37]. For example, the carbon footprint of an average resident of Helsinki, the capital of Finland as well as one of the case cities of this dissertation, has been reported in different publications to vary from roughly four tons of GHGs to almost 13. The minimum is reached with assessments limited in scope in both a geographic and a life cycle perspective [14], whereas the consumption-based approach of the dissertation, aiming to account for all life cycle emissions related to all consumption of goods and services of an average resident of the city, results in the highest figure. Neither of these can be claimed to be false as such, but the approach based on limited scopes can hardly be argued to produce sufficient data for efficient city-level management of the global phenomenon of climate change.

The dissertation consists of altogether five individual but interrelated studies reported in four academic journal papers in 2011 and one conference proceeding in 2010. The studies analyze the consumption-based carbon emissions of the inhabitants in different types of urban structures in the Finnish geographical context, examining the impact of the structure and the consumption volume of the emissions. Thus, while the work with the assessment techniques contributes to the field of city-level consumption-based GHG assessments, the key argument of the dissertation arises from the findings of the five studies. This argument, explained and discussed in detail throughout the dissertation, is that in the context of the study, the urban structure of an area *per se* seems to have little effect on the carbon emissions of an average consumer of the area. The key factors lie elsewhere. The overall consumption volume seems to affect the carbon consumption so strongly that a higher consumption volume indicates higher carbon consumption regardless of the type of the urban structure. Thus, while the environmental, social and functional importance of high urban density and the building type have been demonstrated in a number of studies, from the climate change perspective these factors are not sufficient indicators. However, the research also indicated means to break the connection between consumption volume and carbon consumption, as will be discussed later.

The result contradicts with some earlier findings [15, 16], but the reasons for the contradiction have been found and reported in some earlier studies as well. For example, Sovacool and Brown (2010) find that the carbon footprints of city residents are substantially higher than country averages in

many developing countries, whereas in the developed countries the situation is reversed in general [10]. They state the significantly higher level of the standard of living in the urban areas in the developing countries as one of the key reasons for the result. According to this dissertation, the same argument may also apply in the context of a developed country when the consumption of all the goods and services and their life cycle emissions, which were excluded from the inventory of Sovacool and Brown, are included. City residents outsource a significant amount of their emissions, especially in the developed countries where the heavy industry is often located outside of the cities and even the countries, and imports form a significant share of the overall supply. Thus, their per capita emissions may well be substantially higher than those of the surrounding areas when comprehensive consumption-based analyses are conducted.

The results reported by Ramaswami et al. (2008) and Schulz (2007 & 2009) on cities importing a significant share of the goods consumed, and thus GHGs as well, also support the finding of city residents outsourcing their emissions [5, 8, 13]. Evidence for the outsourcing of the emissions taking place on an economy level has also been presented by Wagner (2010), who argues that the energy embedded in the imports of the developed countries may cause their per capita emissions to actually increase even when national inventories would seem to show decreasing patterns [17].

As said above, the argument of the dissertation results from altogether five studies. In the studies, a comprehensive consumption-based assessment model is developed for carbon consumption assessments in different types of areas. The papers present together a coherent set of multiple case studies, all producing similar outcomes. The overall key argument was initially reported already in Paper I of the dissertation. The latter studies, published in Papers II-V, all support the initial finding. In the five papers, the carbon effects of urban structure and consumption volume are analyzed in different types of urban structures and on different levels of urbanization: on the city level with multiple cases of different types of cities (Papers I and II), on the level of metropolitan areas with two distinct metropolitan centers including several cities (Paper III), on a national level based on four types of urban structures (Paper IV), and finally on a sub-city level (Paper V).

The remainder of the dissertation is structured as follows. Section 2 presents the research problem and the context in which the problem is analyzed. Section 3 concentrates on the methodology, presenting first the methods employed in the different papers of the dissertation, and then the wider methodological context of the whole dissertation. In Section 4 the

contributions of individual papers are summarized and linked to the research problem as well as to the overall argument of the dissertation. Section 5 summarizes the results and the contribution of the dissertation is put together. Section 5 also evaluates the validity and reliability of the research and assesses needs for future development around the topics of the dissertation. Papers I-V follow the references in Section 6.

## 1.1 Terminology

The dissertation aims at consistent and generally accepted use of terms. However, some terminology is employed in multiple meanings and some may be specific to the research. Short explanations are given below to clarify these.

**Research**

In the dissertation, the term "the research" refers to the entirety of the dissertation as a whole.

**Study/studies**

The dissertation consists of multiple interconnected but individual studies. The terms "the study" or "the studies" refer to the individual studies reported in the published papers of the dissertation.

**Carbon emissions**

In the dissertation, including the individual publications, the term "carbon emissions" refers to all the included GHGs ($CO_2$, $CH_4$, $N_2O$ and HFC/PFCs) in carbon dioxide equivalents ($CO_2e$).

**Carbon consumption**

The term "carbon consumption" is employed to indicate the GHGs released as a result of consumption, when a consumer responsibility perspective is utilized, that is, allocating to a consumer the life cycle emissions (including production and delivery chains) of all his/her consumption.

# 2 Research problem

The dissertation had no explicit research problem to begin with. Each individual study had their purposes, which resulted in the research problem of the dissertation in the course of the research. The field of research was familiar via previous literature on the subject, but no hypotheses were set *a priori*. When the research progressed, the prior stages were utilized to set working hypotheses for the next stages as well as to guide the case selection. However, the findings led early to the forming of the first version of the research question which, with minor modifications, is now expressed as:

> **What are the effects of urban structure and the related consumption patterns on the carbon emissions of an average consumer?**

All the five papers of the dissertation contribute to the research question above. The research question is examined from several perspectives utilizing multiple case studies that represent different contexts. The dissertation creates new knowledge on the carbon implications of the urban structure and the related consumption patterns of the inhabitants in different area types. The results, in addition to contributing to academic research, can be of high value in advancing the important topic of city carbon management, and should thus be brought into the awareness of urban policy makers alongside the academic community.

The broader context in all the papers of the dissertation is the Finnish economy. This limits the generalizability of the results, which is analyzed in more detail in the papers, especially in Paper V. However, as the perspective on the carbon emissions is global, a similar approach could be employed elsewhere as well, even if the results of this dissertation would not be directly applicable as such.

# 3 Methodology

## 3.1 Carbon consumption assessment methods

The dissertation approaches the research question by utilizing a consumption-based assessment of the emissions, that is, allocating to a consumer the GHG emissions caused by his/her consumption regardless of the geographic location of the occurrence of the emissions. The method employed is life cycle assessment (LCA), which is capable of capturing the emissions of production and supply chains globally. More specifically, the research employs streamlined input-output (IO) and IO-based hybrid LCA approaches [18]. The approach is streamlined to concern only one impact category of global warming. In more detail, the carbon consumption is assessed on the level of annual per capita emissions. Paper I employs a direct IO LCA method. In Papers II to V, the assessment model is further developed into an IO-based hybrid LCA model according to the tiered hybrid LCA method [18, 19].

The selected methods were assessed as the most suitable due to the complex nature of the research object, the carbon emissions of private consumption. The IO LCA-based methods are especially suitable for analyses in the context of the built environment [18]. The method allows analyses of complex systems with much less labor than more traditional process LCAs as it utilizes monetary inputs to assess the GHG emissions based on output tables derived from the economic IO accounting of an economy [20].

The model exploited for the direct IO assessment and used as the basis for the developed IO-based hybrid LCA model is the Carnegie-Mellon University economic input-output LCA (EIO-LCA), which is freely available in the Internet [21]. Although not based on the Finnish economy, the model was assessed as the most suitable one to be employed in the research. In-depth analyses on the applicability as well as the general strengths and weaknesses of the EIO-LCA model and the hybrid model developed are presented throughout Papers I-V of the dissertation.

The IO method in general was first introduced by the Nobel laureate Wassily Leontief in the 1930s. In the 60s the approach was extended to

cover the environmental perspective [18, 22] as well as regional, sub-economy, multi-regional, and multi-economy contexts [23-25]. More recently, city level assessment models have also been developed based on the IO method [e.g. 35].

The employed IO and IO-based hybrid LCA methods are in accordance with the ISO 14040 standard for conducting LCA analyses [18, 19]. In the dissertation as a whole, the goal and the scope are defined by the research question and they are described in more detail in the paragraphs above. An average consumer was chosen as the functional unit to allow comparisons between different types of consumers and to maintain the comparability of the results throughout the dissertation. The system boundary, set by the selected method, is infinite in the number of upstream processes included [e.g. 18, 26], but limited to the national economy in treating all products and the entire production and supply chains as domestic. The boundary is also economic, as the processes where a monetary transaction between two sectors occurs are included. Furthermore, according to Crawford (2011), the IO-based hybrid LCA approach provides the most comprehensive system boundary possible [18].

Viewed from another perspective, the assessment model developed in the dissertation is in accordance with the definition of the WRI Scope 3 standard [27]. The WRI Scope 3 standard requires that the upstream life cycle emissions are taken into account for all the goods in the scope of the assessment, a quality rarely found in the assessment models presented in previous studies in the field [5].

Following from the qualities of the assessment model presented above, the dissertation contributes to the field of city and sub-city level IO-based hybrid LCAs with regard to method by including all private consumption in the assessment. The problems and uncertainties related to the selected method and the consequences in interpreting the results are covered in detail in Papers I-V of the dissertation.

### 3.2 Methodological context

The approach described above falls into a wider methodological context of mixed method studies [28]. The background is predominantly quantitative, the research data being entirely quantitative. However, as many methodologists have stated [i.e. 29, 30], all findings, whether based on qualitative or quantitative data, must be interpreted by the researchers. In this dissertation, the emphasis is in fact on the interpretation of the results in which a qualitative analysis is utilized instead of a statistical approach.

Another wider perspective on the methodological context is found from the case study approach. The five papers of the dissertation all contribute to the same research problem, creating a strong case-based theory as

described by Eisenhardt (1989) and Eisenhardt and Graebner (2007) [31, 32]. According to Eisenhardt and Graebner, this type of theory can be "accurate, interesting and testable". In addition, they state that "[the theory is] more accurate, and more generalizable (all else being equal) when it is based on multiple case experiments" [32]. The papers have different contexts and present different cases, but all produce an outcome that verifies the findings of the earlier papers regarding the research question.

The setting of the dissertation follows the process of building a case study theory of Eisenhardt [31] in the research design, the setting and shaping of hypotheses as well as in employing literature to build higher validity. The research began without any set hypotheses about the outcome. The cases were selected along the progress of the research according to the theoretical sampling principle. The earlier cases and their results were utilized to set up hypotheses that were tested and developed further by advancing the research around the identified phenomena using divergent cases. Existing literature was employed both to find support for the results and to analyze the reasons for the conflicts with findings reported earlier.

In Papers I and II the case study objects are cities, seven cities in Paper I and two in Paper II. Paper III consists of two cases: the two largest metropolitan areas in Finland, both consisting of several cities. Paper IV was set to test the results of the three earlier studies at the national level, and it leans more on national census data than specific case data. In Paper V the case study approach was employed again, but within a city context.

Due to the nature of the research objects described above, as well as the assessment method, the data collection and analysis differ somewhat from the type of case-based theory described by Eisenhardt [31]. The input data employed is predominantly statistical and collected by a third party, rather than being collected from within the case organizations. However, while the census data of Statistics Finland [33] is the primary data source in all of the studies, multiple other sources of data were utilized, such as data provided by the case organizations. The data sources and their utilization are explained in detail in the papers.

# 4 Summaries of the research papers

The papers of the dissertation form a very coherent body. They all deal with the same research question from slightly different perspectives, thus giving a basis for strong conclusions. In the course of the research, a 10-category distribution of the emissions was developed to allow the analyses of the effects of urban structure and consumption patterns on the emissions. The distribution was employed in Papers I-IV. For Paper V, the distribution was aggregated into five categories. The 10-category distribution of the emissions in Finland on average (from Paper IV) is shown in Figure 1.

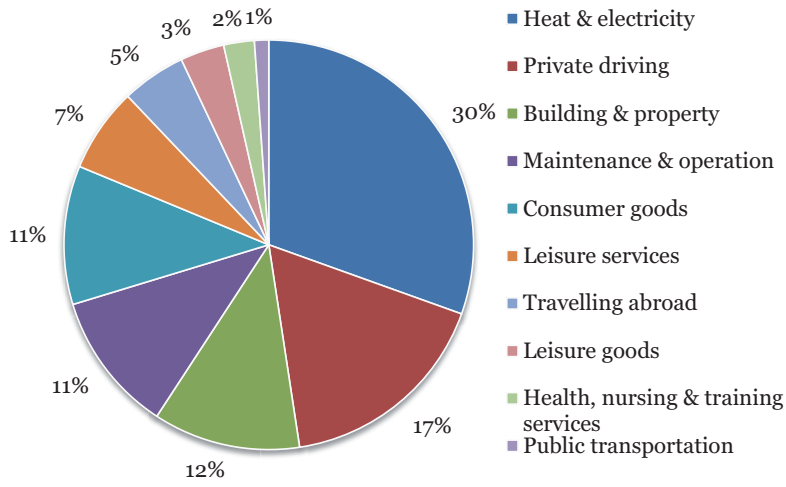


Figure 1: The distribution of the carbon consumption of an average resident in Finland.

As the figure depicts, 70% of the emissions in Finland on average come from sources very closely related to urban structure: 30% from Heat & electricity, 17% from Private driving, 12% from Building and property, 11% from Maintenance and operation (of buildings) and 1% from Public transportation. Now, in all the five studies including roughly 20 areas, only the emissions in the category of Private driving were found to decrease along with an increase in the density of the urban structure. In all the other categories, the relation observed is the reverse or ambiguous in general.

The overall emissions were found to increase (rather than decrease) following an increase in the density. However, the possible causality between the density and the emissions was not studied. The observations describe the current state of the issue, which is that the consumption volume tends to increase towards denser structures, and this causes the emissions to increase in all but the category of Private driving.

Some interesting findings were made concerning the differences between the areas studied. In the areas with higher consumption volumes, a larger share of the consumption is directed at consumption categories with lower carbon intensity, such as services, which might have a positive effect on the overall carbon consumption. However, the observed increase in the consumption in other categories as well hinders this positive effect and leads only to a further increase in the overall emissions.

Next, the five individual papers and their findings are presented. Figure 2 presents the overall setting, and the following chapters briefly describe Papers I-V and their key findings.

**RESEARCH QUESTION**
**What are the effects of urban structure and the related consumption patterns on the carbon emissions of an average consumer?**

| | Paper I | Paper II | Paper III | Paper IV | Paper V |
|---|---|---|---|---|---|
| TITLE | A Life Cycle Assessment of Carbon Mitigation Possibilities in Metropolitan Areas | Case study on the carbon consumption of two metropolitan cities | Implications of urban structure on carbon consumption in metropolitan areas | A Carbon Consumption Comparison of Rural and Urban Lifestyles | Dense downtown living more carbon intense due to higher consumption: a case study of Helsinki |
| PURPOSE | To examine the applicability of an IO-based screening-LCA method in modeling GHG emissions of consumption in a specific urban structure. To test whether GHG emissions related to urban structure and income level can be identified with the method. | To advance the research on city level LCA studies from a consumption perspective. To open a discussion on the results of earlier studies that have identified urban density as the key element for lower carbon emissions. | To demonstrate the effects of density, dominant building type, private driving and income on the carbon consumption. | To conduct a consumption-based analysis of consumer carbon footprints for comparing the carbon emissions of average inhabitants living in different types of urban structures. | To provide an in-depth analysis on the effect of urban density on carbon emissions in the case of a city with a high income downtown area. To estimate the annual per capita carbon load on two different levels of urban density within a city context. |
| CASES | Seven case cities in the Helsinki region in southern Finland | The Finnish capital Helsinki and Porvoo, a smaller city within the Helsinki economic region | The two largest metropolitan areas in Finland: the Helsinki metropolitan area and the Tampere metropolitan area | Finland divided into four different area types: rural, semi-urban, city and metropolitan | Helsinki divided into the suburban regions and the downtown core |

| | | | | | |
|---|---|---|---|---|---|
| KEY FINDING | The annual per capita carbon emissions tend to increase when the disposable income increases. The case studies also indicate that the correlation between the level of consumption and the carbon emissions, while close, is not linear but diminishing. | The carbon reducing influence of city density is easily overridden with factors such as the type of energy production, the energy efficiency of the housing stock and increased use of services. | The type of the urban structure, whether a dense metropolitan core with apartment buildings or a less dense suburban area with primarily detached housing, has little effect on the carbon emissions. | Cities may not be more sustainable in nature compared to the surrounding suburban and rural areas concerning climate change when a demand-based approach is taken. The per capita emissions related to city lifestyle are substantially higher than those related to rural and semi-urban lifestyles. | The socioeconomic standard of living in the city center potentially combined with the easy access and availability to goods and services seems to generate substantially higher per capita carbon loads than are generated in the suburban areas with a lower standard of living. |

**CONCLUSION**

**The urban structure of an area as such seems to have little effect on the carbon emissions of an average consumer of the area compared to the impact of overall consumption volume. Thus, the key factor is the consumption, which affects the carbon consumption so strongly that a higher consumption volume indicates higher carbon consumption regardless of the type of the urban structure. When real consumption data is analyzed, in denser urban structures the transportation generates lower, housing similar, and goods, services and travel significantly higher carbon emissions.**

Figure 2: The research problem, purposes and key findings of Papers I-V and conclusion.

### 4.1 Paper I: A Life Cycle Assessment of Carbon Mitigation Possibilities in Metropolitan Areas

The purpose of the first paper was to create a first picture about the feasibility of a consumption-based life cycle assessment in modeling the carbon emissions of different types of urban structures. The paper examined the applicability of the IO-based screening-LCA method in modeling GHG emissions from consumption. Moreover, the paper provided increased understanding of the possible future utilization of the method in urban development.

The study utilized the Consumer survey 2006 data from Statistics Finland [33] to assess the consumption-based carbon emissions of the average consumers of seven Finnish case cities from the Helsinki Region: Espoo, Helsinki, Hyvinkää, Kerava, Nurmijärvi, Porvoo and Vantaa. The cities represent a dense metropolitan core, the capital city Helsinki, and two circles of smaller and less dense cities around Helsinki. The paper followed the pure IO LCA method utilizing the Carnegie Mellon University EIO-LCA model [21]. With the paper, we thus also set the ground for the future utilization of the EIO-LCA model in the Finnish context.

For the purpose of revealing the connections between different types of urban areas and carbon emissions, we divided the overall consumption into 10 consumption classes, namely Heat and electricity, Building and property, Maintenance and operation, Private driving, Public transportation, Consumer goods, Leisure goods, Leisure services, Travelling

abroad, and Health, nursing and training services. The study showed that the annual per capita carbon emissions tend to increase when the disposable income grows, when the living space per capita grows and when no commuter connections are available. Also, the study showed that a large share of the overall per capita emissions is attributable to the consumption of daily goods and leisure goods and services, which have often been left out of the carbon emissions assessments. Table 1 presents the LCA results divided into the 10 consumption categories.

Table 1 (from Paper I): The annual consumption (€) and per capita carbon emissions (t $CO_2$e.) in the seven Helsinki Region cities.

| | Hyvinkää | Vantaa | Kerava | Porvoo | Helsinki | Espoo | Nurmi-järvi |
|---|---|---|---|---|---|---|---|
| Private consumption | 13.300 | 16.000 | 17.200 | 15.900 | 17.400 | 18.800 | 20.400 |
| Carbon footprint | 12,1 | 13,8 | 14,6 | 15,1 | 15,3 | 17,3 | 18,4 |
| Building energy | 5,56 | 5,62 | 5,78 | 6,18 | 6,13 | 6,87 | 7,43 |
| Building and property | 1,21 | 1,34 | 1,18 | 1,40 | 1,36 | 1,71 | 1,70 |
| Maintenance & operation | 1,03 | 1,30 | 1,51 | 1,46 | 1,64 | 1,27 | 0,99 |
| Private driving | 1,19 | 1,54 | 2,08 | 2,17 | 1,42 | 2,16 | 3,11 |
| Public transportation | 0,20 | 0,63 | 0,36 | 0,48 | 0,64 | 0,45 | 0,47 |
| Travelling abroad | 0,48 | 0,50 | 0,89 | 0,68 | 0,89 | 1,45 | 1,09 |
| Consumer goods | 1,23 | 1,33 | 1,26 | 1,39 | 1,61 | 1,56 | 1,49 |
| Leisure goods | 0,32 | 0,45 | 0,38 | 0,41 | 0,34 | 0,45 | 0,78 |
| Leisure services | 0,66 | 0,80 | 0,72 | 0,70 | 0,99 | 1,08 | 1,02 |
| Health, nursing and training services | 0,26 | 0,26 | 0,46 | 0,17 | 0,29 | 0,31 | 0,28 |

### 4.2 Paper II: Case study on the carbon consumption of two metropolitan cities

In the second paper, the model created in the first paper was developed further. The first study, while demonstrating that the screening-LCA is efficient to use, revealed also sources of bias that needed to be resolved. Thus, in the second paper we enhanced the model with Finnish process data on housing energy and fuel combustion of private driving according to the tiered hybrid LCA method [19]. In addition, we applied price level adjustment factors to property prices and disaggregated the housing charges to be able to assess the housing related emissions in detail.

The purpose of the second study was to validate and analyze further the findings of the first study. Furthermore, with the second paper we argued for the importance of the utilization of a consumption-based assessment in city level carbon management, as well as for the high value of the inclusion of all the emissions of private consumption into the assessment.

We selected the capital city Helsinki and the city of Porvoo, a smaller city about 50 kilometers away from Helsinki, as the case cities of the study.

These two present interesting variation in the city structures while belonging to the same economic region. The city sizes, population densities, housing types and income levels differ substantially on the city structure level. In addition, Porvoo is dependent on Helsinki for workplaces and services, which generates a significant amount of commuting. And, even more importantly, the fuel mixes of the local energy production differ significantly, as the production is predominantly based on renewable fuels in Porvoo and fossil fuels in Helsinki.

The key finding, supporting the result of Paper I with the more accurate hybrid version of the assessment model, was that the influence on the carbon consumption of the urban density and the dominant building type of the area may be negligible. The study showed that the carbon consumption is on a substantially higher level in Helsinki than in Porvoo. The impacts of a higher consumption volume and, especially in the case of this study, the fossil-based fuel mix in Helsinki overrule the effects of the higher level of private driving and larger average living space that increase the emissions in Porvoo. This, however, indicates that decreasing the emissions of local energy production would be very efficient city-level carbon management. According to the study, the annual carbon consumption of an average inhabitant of Helsinki is 13.2 t $CO_2e$ and 10.3 in Porvoo, as illustrated in Figure 3.

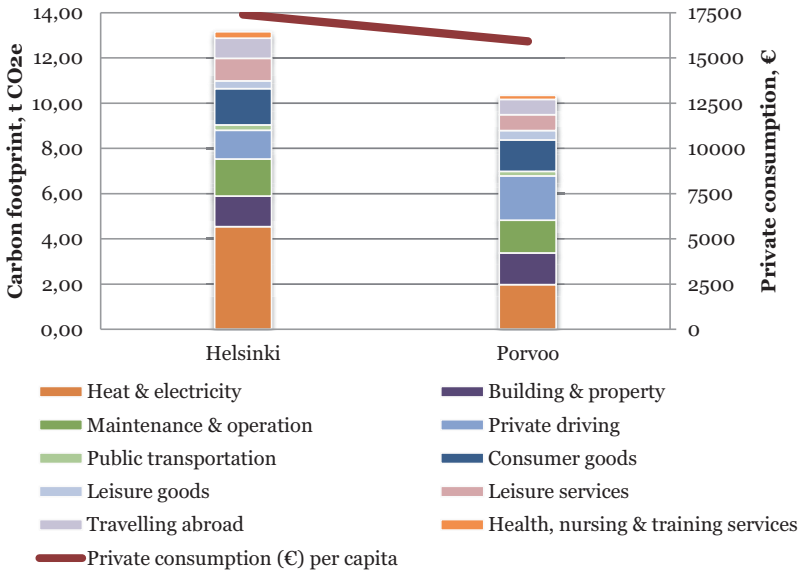


Figure 3 (modified from Paper II): The annual per capita carbon consumption in Helsinki and in Porvoo together with the volume of private consumption.

### 4.3 Paper III: Implications of urban structure on carbon consumption in metropolitan areas

The third paper forms a continuum for the first two papers. The paper concentrated on analyzing the connection between urban structure and carbon consumption. In the study, the two largest metropolitan areas in Finland were analyzed: Helsinki with the surrounding cities of Espoo and Vantaa, and Tampere with the seven surrounding cities divided according to the level of urbanization into two groups, urban cities in the Tampere Region (UCT) and rural cities in the Tampere Region (RCT).

The purpose of the third paper was to analyze the effects of density, dominant building type, private driving and income on the carbon consumption. In accordance with the first two papers, the study found no clear connection between urban structure and carbon consumption. The shares of the total emissions of the consumption of tangible goods and services seem to be high enough, and have a high enough variation for the overall consumption volume of the average resident of an area to become the key factor in the carbon consumption, rather than the urban structure.

With regard to urban structure, the study showed that the dominant sources of carbon emissions are housing energy and the construction and maintenance of the residence. While it is highly relevant for the urban authorities to understand the structure of the overall emissions, the highest mitigation potentials related to urban structure are related to these two sources. Figure 4 demonstrates the volume and division of the carbon consumption in the two metropolitan areas.

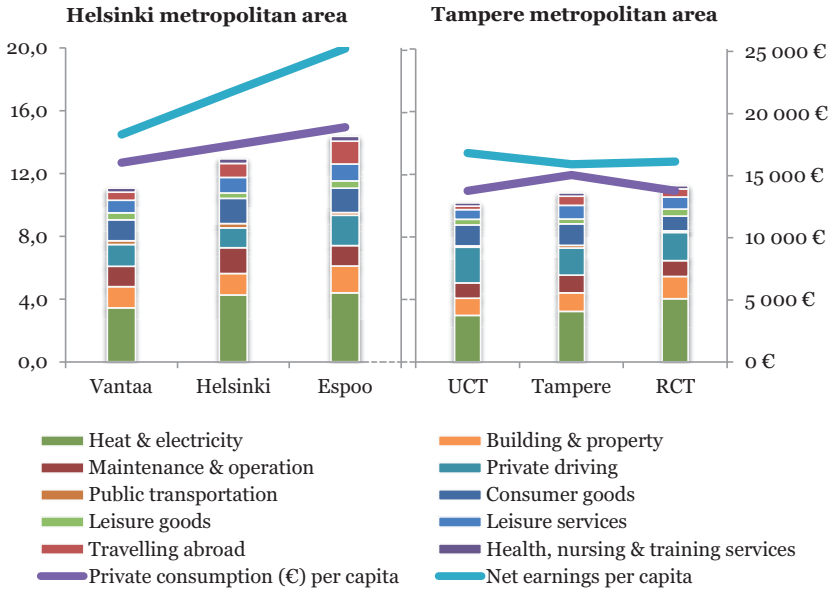


Figure 4 (modified from Paper III): The annual per capita carbon consumption (t CO2e) together with private consumption (€) and net earnings per capita (€) in the two metropolitan areas.

### 4.4 Paper IV: A Carbon Consumption Comparison of Rural and Urban Lifestyles

All the first three papers indicated that, at least in certain conditions, the link between urban density and the carbon consumption of an average resident is weak or even negligible. The housing type or differences in private car usage seemed to be easily overridden by the carbon emissions from the consumption of all other goods and services, making the consumption volume the decisive factor with regard to the differences in carbon consumption between the studied cities. However, none of the studies had a very diverse basis, being mere case studies.

This setting gave rise to the fourth paper, which focused on differences in carbon consumption in different area types in Finland as a whole. The study included four data samples representing four different area types in Finland: rural, semi-urban, city and metropolitan (Helsinki Metropolitan Area). For these, the carbon consumption of an average resident of each type was assessed. The results of the study were interesting, as according to the results, the carbon consumption grows along with the degree of urbanization, as Figure 5 shows.

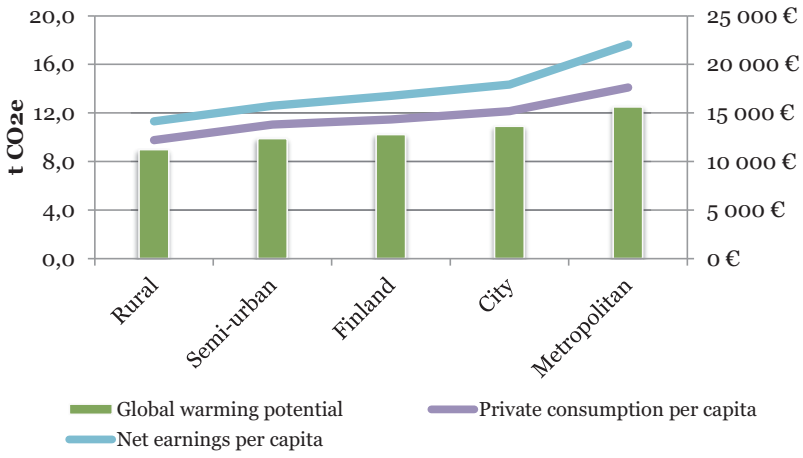


Figure 5 (modified from Paper IV): The annual average per capita carbon consumption (t $CO_2e$), private consumption (€) and disposable income (€) in the four area types in Finland.

When each of the 10 consumption areas utilized were analyzed separately, the result was that only the emissions related to private driving increase when the degree of urbanization decreases, as Figure 6 shows. One of the primary reasons explaining the findings is that in housing energy, no clear differences in the monetary consumption were found between the area types, but due to a better fuel mix, such as increased use of wood, the emissions are lower in rural and semi-urban areas. In all other consumption areas the emissions were found to grow along with the degree

of urbanization. The key factor is the consumption volume, which increases on average as the scale of urbanization increases.

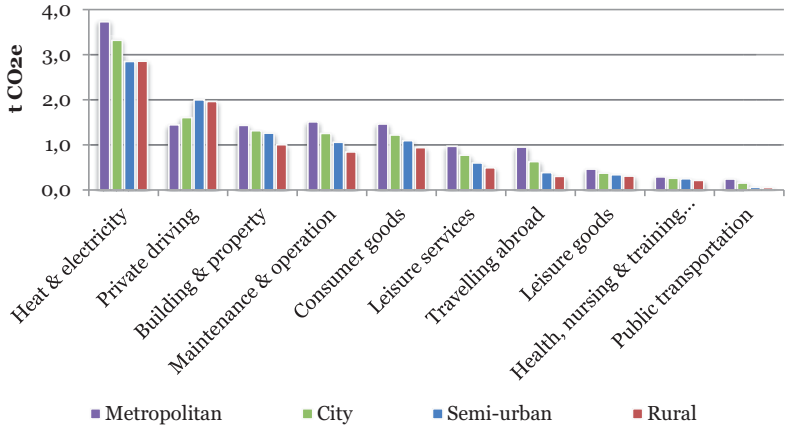


Figure 6 (modified from Paper IV): The average annual per capita carbon consumption within the 10 consumption areas in the different area types.

### 4.5 Paper V: Dense downtown living more carbon intense due to higher consumption: a case study of Helsinki

The fifth and final paper of the dissertation provides a continuum for the earlier papers, advancing both the method and especially the discussion of the third paper on the implications of urban structure on the carbon consumption of the inhabitants. The purpose of the study was to analyze further the implications of income and area type on the emissions. The study moved into a sub-city context, analyzing the annual per capita carbon load on two different levels of urban density within Helsinki, the suburban regions (Helsinki SU) and the downtown core (Helsinki DT). The Finnish capital city Helsinki provides an urban structure where the dense downtown area attracts wealthier residents and the less dense suburban areas attract lower income residents on average, although with the income level being well above the Finnish average in the suburbs, as well.

For the study, the hybrid LCA model for the carbon consumption assessment was developed further. The aggregation of the consumption sectors was decreased, increasing the overall number of sectors up to 59 from the 43 of the previous version of the model. Also, the number of the consumption categories to present the results was dropped down to five: Housing, Ground Transport, Tangible Goods, Services and Air, Maritime and Package Travel to clarify the demonstration of the results.

The findings of the study follow the pattern identified in the previous studies. The carbon consumption is on a substantially higher level in the much denser downtown core following the difference in the income levels. In the downtown area, the figure is 14.7 ton $CO_2e$ per capita with the annual consumption volume of 19.800 €, but in the suburbia only 12.0 tons with

16.800 € in purchases. Carbon consumption seems to increase especially in the categories of Tangible Goods, Services and Air, Maritime and Package Travel with the increase in the disposable income. As in the previous studies, the carbon consumption increases in each category but Ground Transport. Interestingly, the emissions increase also in almost each individual consumption sector, as Table 2 showing the three largest sectors of each category demonstrates.

Table 2 (from Paper V): The largest emission sources in each sector and the respective consumption volumes.

| Sector/Category | Helsinki DT | | Helsinki SU | | Finland | |
|---|---|---|---|---|---|---|
| **Housing** | 6.3 t $CO_2$e | 6,660 € | 5.5 t $CO_2$e | 5,630 € | 4.7 t $CO_2$e | 4,580 € |
| Heat | 2.3 t | 360 € | 2.0 t | 320 € | 1.5 t | 310 € |
| Construction | 1.4 t | 2,230 € | 1.3 t | 2,080 € | 1.2 t | 1,890 € |
| Electricity | 0.7 t | 220 € | 0.8 t | 250 € | 0.9 t | 330 € |
| *Other* | *1.9 t* | *3,890 €* | *1.4 t* | *2,950 €* | *1.1* | *2,070 €* |
| **Tangible Goods** | 3.9 t | 6,440 € | 3.0 t | 4,670 € | 2.8 t | 4,240 € |
| Food | 1.9 t | 2,120 € | 1.8 t | 1,870 € | 1.6 t | 1,810 € |
| Clothing | 1.1 t | 1330 € | 0.5 t | 660 € | 0.5 t | 550 € |
| Sports and leisure eqp. | 0.5 t | 300 € | 0.5 t | 270 € | 0.5 t | 290 € |
| *Other* | *0.4 t* | *2,690 €* | *0.2 t* | *1,870 €* | *0.2 t* | *1,590 €* |
| **Transport** | 1.6 t | 1,730 € | 1.7 t | 2,070 | 2.1 t | 2,170 € |
| Fuel combustion | 1.0 t | 380 € | 1.0 t | 390 € | 1.4 t | 550 € |
| Vehicles acquisition | 0.2 t | 570 € | 0.4 t | 920 € | 0.4 t | 1,070 € |
| Public transport | 0.3 t | 350 € | 0.2 t | 320 € | 0.1 t | 140 € |
| *Other* | *0.1 t* | *430 €* | *0.1 t* | *440 €* | *0.2 t* | *410 €* |
| **Services** | 1.6 t | 4,600 € | 1.2 t | 3,520 € | 0.9 t | 3,070 € |
| Hotels and restaurants | 0.7 t | 1,230 € | 0.5 t | 820 € | 0.3 t | 600 € |
| Recreation and culture | 0.5 t | 820 € | 0.3 t | 490 € | 0.2 t | 430 € |
| Health care | 0.2 t | 590 € | 0.2 t | 620 € | 0.2 t | 500 € |
| *Other* | *0.2 t* | *1,960 €* | *0.2 t* | *1,590 €* | *0.2 t* | *1,540 €* |
| **Air, Maritime and Package Travel** | 1.4 t | 740 € | 0.7 t | 380 € | 0.5 t | 280 € |
| Package holidays | 0.9 t | 490 € | 0.4 t | 210 € | 0.4 t | 210 € |
| Air and maritime overseas travel | 0.4 t | 220 € | 0.3 t | 150 € | 0.1 t | 60 € |
| *Other* | *0.1 t* | *30 €* | *0.0 t* | *20 €* | *0.0 t* | *10 €* |

# 5 Discussion and conclusions

This research was aimed to analyze the GHG emissions caused by the inhabitants in different types of urban structures, i.e. their carbon consumption. One key finding early on in the research was that the urban structure, especially population density and the dominant building type, has little impact on the carbon consumption of the inhabitants. This lead to the formation of an early version of the research problem, which then during the course of the research developed into the present form:

> **"What are the effects of urban structure and the related consumption patterns on the carbon emissions of an average consumer?"**

As shown in Section 4, all the five papers returned the same outcome: The carbon consumption is defined largely by the overall consumption and only to a very limited extent by the urban structure. Throughout the research the results indicated that the urban structure has a consistent direct impact only on the emissions from private driving, whereas the emissions from other consumption activities follow closely the overall consumption. Interestingly, even concerning the emissions of housing energy, the area or the building type seem to have little influence as such, the per capita emissions being very similar on average in all types of buildings and structures. While contradictory to some results reported earlier, as well as to the prevailing belief, the arguments are clear. As analyzed in detail in Paper IV, smaller than average household sizes, energy use of common spaces in apartment buildings, emissions derived from secondary homes, all of which are mostly associated with to higher income city residents, significantly narrow down the differences between housing related emissions of city and rural area residents. Furthermore, the share of the carbon consumption of the goods and services categories outside of housing energy and transport was found to be significant enough to create an increase in the consumption in these categories to result in emissions large enough to easily hinder the potentially positive effect of urban density.

The dissertation strongly supports the findings also indicated earlier [5, 8, 13, 35]. Cities may outsource such a high share of the emissions that the

GHG emissions may easily rise well above those of the rural and semi-urban areas. This is due to the tendency of production to be located outside of the cities, while the emissions are allocated to the city residents if assessed from the consumption perspective. The results of Sovacool and Brown (2010) as well as those of Lenzen et al. (2004) would seem to depict the same phenomenon. If the consumption volume is on a higher level in a city, the result might be carbon consumption exceeding the country average. In addition, both studies bring up the significance of the income level and suggest that the GHG emissions may relate much more to purchasing power than structural features [10, 35]. Overall, two main characteristics would seem to largely explain the contradiction between the results of the dissertation with some findings reported earlier [12, 15, 16]. First, the rather large share of emissions derived from consumption not related to the residence, which is often left outside the scopes of the assessments, is included in the dissertation. Second, the dissertation is placed in the context of actual lifestyles. It would seem that, as discussed in more detail in Paper IV, for example theoretic differences in energy consumption between different building types diminish when real consumption data is analyzed. In theory, increasing the living space per person naturally increases demand for heating and cooling (*ceteris paribus*), but it is by no means a new idea that the lifestyles and choices of the occupants may significantly change the outcome of the theoretic assessment [e.g. 38].

An interesting continuum indicated in Paper V, while not analyzed in detail, is that the same phenomenon of outsourcing the emissions seems to apply in a sub-city context as well. A higher consumption of services in the dense downtown area, especially in categories such as cafes, restaurants, hotels and movies, might decrease the emissions from, for example, housing electricity use and food consumption. In more limited scope emissions assessments, this might also create a bias in the results.

Including altogether a reasonably high number of studied areas, around 20, the reported findings seem robust. Even with the identified uncertainties, discussed in the papers, the overall arguments are strong. While IO-based LCA approaches in general are subject to potential biases, the identified increase in the consumption volume in monetary terms in almost each consumption category along with an increase in the income level strongly supports the leading argument.

This said, the studies also indicated ways to break the connection between the income level and emissions from consumption. First, a general pattern found was a decrease in the carbon intensity of consumption relative to the income level. It would seem that the share of the disposable income

consumed decreases as the income level increases. Similar, although much weaker, connection could also be identified with the carbon intensity of consumption. On higher overall consumption levels, a larger share of the consumption is targeted to goods and services with lower-than-average carbon intensity than on lower income levels. Second, the city of Porvoo, the case presented in Paper II, provides an example of the impact of low carbon local energy production on the carbon consumption of an average resident. The results of Paper II indicate that cleaner local energy could reverse the situation of a specific city compared to the country average even with the income level higher than the country average. As the cleaner local energy would also affect the carbon load of all the consumption allocated to goods and services produced with the same energy, the potential impact is significant.

The arguments of the dissertation, while intended to be proved robust throughout this work, should be understood in their specific context. Whereas detailed discussion about the validity and the reliability of the arguments is provided in the next sections, and on the uncertainties related to the method and the specific findings in the published papers, some general level limitations are provided here as well. First, the arguments should only be applied to the level of an average resident of the area in concern. The method employed should not be reckoned to be applicable to the level of an individual. With individual choices, a person is able to affect his/her carbon consumption so significantly that the presented argument on the connection between the overall consumption volume and the carbon consumption would not apply. Second, the context of the study is Finland, and country specific factors may lead to results contradictory to the situations in other geographical contexts, as is discussed in more detail in Section 5.1.

Furthermore, the place in which a certain individual resides does not define their carbon consumption in a way that could be predicted by the average. For example, the depicted higher carbon consumption in a certain area compared to the surrounding area does not indicate a decrease in the carbon consumption if a person moved from the higher carbon consumption area to the surrounding area. In a city versus rural or suburban area comparison this would most probably lead to a further increase in the carbon consumption, as the city lifestyle with the adapted consumption patterns would be likely to remain and the emissions from at least private driving would increase, unless the move would be accompanied with a decrease in the disposable income. Similarly, the, if a person were to move from a rural area to a city center, into a smaller apartment and close to divergent public transportation opportunities,

carbon consumption would likely decrease, assuming that the other consumption patterns would remain.

Finally, the dissertation also contributes to the methods of city and sub-city level LCAs. As was brought up, the area is of high importance, with cities being accountable for the majority of the global GHG load. Similar approaches can be employed in other contexts to produce a more comprehensive understanding of how carbon emissions are related to different types of cities and communities. If complementing the results with production-based assessments, the two together create a comprehensive basis for city level carbon management.

## 5.1 Validity of the research

There are two different dimensions in assessing the validity of the study. The concept of validity is divided into two perspectives: the internal validity and the external validity. In addition, concerning the dissertation, the validity assessment should cover both the research as a whole and the individual elements within the entirety. The validity assessment is conducted mirroring the guidelines of Ruane (2004) [29].

The internal validity refers to the results and conclusions involving causality assumptions [29]. The overall internal validity of the research arises from the selected method. The multiple case study method with such a high number of studied areas as assessed in the dissertation provides a high degree of internal validity [31]. Furthermore, obeying the case study method in setting no *a priori* hypotheses for the research and following the selective sampling principle as the research advanced supports the argument of high internal validity, as very distinct cases produced similar outcomes.

Notwithstanding, as discussed in detail in the individual papers, the measurement employed can only produce estimates, not exact information. From the accuracy perspective, the deviation of the results from their true values [e.g. 34], there are numerous factors (aggregation of the input data, asymmetries between the data and the LCA model, errors in the output vectors of the model, aggregation of the output industry sectors) that decrease the accuracy of the results. Keeping this in mind, the high validity argued above is not compromised, however. The results are still good estimates and, as the internal validity is good, the conclusions are robust.

On the level of the assessment methods, the concept of internal validity can be divided into two perspectives: the part of the independent variables, the causes for the outcomes, and the dependent variables, here the sectoral emissions factors. When the independent variables, here the input data, are concerned, the dissertation is assessed as being of high validity. On the aggregate level where the research is positioned, an increase in the amount

of each consumed good or service *ceteris paribus* increases the carbon emissions. The utilized numeric input data, describing the average consumption in different areas, describes the consumption volumes and changes in them relatively well as long as average consumers purchasing average goods are considered.

More assumptions relate to the dependent variables, i.e. the output of carbon emissions caused by the purchases of goods and services. The uncertainties have been analyzed in Papers I-V, but in general there may be occasions where an increase in the consumption volume does not indicate higher emissions. This type of bias would occur if a low-carbon good was more expensive than the market average. The increased consumption would incorrectly result in higher carbon consumption in an IO-based assessment. However, it is very unlikely that the overall results would be compromised due to this uncertainty, as only average consumers are considered in the dissertation. In addition, the multiple study approach reduces the risk of this type of bias in the sense of the impact potential of individual abnormal consumption behavior. The probability is low with large sample sizes and decreases also if multiple cases produce similar outcomes. Furthermore, in Finland in general, the regional price differences are small, except for the housing prices, for which a price correction factor was employed. Additionally, given the consistent results in all of the studies, the deviations from the average goods would need to be predominant, and lead consistently to either an increase or a decrease in the carbon consumption, in order to affect the results significantly. Finally, none of the samples represent extreme consumer types, where a possibility of deviations from average goods would be more likely.

Two inherent weaknesses of IO-based analyses, namely proportionality and homogeneity assumptions, describe the situation in general terms. An assumption that inputs to some sector of an economy would be linearly proportional to the output is referred to as the proportionality assumption, whereas the homogeneity assumption refers to the idea that price and sector outputs would have a consistently linear relation [e.g. 35].

The conclusions drawn from the results are also subject to potentially weak internal validity. They easily include causality assumptions that are not supported by the results [29]. The research refrains from presenting strict causalities, but aims instead to understand the phenomena. Despite this, many conclusions were narrowed down, focused better or argued through additional data during the review processes of the dissertation papers. In general, the context of all the studies is Finland, thus restricting the strongest and the most robust findings to Finland. Some estimations about the broader generalizability of the findings are presented in the

papers, but they also note the importance of sufficient similarity with the urban as well as socioeconomic structures. This level of generalization is strongly supported by the findings of Lenzen et al. (2004), who report increasing energy demands in the city center, and denote higher income levels as one of the primary reasons [36]. However, this also means that in some other context other factors may be dominating, as for example Crawford and Fuller (2011) and Fuller and Crawford (2011) demonstrate with regard to location, type and size of the residence in Australia [39, 40].

The generalizability also defines the external validity of the research. The power of the sample to represent a larger population or different populations is an important perspective of the external validity of the dissertation. In the Finnish context this sample generalizability is assessed as high. Again, the multiple case study approach, representing altogether a diverse body of Finnish consumers, makes this dimension of external validity within the Finnish context fairly good. In broader contexts the external validity inevitably decreases. However, there are different levels of external validity. It is less risky to state that a similar method and model could be used globally, as has been argued, than to claim that the results would be the same. This distinction has also been made in the papers of the dissertation.

## 5.2 Reliability

The reliability of the dissertation and the arguments arising from the results have been discussed in several occasions above. When specifically considering the consistency of the measures in producing the same outcome each time [29], the measures utilized are of very high reliability. A key characteristic of the method, constant emissions vectors of the output matrices, makes it very consistent, thus allowing the repeatability of the research relatively easily concerning the measurement perspective.

When also considering the input data, the picture gets slightly more complex. As has been discussed in the individual papers, the input data contains uncertainties that may affect the reliability of the research. Especially in Paper I of the dissertation, small sample sizes left room for errors arising from abnormal observations. However, as all of the cases later in the course of the research produced similar outcomes, the possibility of this kind of error related to the initial results was significantly reduced, as the multiple case study method suggests [31].

Notwithstanding, while the input data represent averages of the sample, they are probably not exact averages. If another sample of the same magnitude was taken, the figures would probably change. With sufficient sample sizes the variation would be small, but it would still exist. Given that the sample sizes are sufficient in the studies of this dissertation, as was

argued above, this kind of non-patterned error, called noise [29], does not compromise the results.

Another perspective to the reliability issue when the input data is considered is longitudinal reliability. Would the results change significantly if the input data was taken from another year? This perspective brings along new uncertainty issues related to currency fluctuations and inflation. In the early stage studies of the dissertation, this perspective of reliability was tested with a comparative longitudinal analysis of the same cases with input data from an earlier year. The results were very similar except for the magnitude, in which the difference was most likely due to the inflation and currency fluctuation issues mentioned. This was accepted as a sufficient test of the longitudinal reliability.

In a longer time span, longitudinal fluctuation is likely to occur due to changes in lifestyles. Moreover, production technologies will also change with time, which affects the carbon emissions. Thus, while the results seem robust from the reliability perspective, they are tied to the time of the measurement. Lifestyles as well as technologies change slowly in general, but in the context of the built environment, long time spans are often considered, calling for caution when the results are utilized in long-term planning.

## 5.3 Future research needs

The research path started in this dissertation is but in the beginning. The findings of the dissertation open a variety of directions to continue the work. Some steps have already been taken, while some still remain as mere ideas. The first early attempts have been made to merge the consumption-based GHG assessment model with a construction phase emissions assessment model to create a temporal LCA of a residential area. The idea is very interesting in its ability to demonstrate the effects of construction phase choices, but there are still plenty of difficulties especially with regard to the temporal perspective. On the other hand, a study trying to incorporate new environmental impact categories into the assessment model is underway.

Another direction, important but still in an initial stage, would be the testing of the results in international contexts. The generalizability of the results of the dissertation is so far restricted to the Finnish economy and, with some degree of uncertainty, to other societies with similar structures, as argued earlier. Comparative analyses would be very interesting and might produce important information from both academic and policy making perspectives.

# 6 References

[1] Lomborg, B. (2001): The Skeptical Environmentalist: Measuring the Real State of the World, The Cambridge University Press.
[2] Plimer, I. (2009): Heaven and Earth: Global Warming, the Missing Science, Taylor Trade Publishing.
[3] IPCC (2007): Climate Change 2007: Synthesis Report, An Assessment of the Intergovernmental Panel on Climate Change.
[4] European Commission (2009): The Sixth Environment Action Programme of the European Community 2002-2012. Available at: http://ec.europa.eu/dgs/clima/mission/index_en.htm [Accessed September 30, 2009].
[5] Ramaswami, A.; Hillman, T.; Janson, B.; Reiner, M.; Thomas G. (2008): A Demand-Centered, Hybrid Life-Cycle Methodology for City-Scale Greenhouse Gas Inventories, *Environmental Science & Technology*, 42 (17), 6455-6461.
[6] Wiedmann, T.; Lenzen, M.; Turner, K.; Barrett, J. (2007): Examining the global environmental impact of regional consumption activities -- Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade, *Ecological Economics*, 61 (1), 15-26.
[7] Kennedy, C.; Steinberger, J.; Gasson, B.; Hansen, Y.; Hillman, T.; Havránek, M.; Pataki, D.; Phdungsilp, A.; Ramaswami, A.; Villalba Mendez, G. (2009): Greenhouse gas emissions from global cities, *Environmental Science & Technology*, 43, 7297-7302.
[8] Schulz, N. B. (2010): Delving into the carbon footprints of Singapore—comparing direct and indirect greenhouse gas emissions of a small and open economic system, *Energy Policy*, 38, 4848–4855.
[9] Weber, C. L.; Matthews, H. S. (2008): Quantifying the global and distributional aspects of American household carbon footprint, *Ecological Economics*, 66 (2-3), 379-391.
[10] Sovacool, B. K.; Brown, M. A. (2010): Twelve metropolitan carbon footprints: A preliminary comparative global assessment, *Energy Policy*, 38 (9), 4856-4869.
[11] UN *(2007)*: City Planning Will Determine Pace of Global Warming, Un-Habitat Chief Tells Second Committee as She Links Urban Poverty with Climate Change, Available online: http://www.un.org/News/Press/docs/2007/gaef3190.doc.htm (accessed on 7 April 2011).

[12] Dodman, D. (2009): Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. *Environment and Urbanization*, 21, 185-201.
[13] Schulz, N. B. (2007): The Direct Material Inputs into Singapore's Development, *Journal of Industrial Ecology*, 11 (2), 117-131.
[14] CO2-report (2010): Greenhouse gas emissions in Finnish municipalities 2008-2009 (Kasvihuonekaasupäästöt kunnissa 2008-2009), Annual report.
[15] Glaeser E. L.; Kahn, M. E. (2010): The greenness of cities: Carbon dioxide emissions and urban development, *Journal of Urban Economics*, 67 (3), 404-418.
[16] Norman, J.; MacLean, H. L.; Kennedy, C. A. (2006): Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions, *Journal of Urban Planning & Development*, 132 (1) 10-21.
[17] Wagner G. (2010): Energy content of world trade, *Energy Policy*, 38, 7710–7721.
[18] Crawford, R. (2011): Life Cycle Assessment in the Built Environment, Spon Press London, UK.
[19] Suh, S.; Lenzen, M.; Treloar, G. J.; Hondo, H.; Horvath, A.; Huppes, G.; Jolliet, O.; Klann, U.; Krewitt, W.; Moriguchi, Y.; Munksgaard, J.; Norris, G. (2004): System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches, *Environmental Science & Technology*, 38 (3), 657-664.
[20] Hendrickson, C. T.; Lave, L. B.; Matthews, H. S. (2006): Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach. Resources for the Future Press.
[21] Carnegie Mellon University Green Design Institute (2008): Economic Input-Output Life Cycle Assessment (EIO-LCA), US 2002 Industry Benchmark model [Internet], Available: http://www.eiolca.net/. [Accessed: 01-Feb-2010].
[22] Nersund Larsen, H. (2011): Developing consumption-based greenhouse gas accounts: The carbon footprint of local public service provision in Norway, Doctoral theses at NTNU, 2011:58.
[23] Miller, R. E.; Blair, P. D. (1985): Input-output analysis: Foundations and extensions, Prentice-Hall (Englewood Cliffs, N.J.).
[24] Hewings, G. J.D. (1970): Regional Planning: Problems in the Application of Interregional Input-Output Analysis to State Planning and Program Activities, *Annals of Regional Science*, 4 (1), 114-122.
[25] Hewings, G. J.D.; Jensen, R. C. (1988): Emerging Challenges in Regional Input-Output Analysis, *Annals of Regional Science*, 22, Festschrift Issue, 43-53.
[26] Hendrickson, C. T.; Horvath, A.; Joshi, S.; Lave, L.; Economic Input-Output Models for Environmental Life-Cycle Assessment, *Environmental Science & Technology*, 32 (7), 184A-191A.
[27] World Resources Institute (2009): Greenhouse Gas Protocol Initiative: New Guidelines for Product and Supply Chain Accounting and Reporting, World Business Council for Sustainable Development: Geneva, Switzerland.

[28] Creswell, J. W. (2009): Research design: qualitative, quantitative, and mixed methods approaches, Sage Publications Ltd.
[29] Ruane, J. M. (2004): Essentials of research methods: a guide to social research, Wiley-Blackwell.
[30] Yin, R. (1994): Case study research. Design and methods, Sage Publications Ltd.
[31] Eisenhardt, K. M. (1989): Building Theories from Case Study Research, *Academy of Management Review*, 14 (4), 532-550.
[32] Eisenhardt, K. M.; Graebner, M. E. (2007): Theory Building from Cases: Opportunities and Challenges, *Academy of Management Journal*, 50 (1), 25-32.
[33] Statistics Finland: The Finnish Consumer Survey 2006, the data partly publicly available: http://www.stat.fi/. [Accessed: 01-Feb-2010].
[34] Rabinovich, S. G. (2009): Evaluating Measurement Accuracy: A Practical Approach, Springer.
[35] Treloar, G. J. (1997): Extracting embodied energy paths from input-output tables: Towards an input-output based hybrid energy analysis method, *Economic Systems Research*, *9*(4), 375.
[36] Lenzen, M.; Dey, C.; Foran, B. (2004): Energy requirements of Sydney households, *Ecological Economics*, 49, 375-399.
[37] Baynes, T.; Lenzen, M.; Steinberger, J., K.; Bai, X. (2011): Comparison of household consumption and regional production approaches to assess urban energy use and implications for policy, *Energy Policy*, 39, 7298–7309.
[38] Wright, A. (2008): What is the relationship between built form and energy use in dwellings?, *Energy Policy*, 36, 4544–4547.
[39] Crawford, R., H.; Fuller, R., J. (2011): Energy and greenhouse gas emissions implications of alternative housing types for Australia, *Proceedings of the State of Australian Cities National Conference 2011*, Melbourne.
[40] Fuller, R., J.; Crawford, R.,H. (2011): Impact of past and future residential housing development patterns on energy demand and related emissions, *Journal of Housing and the Built Environment*, 26(2): 165-83.

# 7 Papers I-V

Papers of the dissertation can be downloaded from the following sources:

Paper I: Heinonen, Jukka; Junnila, Seppo; Kuronen, Matti (2010): A Life Cycle Assessment of Carbon Mitigation Possibilities in Metropolitan Areas, SB10 Finland, Sustainable Community - BuildingSMART, Espoo, 22.-24.9.2010, Finnish Association of Civil Engineers RIL, Conference Proceedings.

-

Paper II: Heinonen, Jukka; Junnila, Seppo (2011): Case study on the carbon consumption of two metropolitan cities, International Journal of Life Cycle Assessment, 16, 569-579.

http://www.springerlink.com/content/hm140801g7347246/

Paper III: Heinonen, Jukka; Junnila, Seppo (2011): Implications of urban structure on carbon consumption in metropolitan areas, Environmental Research Letters, 6, 014018.

http://iopscience.iop.org/1748-9326/6/1/014018

Paper IV: Heinonen Jukka; Junnila Seppo (2011): Carbon Consumption Comparison of Rural and Urban Lifestyles, Sustainability, 3 (8), 1234-1249.

http://www.mdpi.com/2071-1050/3/8/1234

Paper V: Heinonen, Jukka; Kyrö, Riikka; Junnila, Seppo (2011): Dense downtown living more carbon intense due to higher consumption: a case study of Helsinki, Environmental Research Letters, 6, 034034.

http://iopscience.iop.org/1748-9326/6/3/034034

Urban areas hold a central position in the search for feasible climate change mitigation opportunities as a significant share of all the global greenhouse gas (GHG) emissions is closely related to urban structures. However, mitigation strategies are still evolving. One explanation is that the cities and urban areas in developed countries are demand and consumption centers where the majority of all consumed goods are imported from outside of the city boundaries. Thus, the traditional geographically restricted assessment methods cannot produce sufficient information for effective carbon management. The dissertation argues that in order to create city level carbon mitigation strategies, it is necessary to identify and understand the emissions caused by the consumers. The main argument of the dissertation is that the overall consumption volume seems to affect the carbon consumption so strongly that a higher consumption volume indicates higher carbon consumption regardless of the type of the urban structure.

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