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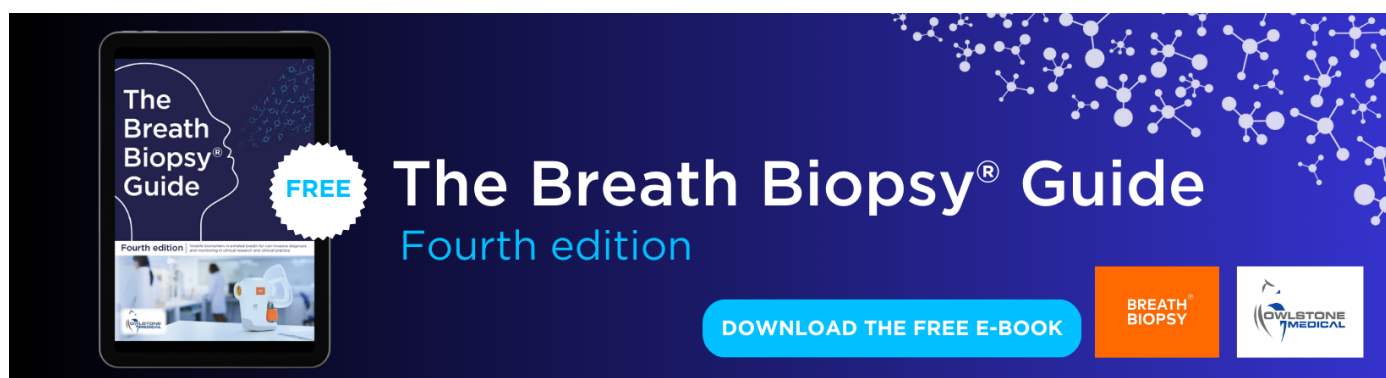
Dense downtown living more carbon intense due to higher consumption: a case study of Helsinki

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

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Abstract

Hindering urban sprawl is one of the main goals for contemporary urban planning. Urban density is considered crucial in climate change mitigation since it reduces automobile dependence and decreases unit sizes, for example. This letter analyzes the effect of density in a city context. In the study the Finnish capital Helsinki is divided into two areas of different urban densities: the high density downtown area and the more scarcely populated suburbs. The study is a continuation of a recently published study on the implications of urban structure on carbon emissions, and analyzes further the main finding of the first study—that higher urban density might have negligible or even reverse effect on the per capita carbon emissions. Similarly to the previous study, a consumption based tiered hybrid life cycle assessment (LCA) approach is employed in order to produce a comprehensive assessment, free of territorial boundaries and system cutoffs typical of traditional LCAs. Based on the findings of the previous study, it is hypothesized that when assessing city level carbon dioxide emissions from a wider, consumer oriented LCA perspective, increased urban density may not necessarily reduce carbon emissions. Surprisingly, the study finds that carbon dioxide equivalent (CO₂e) emissions are substantially higher in the dense downtown area than in the surrounding suburbs, which is suggested to imply that the increased consumption due to the higher standard of living increases emissions more than the higher density is able to reduce them. The results demonstrate that, while increasing urban density can be justified from a number of ecological, social and economic viewpoints, density is not necessarily a key parameter in the particular case of climate change. In cities like Helsinki, where wealth is concentrated in the downtown area, climate policies should give higher priority to the energy consumption of buildings, to alternative energy production and distribution modes, as well as to low carbon consumption within the city.

Keywords: life cycle assessment, LCA, urban density, D variables, climate change, consumption, carbon emissions

1. Introduction

Already half of the world's population resides in cities and the share continues to rise, making carbon dioxide (CO₂) emission cuts from urban areas a crucial element of climate

change mitigation. As much as 80% of global green house gas (GHG) emissions can already be allocated to cities [1]. Notwithstanding, people living in city centers are reported by a number of studies to lead a more sustainable life than those in less dense suburban and rural areas [2–4]. In addition, higher urban density has been claimed to be a direct indicator

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of higher sustainability [5]. Even though in heavily populated areas high population density is stipulated by practicalities, in more scarcely populated countries, such as Finland, promoting dense urban structure is a political choice often justified by ecological or social considerations.

Contemporary urban planning follows design principles that are often referred to as the ‘five Ds’, namely, density, diversity, design, distance to transit, and destination accessibility, e.g. [6–8]. These aspects are promoted in both national planning regulations as well as commercial sustainability rating tools, e.g. [7, 9] as an effective and integral part of climate change mitigation strategies. The five D variables are indeed known to affect the travel preferences of people. For instance, dense urban structure reduces vehicle miles traveled (VMT), which in turn reduces CO₂ and other air emissions [10–13]. At the same time, it is known that urban development patterns have a larger influence on daily commuting, while recreational transit is more dependent on the socioeconomic background of the consumer [6]. Moreover, transportation, even though a major source of greenhouse gas emissions, is only one emission source from a consumer perspective.

On a city scale, life cycle assessments (LCA) easily become very complex due to the size of the system studied and the consequent high number of variables. One significant difficulty is that production facilities and airports are often located outside of the city boundaries, while their emissions could be argued to be derived from the city inhabitants using the service. Cutoffs like this are bound to create bias in city level assessments and the impact of the city on the global GHG emissions may seem substantially different, if only emissions occurring within the city boundaries are taken into account. Recent studies by the authors addressing different geographic contexts [13–15] indicate that, when considering full life cycle effects from a consumer perspective, life in less dense and less affluent areas is in fact less CO₂ intensive due to lower overall consumption.

This study provides 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. The aim is to estimate the annual per capita carbon load on two different levels of urban density within a city context in Helsinki, the largest city and capital of Finland. The study also provides a continuum for a recently published letter of the implications of urban structure on carbon consumption in two Finnish metropolises and their surrounding areas [13]. Based on the findings of the previous study, it is hypothesized that density as a dominating factor in urban planning might not be sufficient for city level climate change mitigation, as other factors, i.e. higher consumption volume following higher income level, may be more significant and negate the CO₂ reductions. The Helsinki case presented in the letter demonstrates the situation in a city structure, where the downtown area attracts wealthier residents, and the carbon emissions grow substantially compared to the suburban areas. Furthermore, a consumption based hybrid LCA approach similar to the previous study, is exploited.

The remainder of the letter is structured as follows. The LCA model is introduced in section 2. Next, section 3

describes the data and special characteristics of the study. Main findings are then presented in section 4. The limitations of the study are outlined and analyzed in section 5. Finally, sections 6 and 7 discuss the findings further and conclude the letter.

2. LCA method

LCA may be conducted using one of three approaches, namely, input–output (IO) LCA, process LCA, or a hybrid of the two. The most traditional approach to LCAs is process based analysis, and it is also the most employed [16–18]. Process LCAs estimate environmental impacts based on energy and mass flows within processes. A comprehensive process based assessment requires extensive data and time and can therefore be very laborious to conduct [16, 17]. In fact, to be able to perform a process based LCA, the process under assessment, or system boundaries, need to be clearly defined [16]. As a result, the process based approach inevitably suffers from what is called a truncation error. The cutoffs resulting from system boundary selection may result in underestimating the environmental impacts [16].

IO LCA has a different approach, as it estimates environmental impacts through monetary transactions. IO models have been developed for different economies in an attempt to describe the interdependences between a industry sectors within the economy [18]. The most significant benefit of the IO LCA approach is its comprehensiveness, as no boundary selection is necessary and the truncation error described above can be avoided. A full inventory of environmental impacts attributable to a certain good is provided in the IO models [17], although the end of life stage should be added to achieve improved accuracy [16]. The input–output method is also quick and simple to use [17] and not as data intensive as the process LCA approach. However, typical problems associated with the input–output method comprise the aggregation of industry categories, temporal fluctuation in currency rates, differences in regional and between-industries inflation and regional differences in industry structures. Asymmetries within data and the models, and treating imports as domestic products create further inaccuracies [16–19].

Hybrid LCA approaches generally aim at embracing the positive features of both process LCAs (i.e., accurateness) and IO LCAs (such as, comprehensiveness) while minimizing the respective problematic aspects [16, 20–22]. Three different approaches can be distinguished in hybrid LCAs [16]. One possibility is to disaggregate output sectors by including process data and thus minimize aggregation and truncation errors. Another is a integrated hybrid analysis model which incorporates process level information into the input–output model. Finally, a tiered hybrid LCA addresses the higher order upstream phases with input–output models, but the most important upstream phases and direct impacts with process analysis.

This study employs a tiered hybrid LCA model. The model is primarily based on the output matrices of the Carnegie Mellon University Economic Input–Output Life Cycle Assessment (EIO-LCA) model [23], but assesses the

main emission sources with process data. The higher order upstream supply chain phases of the main emission sources are estimated with IO matrices, however, in order to avoid the truncation error and maintain full coverage of the model. The model is an enhanced version of the hybrid model utilized by Heinonen and Junnila [13, 14]. The enhancements in the model primarily relate to goods consumption, more precisely food, clothes and home furnishings, and aggregation of the consumption categories. The section 3 describes the model enhancements in detail.

3. Study design

The study estimates the carbon emissions of Helsinki divided into two regions: the dense downtown (Helsinki DT) and the more scarcely populated surrounding suburbs (Helsinki SU). Helsinki is the Finnish capital and largest city in the country with approximately 500 000 inhabitants. The population density of Helsinki is 3000 inhabitants m^{-2} ; however, the density varies greatly within the area. While the density in Helsinki city center rises to over 10 000 inhabitants km^{-2} , it is significantly below the 3000 average in the surrounding suburbs. The downtown residential building stock consists of apartment buildings, whereas in the suburbs close to a share of one fifth of the residential buildings are single-family homes or terraced houses [24].

The GHG emissions derived from consumption are assessed on an annual per capita basis for an average city center and suburban consumer, respectively. Thus, while there are substantial differences in the income levels between the residents of, especially, different suburbs, on average the downtown residents have substantially higher income. The study exploits a consumer responsibility approach, e.g. [25], and seeks to incorporate all carbon emissions associated with consumption using a consumption based life cycle approach free of territorial boundaries.

The primary input data used for the IO model is extracted from the Finnish consumer survey conducted in 2006 [26]. The survey comprises data on the consumption of nearly 10 000 consumers in Finland. Of the two samples, the Helsinki DT includes 208 consumers and Helsinki SU 529 consumers. The consumption data retained from the survey are very detailed and comprise approximately 1000 categories and subcategories of goods and services ('consumption categories'). To match the input data with the IO model used, the data was aggregated down to 59 consumption categories. After assessing the GHG emissions, identifying the major carbon sources, and replacing the IO data for major sources with process data the 59 categories were aggregated to five (5) consumption sectors to demonstrate the division of the emissions. The five sectors are considered to be suitable indicators of urban structure and standard of living with regard to carbon emissions. The five sectors, and what they each entail, are presented in table 1 and further described in the following subchapter.

The category 'housing' comprises emissions derived from construction, repair construction, water and waste water, waste and cleaning, household furnishings, as well as all energy associated with housing (space heating, hot water,

Table 1. Aggregated consumption sectors.

Consumption category	Included activities
Housing	Construction, maintenance and operations, energy and electricity use
Ground transport	Private driving, purchase and maintenance of private vehicles, public transportation
Tangible goods	Daily consumption, durable goods
Services	Private health, nursing, and training services, leisure services
Air, maritime and package travel	Flights, ferries, package holidays

and both communal and household electricity). 'Ground transport' incorporates all activities related to private driving, purchases and maintenance of private vehicles, and public transportation, which mainly consists of rail and coach travel. Daily consumption of goods, food and beverages, along with the consumption of durable goods, clothes, sports equipment, home electronics etc are combined under the category 'tangible goods'. The 'services' category mostly comprises inputs for leisure services such as hotels, restaurants, beauty services and communication services. The input data on health, nursing and training services were also included in this category, but only include private services, which in Finland represent a minor share within these sectors due to the large public supply of said services. Finally, all private airline and maritime travel, as well as package holidays are separated into an own category due to their distinct nature.

The earlier assessments [13, 14] had identified two sectors as responsible for two thirds of the carbon consumption, namely, housing and ground transport. Even with some significant model enhancements, these two sectors remain the ones updated with process data. While the rest of the sectors, namely, tangible goods, services and air, maritime and package travel, together formed a significant one third share of the total emissions in the IO LCA and produced some interesting findings, no process data enhancement was seen necessary.

The first measure taken to enhance the housing category was a regional price level correction of property prices based on the regional statistics of The Housing Finance and Development Centre of Finland (ARA) [27], which was done to retrieve the actual emissions derived from construction regardless of property prices driven by market factors. Second, the first tier, or production phase, emissions from housing energy consumption were replaced with relevant process data. The process phase emissions were calculated using the energy method with the production data of the local energy company Helsinki Energy [28], 284 g kWh^{-1} for electricity, 286 g kWh^{-1} for fossil fuel based district heating. In addition, for heating oil combustion a national average of 267 g kWh^{-1} was utilized [29]. Third, using the statistics published from the Helsinki Metropolitan Area [30], communal building energy costs of apartment buildings, usually paid within rent or housing management charges, was re-allocated to the energy consumption category. Furthermore, other operation and

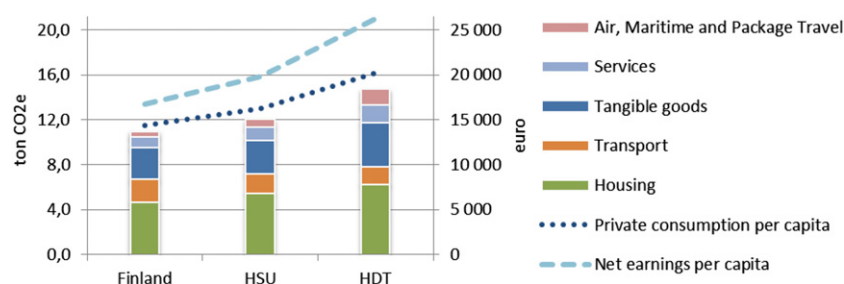


Figure 1. Annual net earnings, private consumption and carbon load (ton CO₂e) per capita in Finland, Helsinki SU and Helsinki DT respectively.

maintenance costs from housing companies (such as, water, waste, cleaning, maintenance and repair construction), were re-allocated under appropriate consumption categories according to the same statistics [28].

For the ground transport category, the emissions related to the fuel combustion of private driving were assessed by using the actual amount of fuel purchased by the consumers and the carbon emissions multiplier 2.35 kg l⁻¹ for the combustion of gasoline and 2.66 kg l⁻¹ for the combustion of diesel oil [31]. The emissions from the higher order tiers were taken from the EIO-LCA utilizing the producer price share of the fuel purchases. Additionally, emissions derived from public transport were re-calculated using the Finnish ENVIMAT [32] matrices for rail, coach and taxi transport instead of the US based EIO-LCA matrix for more accurate results as the sectors differ heavily between the two economies.

In addition to the process data and Finnish IO data enhancements, the model was updated from the study forming the background of this letter [13] with regard to purchases of food, clothing and home furnishings by disaggregation of the input categories. The 43 consumption categories of the previous version of the model were disaggregated to 59 categories with emphasis on more detailed modeling of food and home furnishings. Especially the more careful assessment of food consumption related categories was conducted, which actually ended in an increase of the overall carbon consumption figures of an average Finnish consumer compared to the earlier study [13]. This is presented in more detail in section 4.

4. Results

The set hypothesis on higher urban density signifying higher carbon emissions in the context of a relatively affluent city like Helsinki held. Surprisingly, the results show that the surrounding Helsinki SU areas with substantially lower density produce clearly less CO₂e emissions per capita than the dense Helsinki DT area on per capita level. The LCA gives an annual carbon load of 14.7 ton CO₂e per capita in Helsinki DT with nearly 10 000 inhabitants km⁻² compared to 12.0 ton CO₂e in the Helsinki SU with less than 3000 inhabitants km⁻². As a reference, the average per capita carbon load in the country was assessed at 11.0 ton CO₂e by updating the result of assessed in Heinonen and Junnila (10.2 ton CO₂e) [13] with the current version of the model.

The differences in the carbon consumption between the two areas are, according to the model used, mainly due to the higher standard of living and the consequent higher consumption in the downtown area. In Helsinki DT, the average annual net earnings are 26.300€ per capita [26] while in the Helsinki SU the respective figure is 19.800€. For comparison, the Finnish average net earnings amount to 16.800€. Some of the difference, however, cannot be explained by simply the higher earnings, as it appears that also the distribution of the consumption is different between the different areas. Also, when income levels rise, the share of the income spent decreases, which evens out the differences in consumption. Figure 1 presents the annual net earnings, private consumption and carbon load (ton CO₂e) per capita in Finland, in downtown Helsinki and in the suburbs respectively.

The figure 1 shows that the structure of the carbon load for both area types is fairly similar, but contains some interesting variations. Generally, the load grows fairly closely with the consumption volume which, as stated before, is highest in Helsinki DT.

Of the five categories, housing and ground transport, the two categories closely related to the urban structure (enhanced with detailed process data for improved accuracy) dominate the total carbon consumption with a share of 60–75% in all area types. The share is higher in the lower income areas, likely indicating the ‘necessary goods’ character of these two categories. However, surprisingly the absolute amount of emissions, 5.4 ton CO₂e per capita, from the housing category are lower in Helsinki SU and higher, 6.2 ton CO₂e per capita, in Helsinki DT. This result is due to the consumption volume being slightly higher in Helsinki DT in almost each of the 22 categories comprised as housing, including all maintenance expenses, home appliances and home decoration in addition to the categories shown in the table 2.

An anticipated pattern visible from the results is the reverse pattern between urban density and emissions from transport. However, interestingly the difference is very small between Helsinki DT and Helsinki SU, the only deviating factor being found from the car purchases (table 2). Taking into account all emissions derived from private driving, car manufacture, deliveries and maintenance, as well as all public transport, the carbon emissions comprise 1.6 ton CO₂e in Helsinki DT and 1.7 ton CO₂e in Helsinki SU, but as much as 2.1 CO₂e in Finland on average. The result is mostly due to the increase in private driving in the less dense areas

Table 2. The largest emissions sources in each sector and the respective consumption volumes.

Sector/category	Helsinki DT		Helsinki SU		Finland	
Housing	6.3 t CO ₂ e	6660€	5.5 t CO ₂ e	5630€	4.7 t CO ₂ e	4580€
Heat	2.3 t	360€	2.0 t	320€	1.5 t	310€
Construction	1.4 t	2230€	1.3 t	2080€	1.2 t	1890€
Electricity	0.7 t	220€	0.8 t	250€	0.9 t	330€
Other	1.9 t	3890€	1.4 t	2950€	1.1	2070€
Tangible goods	3.9 t	6440€	3.0 t	4670€	2.8 t	4240€
Food	1.9 t	2120€	1.8 t	1870€	1.6 t	1810€
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	2690€	0.2 t	1870€	0.2 t	1590 €
Transport	1.6 t	1730€	1.7 t	2070	2.1 t	2170€
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	1070€
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	4600€	1.2 t	3520€	0.9 t	3070€
Hotels and restaurants	0.7 t	1230€	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	1960€	0.2 t	1590€	0.2 t	1540€
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€

compared to the denser capital city with better public transport, and it is in accordance with several earlier Finnish studies, e.g. [12–14, 33]. Within the city of Helsinki it would seem that the public transport system retains the same efficiency through the suburban areas, which affects both the private driving and the use of public transport options. According to the survey of the Helsinki Region Transport (HSL), the increase in private driving within the Helsinki Region context from Helsinki DT to Helsinki SU is around 25% between the areas [34]. However, the wealthier downtown residents possess more leisure cabins [26] which increase longer distance private driving and seem to even out the carbon emissions related to transport.

Carbon load from the remaining three categories, tangible goods, services and air, maritime and package travel follow the income levels and consumption volume straightforwardly accounting for 4.8 ton CO₂e in Helsinki SU and, 6.9 ton in Helsinki DT, the Finnish average being 4.3 ton. All the three categories show clearly the connection between income and consumption. The purchases of tangible goods in Helsinki DT lead to carbon emissions of 3.9 ton, 3.0 ton in Helsinki SU and 2.8 in Finland on average with average expenditures of 6400€, 4700€ and 4200€ respectively. Interestingly, food consumption varies little between the areas, a Helsinki DT resident causing 1.9 ton CO₂e emissions, only slightly more than the 1.8 ton of a Helsinki SU resident as well as an average Finn. Clearer difference is found from clothes consumption, where the 1.0 ton emissions attributable to the consumption of an average downtown resident are more than double compared to average suburb and Finnish consumers.

A similar pattern can be found in the Services sector. The carbon emissions of a Helsinki DT resident are 1.6 ton CO₂e with the consumption volume of 4600€, and 1.2 ton CO₂e in Helsinki SU with 3500€ worth of purchases. In the

whole of Finland the average per capita emissions are 0.9 ton with 3100€ purchases. The dominant categories within the services sector are hotels and restaurants together with cultural services that account for 60%–70% of the total services related emissions.

Finally, the sector comprising emissions from flights, maritime travel and holiday accommodation abroad, while being the smallest sector overall, continues the same pattern. Dominated by package holidays, the sector shows 1.4 ton CO₂e emissions for a downtown resident, double that of a suburbia consumer, and almost triple compared to the Finnish average. Table 2 shows the largest carbon contributors of each sector and their shares together with the respective monetary consumption figures. The carbon sources shown in the table, such as food, may contain several consumption sectors.

Finally, we analyzed the carbon intensities of consumption in the sample areas and compared them to the Finnish average. Two different intensities were calculated: carbon emissions per euro consumed and carbon emissions per euro income. Interestingly, the differences are very small in the carbon emissions per euro consumed category meaning that despite the difference in the consumption volume the structure of the consumption is not very different between the areas. These intensities are 0.73 kg CO₂e/€ in Helsinki DT, 0.74 kg in Helsinki SU and 0.77 kg in Finland on average. For the second category the differences are larger, as the rate of savings is different on different income levels. Now the Helsinki DT resident stands out with an intensity of 0.56 kg CO₂e/€ compared to 0.61 kg in the Helsinki SU and 0.66 kg in Finland.

5. Study limitations

The input data used in the study comprise the purchaser price data from the 2006 Finnish Consumer survey [26]. The level

of detail in the data is very high and the data is sufficiently disaggregated with close to 1000 categories and subcategories of goods and services. Furthermore, the sample size is considered representative, as it includes approximately 10 000 subjects (0.2% of the Finnish population) which makes data reliability high on aggregate level. However the sample sizes of Helsinki DT and Helsinki SU, 208 and 529 respectively, decrease the reliability of the data concerning infrequent purchases. The potential bias was assessed relatively minor, though, as each of the 59 combined consumption categories include rather large number of categories of the survey data, which decreases the effect of possible abnormal purchases of individual participants of the survey.

Nevertheless, some more significant sources of bias are associated with this study. All IO LCA models are subject to a few inherent problems discussed earlier in section 2. Of these, the mentioned potential inaccuracy arising from data aggregation was assessed relatively low in this study due to the enhancement of the most significant consumption categories with process data. In addition, the EIO-LCA model selected as the basis of the hybrid model, is the most disaggregated model available. Lenzen *et al* argue that the level of disaggregation has significant impact on the results and thus the most disaggregated model should be employed [35].

The input data entails one clear bias: the Finnish economic structure is characterized by free and heavily subsidized services, which represent a notable portion of the total private consumption. No corrective action was taken, as it is confirmed by the Finnish ENVIMAT study, that this creates bias mainly in the category 'health, nursing and training services' [32] which was not considered to have a significant role in this study. Another potential source of bias stems from the chosen IO model, which is based on a foreign economy, namely the US. The suitability of the model to the Finnish economy has previously been with tested by Heinonen and Junnila [13, 14] and also earlier Junnila [17], and the results were comparable. As a measure to address the issue of temporal and currency rate differences between the US model and Finnish data, purchasing power parity (PPP) [36] was applied to the prices, an adjustment which has recently been utilized by Weber and Matthews in a study on US household carbon footprints [37].

While the PPP multiplier should in theory eliminate the problems related to price level and currency rate differences between two economies, it cannot tackle the price level differences within one economy. Even within one quite compact region, such as the object of this study, some price level differences exist between the downtown area and the suburbs. In particular, this applies to the property prices that tend to grow when approaching the city center. This study utilized a correction factor for property price level in the Helsinki region [27], but the statistics do not include sub-city data. However, the share of property related emissions is insignificant compared to the overall difference in the carbon consumption between the two areas. Also, the small difference in the property related emissions, 0.1 ton, would indicate that there is no significant bias in the model concerning property prices.

The process data utilized, production phase emissions of the local power producer and the fuel combustion emissions of private driving, on their part, are subject to some inherent data reliability problems of process LCAs. Annual variations in the power plant emissions might potentially be significant, but as the fossil fuels based fuel mix is rather constant, the variation has been low during the last decade [38]. The fuel combustion emissions of private driving slowly decrease as the car stock is renewed, but no sudden fluctuations occur.

Finally, one notable weakness of IO models such as the one employed here is that they are temporally static and thus unable to take into account changes occurring over time, which could have an effect on the allocation of the emissions, such as improvements in emission mitigation technology and cleaner production. Moreover, as greenhouse gases slowly decay in the atmosphere it is not irrelevant when the emissions are released. Construction activities for instance create a high amount of CO₂e emissions over a short period of time. The effect of these 'carbon spikes' cannot be evaluated with the employed model. This deficiency of the model, however, does not affect spatial analysis of the present or past situation of this study, but needs to be kept in mind when long-term policy implications are considered.

6. Discussion

The purpose of this study was to estimate the annual per capita carbon load of city residents from two different levels of urban density within one city: downtown and the suburbs. The study was conducted using a consumption based hybrid LCA approach. Consumption based LCA studies are essential when attempting to assess city level per capita carbon emissions, as they go beyond the traditional territorial assessments. The traditional approaches may underestimate the per capita emissions dramatically, as the impact of production facilities located outside of city centers, where the most consumers of the produced items reside, are ignored, as well as the effect of imports and exports, which may be significant [25].

Not in line with contemporary urban design principles, the study found the carbon load from the dense downtown to be much higher per capita than that from the suburbs. This is mostly due to the higher income levels in the high density city center. The LCA gives an annual carbon load of 14.7 ton CO₂e per capita in Helsinki DT compared to 12.0 ton CO₂e in the Helsinki SU. Respectively, the average annual net earnings in Helsinki DT are 26 300€ per capita and 19 800€ in Helsinki SU, and the annual consumption volume 20 200€ in Helsinki DT and 16 300€ in Helsinki SU [16]. In comparison, the Finnish average carbon consumption is 11.0 ton with an annual income of 16 800€ and consumption of 14 300€.

Another notable finding, in accordance with earlier studies, is that the sector comprising consumption related to Housing covers over 40% of all emissions. Housing's dominant role in all area types indicates that the level of density does not make a major difference on the carbon load from housing related activities. Reducing the carbon load from housing should therefore be the main concern of policymakers.

Interestingly, only in the ground transport sector a connection between denser area type and lesser carbon load could be identified. In all the four other sectors the emissions are higher in Helsinki DT than in Helsinki SU and in Finland on average. In fact, as the table 2 demonstrated, the emissions are higher in almost all the main categories in Helsinki DT compared to the other two reference consumers. With regard to the overall emissions, although CO₂e emissions from ground transport are slightly lower in the downtown area, and lower in Helsinki compared to Finland on average, the difference is not enough to cancel out the higher carbon load from other activities, as the share of the sector on the total carbon emissions is too small. Furthermore, within the Helsinki city the differences relate almost entirely to the volume of vehicle purchases (see table 2), but the public transport services seem equally effective for the suburban residents as for the downtowners.

Finally, the carbon intensities were calculated for per euro consumption and for per euro income. Interestingly, there were no notable differences in the intensities of the emissions from consumption. The per euro emissions compared to the income levels were more favorable to the Helsinki DT residents, indicating that a large share of all consumption is necessary consumption and thus the rate of savings tend to grow as the income level grows.

If the factors behind the somewhat unconventional result of the study are analyzed further, a couple of additional reasons can be brought up. First, the functional unit of an average consumer favors Helsinki SU residents as the family size is 1.93 compared to 1.64 in Helsinki DT [26]. This relates especially to the housing related emissions that tend to increase on a per capita level when the household size decreases. In addition, the detailed modeling of the communal building energy related to common spaces in apartment buildings further benefits the suburbia [15], not only due to the household size but also due to the building stock. These even out the overall per capita energy consumption of residents of different housing types. Further analysis can be found from Heinonen and Junnila [39]. Furthermore, the building stock is older in the downtown area and the use of space is less efficient. There are more common spaces per capita and the apartment volume (m³) is higher increasing the need for heating in Helsinki DT compared to Helsinki SU.

The position of the paper is set by earlier studies contributing to the same topic. While the paper is primarily a continuum of a recently published study on the implications of urban structure on carbon consumption in two Finnish metropolises and their surrounding areas [13], a couple of earlier studies have set the ground for these two studies. Consumption oriented city level carbon assessments have previously been conducted by e.g. Ramaswami *et al* [40], who emphasized the need to include carbon emissions beyond city boundaries into the assessments. The results of Ramaswami *et al* [36] show that inclusion of emissions over spatial borders into the city-scale assessments may change the assessment results significantly. Schulz [41] suggests a similar city level approach to material inputs reporting that a vast majority of all the material use of Singapore is imported, signifying also

the same with the carbon emissions of the city residents. Glaeser and Kahn published quite recently a paper on the differences in carbon emissions between city centers and suburban areas [3] reporting lower emissions from the city center compared to the suburbia. The geographical contexts as well as the calculation methods differ from those of this study, but it is nonetheless interesting that the findings are so reverse. The main explanation seems to be the inclusion of all consumption into the assessment in this study, as the consumption and thus the emissions are higher in virtually all the consumption categories in Helsinki DT (see table 2), but it would be interesting to further analyze the factors behind the reverse result. Similarly to Glaeser and Kahn, Parshall *et al* found a connection between increased areal density and reduced carbon emissions [42]. However, their comparison focused on urban and rural areas rather than on inter-city situations. In addition, the reported differences vary substantially, and are small on the overall level. Again the study excludes the consumption of goods and services, which may easily result in converse findings. In fact, according to the case presented in this letter the effect of this share on the overall carbon consumption is such high that even in conditions where the density has higher mitigating impact on the emissions of private driving and housing energy, it is not clear if the overall emissions would still not yet decrease enough if other conditions are as in the Helsinki case.

7. Conclusions

The grounds for this study were set by Heinonen and Junnila in a recent study that showed only weak or nonexistent relation between population density and carbon emissions [13]. The sub-city setting of this continuum paper allowed us a more explicit analysis of the effect of density. Based on the results, 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 lower standard of living. It is considered very likely that similar results would be obtained elsewhere too as long as the same condition, the dense downtown attracting wealthier residents, is met. However, there are city structures where high income areas are situated outside the downtown area. When examining the situation in the wider Helsinki Metropolitan Area, for example, the highest average income and the highest carbon consumption are found from the relatively low density city of Espoo, 14.4 ton CO₂e per capita, roughly the same as in Helsinki DT [13].

The bottom line, however, is that all consumption causes adverse effects to the environment. Thus, dense and diverse urban structure can be justified from a number of other ecological and social considerations such as exploiting readily available infrastructure, protection of wetlands or other natural habitats, or restoring greenfields for recreational use. Higher density and access to alternative transportation may also promote healthier lifestyles.

Either way, implementing the 'D' variables in urban design will not be sufficient if the primary goal is to mitigate

climate change. Focus should be on energy consumption of buildings, on energy production and distribution modes, as well as consumption patterns. City level carbon management could for instance include requirements for greener energy modes (decentralized on-site production, renewable sources), the energy efficiency of buildings and policies for improving the competitiveness of low carbon products and services. For these efforts, the assessment model utilized in this study could be of high value.

The future research should include studies that compare the carbon consumption of inhabitants in different area types as well as in different housing types, but with equal income levels. Furthermore, the applicability of the results in should be analyzed by conducting similar studies in different country contexts.

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