Implications of urban structure on carbon consumption in metropolitan areas

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Abstract
Urban structure influences directly or indirectly the majority of all green house gas (GHG) emissions in cities. The prevailing belief is that dense metropolitan areas produce less carbon emissions on a per capita basis than less dense surrounding rural areas. Consequently, density targets have a major role in low-carbon urban developments. However, based on the results of this study, the connection seems unclear or even nonexistent when comprehensive evaluation is made. In this letter, we propose a hybrid life cycle assessment (LCA) method for calculating the consumption-based carbon footprints in metropolitan areas, i.e. carbon consumption, with the emphasis on urban structures. The method is input–output-based hybrid LCA, which operates with the existing data from the region. The study is conducted by performing an analysis of the carbon consumption in two metropolitan areas in Finland, including 11 cities. Both areas consist of a dense city core and a less dense surrounding suburban area. The paper will illustrate that the influence of urban density on carbon emissions is insignificant in the selected metropolitan areas. In addition, the utilized consumption-based method links the climate effects of city-level development to the global production of emissions.

Keywords: urban planning, life cycle assessment, carbon, climate change, urban structure

1. Introduction
The majority of all green house gas (GHG) emissions are directly or indirectly influenced by the urban structure. According to several studies, buildings account for 30–40% of global GHG emissions [1, 2]. The share of transportation is 13% globally and one fifth in the EU [3, 4]. Cities as a whole have been estimated to produce up to 80% of global GHG emissions [5]. Thus, decisions on the structure, including the building types, density, location and public transport, delineate the long-term frames for the GHG emissions of a community. The effect is also exceptionally long-lasting and comprehensive, raising the importance of understanding the connections between the urban structure and GHG emissions.

From the urban development perspective, the current practice of assessing the emissions from some specific subsectors, such as buildings or transportation, does not seem sufficient. It could be argued that all GHG emissions related to living and to consumer behavior should be included as part of the design of urban metabolism. Some early studies have indicated that the consumption-based carbon footprint, carbon consumption, can be used in urban studies to capture all GHG emissions related to living and consumption, and that a major share of these emissions can be influenced by urban development [17, 33, 37].

It has been demonstrated in numerous studies that a significant share of all GHGs attributable to a certain product or a service is actually produced at the second or third tier of the supply chain [14]. Thus, life cycle assessment (LCA) has been widely accepted as the suitable method for studying holistically the GHGs of a product or a service [7]. However, when complex systems are concerned, comprehensive LCAs tend to be very laborious to conduct [8]. This problem is eminent especially when urban structures are concerned, for the number of variables is always extremely high.
Also, while city or regional level LCA studies exist, the vast majority of them are conducted from a producer perspective, meaning that they allocate for a certain region the emissions originating inside the borders of the region [9, 34, 35]. This, while being an important perspective, could lead to biased conclusions. For example, in production-oriented inquiries, the outsourcing of heavy industry improves the carbon performance of the region [6, 9], while having zero net effect on the global emissions. And, even without this existing problem, consumption-based assessments can produce highly relevant new information to complement production-based studies.

In this letter, we propose a hybrid LCA method for calculating the consumption-based carbon footprints of the metropolitan consumers, i.e. carbon consumption, with the emphasis on urban structures. The method provides a basis for efficient metropolitan area carbon management. The method is input–output-based hybrid LCA, which is efficient and can operate with the existing data from the region, qualities that rarely relate to system-level LCA approaches.

Further, we present the results of comprehensive carbon consumption assessments of two metropolitan areas in Finland, including 11 cities. With the assessments, we demonstrate the effects of density, dominant building type, private driving and income on the carbon consumption. The letter will illustrate that the carbon influences of urban density and dominant building type are insignificant in the selected metropolitan areas due to the divergent influences of the emissions in urban structure and in service-related consumption classes.

We consider this kind of approach highly relevant for urban development. While cities set targets for ambitious cuts in GHG emissions [10–13], more precise information is needed to target the actions effectively. Simultaneously, while the approach of allocating emissions on a city or regional level is important for management and policy purposes, it is as important to understand the climate effects of city-level decisions at the global level, a perspective inherent in the method proposed here.

2. Method

The study presented in this letter was conducted with a LCA method. In life cycle assessments, three different approaches exist: input–output LCA, process LCA and hybrid LCA. Process LCA is the most common way of conducting an LCA [14–16]. In process LCAs, the emissions are assessed based on the energy and mass flows in the main production and supply chain processes. The second approach, input–output LCA, is a method where the emissions are calculated based on monetary transactions. The approach uses monetary sectoral transaction tables according to sectors to describe the interdependencies between industries in an economy [16]. As the transaction tables are based on national accounts, the assessments always provide a full inventory of the emissions attributable to the studied object with no boundary cutoffs [15], except of the end of life stage, which should be added to the calculations [14].

Hybrid LCA models have emerged both to allow life cycle assessments with lacking information, and to create models that combine the strengths of the two presented approaches. There are three different categories in hybrid LCAs. First, in tiered hybrid LCAs, higher-order upstream phases are covered with an input–output analysis, whereas direct emissions and the most important upstream phases are examined with a process analysis. Second, in an input–output-based hybrid analysis, the output sectors are disaggregated to include process data and to avoid aggregation and truncation problems. The third category is the integrated hybrid analysis model that incorporates process-level information into the input–output model [14].

The model we utilized is an input–output-based application of a tiered hybrid LCA that combines the comprehensiveness of the input–output approach with the accuracy of the process approach [14]. We chose the Carnegie Mellon University Green Design Institute’s Economic Input–Output Life Cycle Assessment US 2002 Industry Benchmark model (EIO-LCA) [18] as the basis of our hybrid model after the initial input–output assessments with the Finnish ENVIMAT model [22] and the EIO-LCA. The model provides output tables for 428 industry sectors, and is thus the most disaggregated model available. This was considered critical, as the input data utilized in the study are highly complex. The model was evaluated as a suitable basis for the hybrid model, as the Finnish economy is a small and open economy with over 50% of the value of total consumption oriented to import goods [19].

The hybrid model is constructed so that key sub-sector data from the output matrices are substituted with process data, but the rest of each matrix is left untouched to maintain the full coverage of the model. The selected method allows us both to radically decrease the inherent truncation error of process LCAs and increase the accuracy of the model compared to direct input–output models. Also, especially as we study the Finnish economy with a model based on the US industry, the hybrid approach enables the inclusion of economy- and region-specific data for the life cycle phases occurring in the region. To solve the temporal asymmetry problem arising from inflation and currency rate differences between US and Finnish economies, we adjusted the output tables with the purchasing power parity (PPP) multiplier [20]. Finally, the emissions tables of the model exclude the use of end of life phases. Here, as we used consumption data including all private expenditure, these phases are also automatically included, as the prices of goods on an aggregate level mostly include the excluded phases and thus create emission profiles for them too. The input data and construction of the hybrid model are described in detail in section 3. The discussion on the strengths and weaknesses of the method can be found in section 5 at the end of the paper.

3. Research design

3.1. Metropolitan areas analyzed

The study consists of carbon consumption modeling and an analysis of the two largest metropolitan areas in Finland. Of
these, the Helsinki metropolitan area consists of Helsinki, the capital, and the two large cities of Espoo and Vantaa surrounding Helsinki. The other metropolitan area studied is the important inland city Tampere, together with the seven surrounding semi-urban cities. The seven cities around Tampere were divided into two groups, rural cities (later in the paper called RCT, rural cities surrounding Tampere) and urban cities (UCT, urban cities surrounding Tampere), according to their structure. This division was essential for maintaining sufficient sample sizes.

The areas studied include the denser center cities, with apartment buildings dominating the housing and diverse public transport, as well as the surrounding cities with a lower density, a high share of detached houses, and weaker public transport. In addition, Helsinki and Tampere represent metropolitan areas on which the surrounding cities rely in terms of workplaces and services. And, as the climate conditions between the cities are similar, no climate adjustments on the results are needed. Table 1 represents some important descriptive figures for the two metropolitan areas.

### Table 1. Key figures for the Helsinki and Tampere metropolitan areas.

| Cities                  | Helsinki metropolitan area | Tampere metropolitan area |
|-------------------------|----------------------------|----------------------------|
|                         | Population                 | 565 000                    | 206 000                    |
|                         | Pop. density (in.          | 3010                       | 344                        |
|                         | residents km⁻²)            |                            |                            |
|                         | Apartment buildings        | 86                         | 72                         |
|                         | of housing stock (%)       | 57                         | 22                         |
|                         | Living space (m²/inhabitant)| 34.0                       | 36.4                       |
|                         | Average household size     | 1.8                        | 2.0                        |
| Employment structure    | Industry (%)               | 9                          | 19                         |
|                         | Commerce and services (%)  | 77                         | 68                         |
|                         | Others (%)                 | 14                         | 13                         |
| Climate                 | Average temperature (°C)   | 4.8                        | 4.0                        |
|                         | Monthly high/low (°C)      | 22.0/−9.0                  | 22.0/−11.0                 |
|                         | Rainfall/year (mm)         | 688                        | 573                        |

The study proceeded in two calculation phases. First, the carbon consumption of the study areas was calculated by using the direct input–output model. Second, this calculation was used for the design of the tiered hybrid LCA model, in which the most important processes producing carbon emissions were enhanced with the process data, based on the input–output model.

### 3.3. Tiered hybrid LCA model

Before the first calculation, the consumption sectors in the input data were aggregated from the original close to 1000 categories to 43 consumption classes that match best the purpose of the study, as well as the industry sectors available in the input–output model. The first carbon consumption assessment was done utilizing two competitive models, the Carnegie Mellon EIO-LCA [18] and the corresponding Finnish model ENVIMAT [22]. As the results of the two assessments were similar, we chose the Carnegie Mellon EIO-LCA as the basis of our hybrid model. The model provides output tables for 428 industry sectors, and is thus the most disaggregated model available, reducing the aggregation error inherent in input–output approaches. This was considered critical, as the input data utilized in the study are highly complex. Also, the Finnish economy is a small and open economy with over 50% of the value of total consumption oriented to import goods [19], which further justifies the selection of the model, as the bias from the assumption of domestic production of import goods in all IO-LCAs would potentially be significant.

In the first assessment, three emission sources were found to cover roughly two thirds of the carbon consumption. These process data were added to the LCA model as primary output data. The process data included power plant-specific emissions of heat and electricity production, average Finnish fuel combustion emissions from private transport and public transport, and the disaggregation of the public transport sector according to the local profiles of public transport use.
sectors were emissions related to housing energy use (heat and electricity), building construction- and operation-related emissions, and transport-related emissions. Following the results of this assessment, these key sectors were enhanced with local data.

Now, in the tiered hybrid LCA model built in the study, the first tier emissions of the key sectors were replaced with process data. For energy, electricity and heat, the production phase emissions were calculated from the production data of the local power companies, published by Finnish Energy Industries [36], using the energy method. In addition, heat consumption was divided into district heat, oil and wood. Of these, the Finnish average emission, 267 g kWh$^{-1}$ [31], was utilized for oil. For wood used for heating, zero carbon emission was assumed. For the higher-order tiers of the production chain, the EIO-LCA sector power generation and supply was utilized.

In addition, communal building energy, normally paid within rent or housing management charges, was added to the energy consumption of a consumer. This disaggregation of rents and housing management charges was done according to a study including 18 housing corporations from the Helsinki metropolitan area, which we evaluated the results of an earlier study by Kiiras et al [26]. Furthermore, all the other operation and maintenance costs included in the rents and housing management charges, water, waste, cleaning, maintenance and repair construction, etc, were re-allocated under the appropriate consumption categories according to the results of Kiiras et al.

Private transport formed the second most important sector in the input–output calculation. Again, the first tier emissions, the fuel combustion phase, were replaced with process data. The method was such that the private expenditure on fuel was divided into producer price and market price shares [23, 24]. The sector petroleum refineries was used for the higher-order tiers according to the producer price share. For the fuel combustion phase, the data from The Technological Centre of Finland’s LIPASTO study [30] were used according to the market price private expenditure.

Next, the emissions from the expenditure on building and property were enhanced with regional data. The share of the price of property has substantial regional variation, and as the emissions related to building and property differ heavily, regional price adjustments were utilized according to the property price statistics of The Housing Finance and Development Centre of Finland (ARA) [25].

Finally, while emissions related to public transport were minor in the input–output calculation, they were enhanced with Finnish data, as the sector forms an important substitute for private transport, and the emissions profile of EIO-LCA differs significantly from that of Finland. Here the enhancement was done by replacing the EIO-LCA output matrix with that of the Finnish ENVIMAT study [22].

As the next step, we divided the initial 43 consumption classes into 10 consumption areas, indicating the level of association to a more urban structure- or lifestyle-related carbon consumption. The consumption areas are:

1. heat and electricity;
2. building and property;
3. maintenance and operation;
4. private transport;
5. public transportation;
6. consumer goods;
7. leisure goods;
8. leisure services;
9. traveling abroad;
10. health, nursing and training services.

Of these ten consumption areas, heat and electricity contains all housing energy use, including both household heat and electricity and the share of the communal building energy. Building and property is dominated by construction, whereas maintenance and operation comprises emissions from maintenance and repair construction, water and waste water, waste and cleaning. Private transport, in addition to gasoline combustion, includes all activities related to driving, purchases and the maintenance of private vehicles. Public transportation consists mostly of traveling by bus or train. These five categories reflect primarily the effect of the urban structure on the carbon consumption, as the structure substantially affects the emissions related to these consumption areas.

The goods and services classes comprise the daily consumption and the consumption of durable goods, so that leisure-related expenses are separated in order to demonstrate the link between the allocation of emissions and lifestyle differences. Traveling abroad includes all private flights and accommodation abroad. Finally, health, nursing and training services are put together as they only include private services, which in Finland form a minor share of all the services of these sectors.

The carbon footprints of the case cities were then calculated with the hybrid model. The results are presented in the next section. After that, the reliability of the results is evaluated.

4. Results

According to the hybrid LCA model, the annual carbon consumption per capita in the studied cities varies from 10.1 to 14.4 tons CO$_2$-ekv. The correlation with the standard of living is high, but patterns related to urban structures were identifiable. First the overall results are analyzed.

In the Helsinki metropolitan area, the carbon consumption is 11.1 ton CO$_2$-ekv in Vantaa, 12.4 tons in Helsinki and 14.4 tons in Espoo. In the Tampere metropolitan area, the respective figures are 10.1 tons in UCT, 10.9 tons in Tampere and 11.1 tons in RCT. In each, the key sectors related to urban structure dominate the emissions; energy related to housing, building and property, maintenance and operation, and transport including private transport and public transport. The share of these sectors of the overall carbon consumption is from 66% to 75% in all areas. In the larger Helsinki metropolitan area, the shares vary from 66% in Helsinki and Espoo to 70% in Vantaa. In the Tampere metropolitan area, the variation is slightly higher, ranging from 69% in the city of Tampere to 74% in RCT and 75% in UCT.
In the Helsinki metropolitan area, the standard of living is higher than in the Tampere metropolitan area. The annual private consumption per capita in the Helsinki metropolitan cities is 16 000 € in Vantaa, 17 400 € in Helsinki and 18 800 € in Espoo. In the Tampere metropolitan area, the figures are 13 800 € in both UCT and RCT and 15 000 € in Tampere. Thus, it seems that growth in the volume of consumption increases all emissions but especially those related to daily goods and leisure goods and services, seen from the decline of the share of the three dominant sectors as consumption grows. Figure 1 demonstrates these results.

According to these results, it seems that there is actually no clear correlation between urban density and the carbon consumption. In the Helsinki metropolitan area, the city of Helsinki has by far the highest density, but is placed between Vantaa and Espoo in carbon consumption. In the Tampere metropolitan area, the city of Tampere has the highest density, UCT the second highest and RCT the lowest. Similarly, the Helsinki metropolitan area has a noticeably higher density than the Tampere metropolitan area, but also a clearly higher carbon consumption on average. In both areas, the carbon consumption varies around that of the densest center city (Helsinki and Tampere, the density figures in table 1).

The structure of the carbon consumption is similar in both metropolitan areas and in each individual city, as was described at the beginning of the section. Here we analyze the activities and sectors with the highest carbon emissions.

First we focus on the highest carbon footprint, namely the one related to heat and electricity consumption. The same pattern is found in all cities. The carbon emissions figures in the Helsinki metropolitan area vary from 3.4 tons CO₂-ekv in Vantaa to 3.7 tons in Helsinki and 4.4 in Espoo, and in the Tampere metropolitan area from 3.0 tons CO₂-ekv in UCT to 3.2 in Tampere and 4.0 in RCT. While a link between better energy efficiency and an urban core with the housing based on dense apartment buildings is typically made, the difference between less dense areas with a higher share of detached housing and the more dense urban areas with mainly apartment buildings is rather small in the results.

An important factor behind this result is the inclusion of all building-related energy (also the energy consumed by the housing company and only indirectly paid by the consumer) to the carbon consumption of a consumer, which appeared to form as much as 50% of the total energy used. On the other hand, one effect of the urban structure on the emissions of housing seems to be the growth of living space as the density of the urban area diminishes, as was shown in table 1, related to the study areas. This should have an increasing effect on the carbon consumption, but the effect seems to be overruled by other factors.

Other building-related emission categories, building and property, and maintenance and operation, account together for two to three tons of CO₂ in the carbon consumption per capita. These emissions are dominated by construction-phase emissions of buildings with a share of 50–70%, home furniture and equipment (20%) and residential maintenance and repair construction (15%). On the other end, emissions from household waste produce only less than 1% of the carbon consumption per capita. Also, water and waste water together only account for less than 2% of the carbon consumption per capita in all the case cities. Table 2 presents the annual carbon consumption per capita of the three categories directly related to housing. The population and population density figures have been added from table 1 to describe the type of each area.

The two remaining categories that are also closely related to urban structure, private driving and public transportation, seem to correlate rather nicely with the urban density, the higher density signifying lower emissions from transportation. However, it is important to notice that the overall influence of transportation seems to be rather low on the overall carbon consumption level. In the Helsinki metropolitan area, the emissions from private transport vary from 1.3 tons CO₂-ekv in Helsinki to 1.4 tons in Vantaa and 1.9 tons in Espoo. In the Tampere area, the figures are 1.7 tons in Tampere and 1.8 tons in RCT, but an average consumer in UCT emits nearly 2.3 tons of CO₂ annually due to private vehicle use. Thus, according to these figures, it seems that the metropolitan centers, where the workplaces and services are located, support a lifestyle that includes less driving. In both Helsinki and Tampere, an average consumer drives less than a consumer in the surrounding areas, even though the differences are small.

Figure 1. The annual carbon consumption per capita (tons CO₂-ekv), private consumption (€) and net earnings (€) in the two metropolitan areas.
Table 2. The annual carbon consumption per capita directly related to housing in the two metropolitan areas.

|                  | Helsinki metropolitan area | Tampere metropolitan area |
|------------------|-----------------------------|----------------------------|
|                  | Vantaa | Helsinki | Espoo | UCT | Tampere | RCT |
| Population       | 190 000 | 565 000 | 235 000 | 64 000 | 206 000 | 69000 |
| Pop. density     | 779    | 3010    | 743    | 84    | 344     | 21 |
| Building and property | 1.3  | 1.4    | 1.7    | 1.1   | 1.1     | 1.4 |
| Maintenance and operation | 1.3  | 1.7    | 1.3    | 1.0   | 1.1     | 1.0 |
| Heat and electricity | 3.4  | 3.7    | 4.4    | 3.0   | 3.2     | 4.0 |
| Total            | 6.1    | 6.7    | 7.4    | 5.1   | 5.5     | 6.5 |

Also, it seems that a reverse connection applies to public transport. In the denser metropolitan centers, more public transportation is used than in the surrounding areas. The share of public transport in the total trip generation is almost 30% in Helsinki, but only around 20% in both the surrounding cities, Espoo and Vantaa. In Tampere, the share is a little less than 20%, and around 15% in the surrounding cities [27]. This same pattern was also found in a Finnish study of the impact of the type and location of the residential area on travel behavior [28]. In addition, there seems to be a connection between the use of public transportation and the availability of rail transport options. The share of public transport is higher in the Helsinki metropolitan area, where commuter, metro and tram connections are available [27]. Table 3 represents the emissions related to transportation.

The rest of the carbon categories, the consumption of goods and services, reflect clearly the effect of income on the emissions. However, this part of the carbon consumption was not the focus of this study, and also cannot be analyzed in depth with the presented hybrid model. The model shows that traveling abroad and the use of services grow as earnings grow, as figure 1 shows, but regarding daily consumption, it is not possible to differentiate amount and quality.

One interesting notion about the relation of income and carbon consumption is that emissions seem to grow as income grows, but with decelerating speed. This can also be read from figure 1, where the dashed line indicates annual net earnings. It seems that the share of savings increases rather rapidly as earnings grow.

5. Discussion

The purpose of this study was to present an application of a tiered hybrid LCA model for assessing the carbon consumption in metropolitan areas with the emphasis on the effect of urban structure on the carbon emissions. In the study, we created a carbon footprint that includes all emissions caused by consumption, including production and delivery chains, using a tiered hybrid LCA model. We also structured the carbon footprint so that urban structure-related emissions could be identified and analyzed. We argue that this type of consumption-based modeling of emissions is of high importance and adds valuable information to the more common assessments based on regional production. Especially, when solutions for low-carbon living and low-carbon urban structures are searched for, consumption-based assessments of emissions are essential.

Table 3. The annual transport-related carbon consumption per capita in the two metropolitan areas.

|                  | Helsinki metropolitan area | Tampere metropolitan area |
|------------------|-----------------------------|----------------------------|
|                  | Vantaa | Helsinki | Espoo | UCT | Tampere | RCT |
| Private transport| 1.38   | 1.27    | 1.94  | 2.28 | 1.74    | 1.80 |
| Public transportation | 0.24  | 0.26    | 0.17  | 0.07 | 0.17    | 0.11 |
| Total            | 1.62   | 1.53    | 2.11  | 2.35 | 1.91    | 1.91 |

The study was conducted by analyzing the carbon consumption in the two largest metropolitan areas in Finland, the Helsinki metropolitan area and the Tampere metropolitan area. Both include a denser city core, Helsinki or Tampere, and less dense surrounding cities that are dependent on the center with regard to workplaces and services.

The hybrid LCA model was created in two phases. In the first phase, we assessed the annual carbon consumption of an average consumer in Finland using two different direct input–output models, the economic input–output-LCA model of Carnegie Mellon University [18] and the Finnish ENVIMAT model [22]. Of these, the EIO-LCA model was assessed to fit better the purpose of the study, and was thus utilized as the basis of the hybrid model.

The first assessment was also used to select the categories that were enhanced with process data. The selection was the following: emissions of energy related to housing, building and property, maintenance and operation of the building, private transport and public transportation, which together were found to account for roughly two thirds of the total carbon consumption.

In the second phase, we assessed the annual carbon consumption per capita of the two metropolitan areas. In the Helsinki metropolitan area, the carbon consumption varies from 11.1 tons CO₂-ekv in Vantaa to 12.4 tons in Helsinki and 14.4 tons in Espoo. In the Tampere metropolitan area, the figures are 10.1 tons in UCT, 10.9 in Tampere and 11.1 in RCT. The volume of private consumption seems to be the main explanatory factor, these figures being 16 000 € in Vantaa, 17 400 € in Helsinki and 18 800 € in Espoo, and 13 800 € in both UCT and RCT and 15 000 € in Tampere. However, some factors related to urban structure were also identified in the study.

Interestingly, the results show that 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 quite a small effect on the carbon emissions. Whereas some earlier studies have shown substantial differences between the core and suburbs (e.g. [29, 32, 37]), no clear pattern between the different types of urban structures was found in this study. The reasons found are twofold. Primarily, after the inclusion of communal building energy to the energy consumption per capita, the differences in the energy consumption and thus in the emissions between the building types decrease radically. Second, even the slight growth in energy-related carbon consumption found in the Tampere metropolitan area in RCT, compared to the denser metropolitan core and UCT, is overruled by the high correlation of income and carbon consumption.

In the Helsinki metropolitan area, the emissions related to energy use in the two cities around Helsinki are 3.4 tons CO₂-ekv in Vantaa and 4.4 tons in Espoo, whereas in the metropolitan center, Helsinki, the figure is 3.7 tons according to the hybrid model. In the Tampere area, the pattern is the same, 3.0 and 4.0 tons CO₂-ekv emissions in UCT and RCT, and 3.2 tons in Tampere. This result would imply that the high density of the city structure is not necessarily an obligatory precondition in creating low-carbon urban structures. On the other hand, the living space per capita would seem to grow as the density of the city diminishes. This has a reverse effect on the carbon consumption, but it is insignificant compared to the effect of income.

The second pattern, complying with several earlier studies (in Finland e.g. [28, 32]), was the relation between the density and the emissions from private transport. In both metropolitan areas, the emissions from private transport are higher in the surrounding areas than in the center city. However, the effect on the overall carbon consumption per capita is quite weak when all the emissions related to driving are calculated, including car manufacture, deliveries and maintenance of vehicles. According to the hybrid model, the share of fuel combustion of all emissions related to private transport is 50–70%, the rest being dominated by emissions related to car manufacture and maintenance. Thus, growth in trip generation due to a decline in the density of the city structure would have a relatively minor effect on the overall carbon consumption.

Third, the denser metropolitan centers seem to support more effective public transport systems, as the use of public transport is more common in both the center cities and in the surrounding areas. In addition, rail connections would seem to influence the use of public transport, as seen in the higher use of public options overall in the Helsinki metropolitan area, when compared to Tampere and its surrounding areas (table 3). And, as they have lower carbon intensities than bus connections [22, 30], they increase further the carbon mitigation effect of public transportation as an alternative for private transport.

Another pattern also identified was that the level of consumption of services grows together with the density of the structure. This seems to be closely related to the income level, but was assumed to also indicate growth in the availability of different services as the urbanization grows.

Overall, despite the identified connections between carbon consumption and urban density, it would seem that the effect of density on carbon emissions is rather low, and that other factors may easily overrule the effect. Thus, other means than only intensifying the urban structure to create low-carbon urban structures are needed. As emissions from housing energy dominate the carbon consumption, this would seem to offer the highest mitigation potential.

In this study, we utilized local emission profiles from energy production. They were found to be close to each other in both the metropolitan and the cities, as well as close to the Finnish average of 240 g kWh⁻¹ for electricity and 286 g kWh⁻¹ for district heat [31]. Thus, this has no significant influence on the results. However, if we choose to use the Nordic electricity pool figure (Nordic-mix (Nordic countries average)), 98 g kWh⁻¹ for electricity, and assume the same intensity for district heat, around 20% would be cut from the overall carbon consumption.

Another way to cut down the energy-related carbon consumption via urban development would be the construction of low energy buildings. The effect is high on the carbon consumption of the inhabitant, but, unlike energy production, would have larger scale effects only over a long period.

The reliability of the study was assessed from four perspectives. First, we studied two metropolitan areas to have a wider set of studied conditions. Second, the results were positioned with regard to previous applicable studies. The closest match was found from the Finnish ENVIMAT study that created output tables based on the Finnish economy, including carbon emissions of consumption [22] among others. According to the published data from the results of that study, the national average carbon consumption per capita would be 10.1 tons CO₂-ekv, almost equal to our result of 10.2 tons. On the method level, a reference has been published quite recently by Weber and Matthews, who used the EIO-LCA approach to study the global and distributional aspects of American household carbon consumption, utilizing the same purchasing power parity correction to diminish possible biases from a temporal incompatibility of the input data and the model [17]. A demand-centered city-level GHG assessment has also been presented by Ramaswami et al [38]. While their method is slightly different from the one utilized in this paper, they argue the importance of including the emissions occurring outside the borders of the assessed city, pointing out that the results of the assessment may be significantly biased if the assessment follows strict regional boundaries. Schulz [40] has come to the same conclusion by studying material inputs. In addition, Ramaswami et al and Parshall et al recognize the effect of inclusion of other consumption, in the form of embodied energy, into the assessment. Ramaswami et al also argue that the EIO-LCA is an interesting and useful tool [38, 39].

Supporting the result in this paper, Glaeser and Kahn and Parshall et al, although using slightly different assessment methods, report similar weak or nonexistent connections between the level of carbon emissions in the downtown core and the suburban areas [37, 39]. A second source of possible biases is the hybrid model itself. As mentioned above, the applicability of the hybrid LCA method for carbon consumption assessments seems to be good. However, as we utilize a model based on US industry to describe a part of
the Finnish economy, the question of the regional (industry structure differences) compatibility of the input data and the model need to be assessed. The choice of the EIO-LCA model was made for four reasons. First, the use of an input–output basis in the assessment model expels the boundary selection problem, and thus the truncation error inherent in process-based assessments [14]. Second, the model is the most disaggregated model available in the industry sectors included, which was considered an important factor in a comprehensive carbon consumption assessment. Third, the model has been evaluated to be applicable in analyzing the Finnish economy by earlier studies of Junnila [7] and Heinonen and Junnila [33]. And fourth, 55% of all consumption of goods in Finland is directed to import goods, meaning that a model based on the Finnish economy would possibly be biased as well. It is also important to remember that process-specific data were used for the most important categories, which cover more than 60% of the total carbon consumption.

However, even with the process data enhancement of the model, the problem of the temporal (inflation and currency rate differences) compatibility of the data and the model remains. The base year of the model is 2002, whereas the reference year of the input data is 2006. As no such detailed information on inflation figures by sector exists for the studied cities, we chose the purchasing power parity (PPP) adjustment, according to the method selected by Weber and Matthews in their study [17].

Finally, the reliability of the input data was assessed. In this study, the Finnish consumer survey [21] provided the primary input data. The level of detail of the data is very high. The survey presents private consumption divided into over 1000 categories of goods and services, providing an excellent basis for IO-LCAs. Also, the sample size is representative, including roughly 10 000 subjects (0.2% of population). Regionally based samples can be constructed, but especially concerning the smaller cities, the number of subjects is substantially smaller, raising the probability of biases due to abnormal observations. In this study, the problems arising from small samples concerned mainly the small cities surrounding Tampere. As a solution, the seven small cities were divided into two groups, rural and urban cities, as was described in section 3.

Despite the high quality input data, free public services and heavily subsidized services create a source of bias in the Finnish economy system. In input–output-based studies, emissions related to these are mostly excluded from the carbon footprint as they are excluded from the monetary values of private consumption. While in Finland these form a noteworthy share of total private consumption, no corrective actions were taken, since the assessment in the Finnish ENVIMAT study showed that the bias concerns predominantly the consumption class ‘health, nursing and training services’, which had a minor significance in this study.

As an additional test of the robustness of the results, we conducted a longitudinal study using preceding consumer survey data from 2001. The test results were very similar, except for a scale difference due to the change in the standard of living between the two surveys. This test strongly supports the robustness of our findings.

The assessment presented here and the model utilized still contain a few deficiencies in general. Even with the 428 industry sectors in the EIO-LCA model, the inherent problem of the high level of aggregation of the industry classifications related to all input–output methods exists. The significance of this problem is very challenging to assess, but some choices of sectors describe rather imprecisely the true emissions of the consumption sector concerned. An example of this kind of weakness in the model is food, which is included in the consumer goods category with a mix of other goods, the emission profile thus being potentially biased. Also, the assumption of the domestic production of imports, which is inherent to all input–output models [14, 15, 17], is a source of bias for the part of the assessment outside of the process data coverage. For example, Weber and Matthews reported a 15% increase in the emissions when the most important foreign trade partners of the USA were examined in detail [17]. Concerning the effect of the income level on the emissions, the model cannot differentiate quality and quantity. Growth in the latter increases the emissions, but if the growth in expenditure is quality-related, the relation with the emissions is unclear. In addition, the combining of the two methods, input–output and process LCAs, creates a source of bias discussed in more detail in e.g. [14].

6. Conclusions

According to the results of this study, we argue that we have presented a useful model for analyzing the emissions of different urban structures that could be used, for example, in urban development, when low-carbon solutions are aspired to. In the study, interestingly, no clear connection between the density of the studied cities and carbon emissions was found. This, together with the reported effect of income in almost all the consumption areas, could also have interesting implications on future low-carbon urban development. However, this study only indicates these implications, and further research is needed to make more robust conclusions.

One direction of future development would be to sample the input data according to the type of housing in addition to geographical sampling. This would allow direct comparisons of, e.g., detached housing and apartment buildings. In this study, only the dominant types of housing could be identified relating to a specific city or region, but a direct comparison would further validate the findings. In addition, the accuracy of the model should be increased by a lower level of aggregation of the consumption data as well as by the inclusion of further process data.

References

[1] Huovila P, Ala-Juusela M, Melchert L and Pouffary S 2007 Buildings and Climate Change, Status, Challenges and Opportunities (Paris: United Nations Environment Programme)
[2] Helio J, Nippala E and Nuuttila H 2005 *Building Energy Consumption and CO2 Emissions in Finland* (Rakennusten energiankulutus ja CO2-ekv päästöt Suomessa) Tampere University of Technology, Finland

[3] European Union 2009 Climate Change (available at [http://ec.europa.eu/environment/pubs/pdf/factsheets/climate_change.pdf](http://ec.europa.eu/environment/pubs/pdf/factsheets/climate_change.pdf), accessed 31 May 2010)

[4] Information Provider on Climate Change (available at [http://www.ilmasto.org](http://www.ilmasto.org), accessed 31 May 2010)

[5] United Nations 2007 City Planning Will Determine Pace of Global Warming (available at [http://www.un.org/News/Press/docs/2007/ga5190.doc.htm](http://www.un.org/News/Press/docs/2007/ga5190.doc.htm), accessed 18 February 2010)

[6] Murakami S, Kawakubo S, Asami Y, Ikaga T, Yamaguchi N and Kaburagi S 2010 Concept and framework of CASBEE-City—an assessment tool of the built environment of cities *Proc. 2010 Conf. Sustainable Building* (available at [http://www.archsia.co.jp/en/index/en/index.html](http://www.archsia.co.jp/en/index/en/index.html), accessed 6 October 2009)

[7] Junnila S, Horvath A and Guggemos A 2006 Life-cycle assessment of office buildings in Europe and the United States *J. Infrastruct. Syst.* 12 10–7

[8] Wong M T N 2004 Implementation of innovative product service systems in the consumer goods industry *Dissertation* University of Cambridge, UK

[9] Dodman D 2009 Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories *Environ. Urban.* 21 185–201

[10] Mayor of London (available at [http://www.london.gov.uk/mayor/priorities/environment.jsp](http://www.london.gov.uk/mayor/priorities/environment.jsp), accessed 15 January 2010)

[11] European Union, Committee of the Regions 2009 Green partnership: EU and US mayors pledge to work together on climate change *Press Release COR/09/92* (available at [http://europa.eu/rapid/pressReleasesAction.do?reference=COR/09/92&format=HTML&aged=0&language=EN&guiLanguage=en](http://europa.eu/rapid/pressReleasesAction.do?reference=COR/09/92&format=HTML&aged=0&language=EN&guiLanguage=en), accessed 19 February 2010)

[12] Association of Finnish Local and Regional Authorities, Anu Kerkkänen 2009 Climate Change Control in Municipal Decision Making (Kuntaliiton eisselvitys: Kokonaisuuden hallinta ja ilmastomuutos kunnan päätöksenteossa) (available at [http://www.hel.fi/wps/portal/Helsinki/Artikkelit/WCM_GLOBAL_CONTEXT=/Helsinki/it/P_1_zsentesko+j+a+hallinta+Kaupunginjohtaja+Kaupunginjohtaja+Jussi+Pajunen+Puheen+energiapoliitikkaa](http://www.hel.fi/wps/portal/Helsinki/Artikkelit/WCM_GLOBAL_CONTEXT=/Helsinki/it/P_1_zsentesko+j+a+hallinta+Kaupunginjohtaja+Kaupunginjohtaja+Jussi+Pajunen+Puheen+energiapoliitikkaa), accessed 19 February 2010)

[13] Mayor of the City of Helsinki Jussi Pajunen’s speech commenting on the report on energy policy 23/01/2008, (Jussi Pajunen puhe energia-politiikan selonteon yhteydessä) (available at [http://www.hel.fi/wps/portal/Helsinki/artikkelit/WCM_GLOBAL_CONTEXT=/Helsinki/it/P_1_ksesenteko+j+hallinta+Kaupunginjohtaja+Kaupunginjohtaja+Jussi+Pajunen+Puheen+energiapoliitikkaa](http://www.hel.fi/wps/portal/Helsinki/artikkelit/WCM_GLOBAL_CONTEXT=/Helsinki/it/P_1_ksesenteko+j+hallinta+Kaupunginjohtaja+Kaupunginjohtaja+Jussi+Pajunen+Puheen+energiapoliitikkaa), accessed 19 February 2010)

[14] Suh S et al. 2004 System boundary selection in life-cycle inventories using hybrid approaches *Environ. Sci. Technol.* 38 657–64

[15] Junnila S 2006 Empirical comparison of process and economic input–output life cycle assessment in service industries *Environ. Sci. Technol.* 40 7070–6

[16] Joshia S 1999 Product environmental life-cycle assessment using input–output-techniques *J. Indus. Ecol.* 3 95–120

[17] Weber C L and Matthews S H 2008 Quantifying the global and distributional aspects of American household carbon footprint *Ecol. Econ.* 66 379–91

[18] Carnegie Mellon University Green Design Institute 2008 *Economic Input-Output Life Cycle Assessment (EIOLCA), US 2002 Industry Benchmark model (Internet)* (available at [http://www.ciolsa.ca](http://www.ciolsa.ca), accessed 1 February 2010)

[19] Statistics Finland, The Division of Aggregate Consumption in Finland (available at [www.stat.fi](http://www.stat.fi), accessed 1 October 2009)

[20] *ICP Global Results: Global Purchasing Power Parities and Real Expenditures* (available at [http://siteresources.worldbank.org/ICPINT/Resources/icp-final-tables.pdf](http://siteresources.worldbank.org/ICPINT/Resources/icp-final-tables.pdf), accessed 20 December 2009)

[21] Statistics Finland 2006 (data only partly publicly available at [http://www.stat.fi](http://www.stat.fi), accessed 1 October 2009)

[22] Seppälä J, Mäenpää I, Koskela S, Mattila T, Nissinen A, Katajajuuri J-M, Häräniemi T, Korhonen M-R, Saarinen M and Virtanen Y 2009 Assessment of the environmental impacts of material flows caused by the Finnish economy with the ENVIMAT model (Suomen kansantalous materiaaliaktiviteitten ympäristövaikutusten arviointi ENVIMAT-malli), The Finnish Environment 20/2009

[23] Finnish Financial Advisors 2006 *Gasoline Prices (Suomen Rahatieto)* (available at [http://www.rahatieto.fi](http://www.rahatieto.fi), accessed 20 December 2009)

[24] Wikipedia *Consumer and Producer Gasoline Prices in Finland* (available at [http://fi.wikipedia.org/](http://fi.wikipedia.org/), accessed 21 December 2009)

[25] The Housing Finance and Development Centre of Finland (ARA) Reports A 12/2006 (available at [http://www.ara.fi/download.asp?contentid=21121&lan=FI](http://www.ara.fi/download.asp?contentid=21121&lan=FI), accessed 23 December 2009)

[26] Kiaras J, Hyart J, Saari A and Kammonen J 1993 Property Maintenance Expenses in Finland 1992 Helsinki University of Technology (Kuistitseijen ylläpidon kustannustieto 1992. Tekniikin korkeakoulu)

[27] The National Travel Survey 2004–2005 (data available for scientific use on request at [http://www.hlt.fi/english/index.htm](http://www.hlt.fi/english/index.htm), accessed 6 October 2009)

[28] Kivari M, Voltti V, Heltimo J and Moilanen P 2007 Asuinalueen tyypin ja sijaintin vaikutus ihmisten liikkuamiseen (Impact of the type and location of the residential area on travel behaviour) *Finnish Road Administration, Finnsa Reports* 28/2007

[29] Norman J, MacLean H L and Kennedy C A 2006 Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions *J. Urban Plan. Dev.* 132 10–21

[30] LIPASTO traffic emissions VTT Technical Research Centre of Finland (available at [http://lipasto.vtt.fi/ksikkoapaasto/tenfeitilokirje/riiliekirje/riiliko_iiece.htm](http://lipasto.vtt.fi/ksikkoapaasto/tenfeitilokirje/riiliekirje/riiliko_iiece.htm), accessed 1 March 2010)

[31] Kurnitski J and Keto M 2010 Emissions from building energy consumption and primary energy use in Finland (Rakennusten energiankulutukset ja ikäpuhdistamien arviointi) (available at [http://www.energia.fi/FI, accessed 20 January 2010](http://www.energia.fi/FI), accessed 20 January 2010)

[32] Rauhala K, Mäkelä K, Estlander K, Tolsa H, Martamo R, Lahti P and Perälä M 1997 Environmentally favorable urban form and transport systems *Technical Research Centre of Finland, VTT Research Notes* 1839

[33] Heinonen J and Junnila S 2010 A life cycle assessment of carbon mitigation possibilities in metropolitan areas *Proc. 2010 Conf. Sustainable Building* (available at [http://www.archsia.co.jp/en/index/en/index.html](http://www.archsia.co.jp/en/index/en/index.html), accessed 6 October 2009)

[34] Carney S, Green N, Wood R and Read R 2009 Greenhouse gas emission inventories for 18 European regions *The Greenhouse Gas Regional Inventory Project* (available at [http://www.archsia.co.jp/en/index/en/index.html](http://www.archsia.co.jp/en/index/en/index.html), accessed 6 October 2009)

[35] Intergovernmental Panel on Climate Change (IPCC) 2006 *Guidelines for National Greenhouse Gas Inventories* (Cambridge: Cambridge University Press)

[36] Finnish Energy Industries, Energiatekniikka 2008 (available at [http://www.energia.fi/](http://www.energia.fi/), accessed 20 January 2010)

[37] Glaeser E and Kahn M 2010 The greenness of cities: carbon dioxide emissions and urban development *J. Urban Econ.* 67 404–18

[38] Ramaswami A, Millman T, Janson B, Reiner M and Thomas G 2006 A demand-centered, hybrid life-cycle methodology for city-scale greenhouse gas inventories *Environ. Sci. Technol.* 40 6455–61

[39] Parshall L, Gurney K, Hammer S, Mendoza D, Yuyu Z and Geethakumar S 2010 Modeling energy consumption and CO2 emissions at the urban scale: methodological challenges and insights from the United states *Energy Policy* 38 4765–82

[40] Schulz N 2007 The direct material inputs into Singapore’s development *J. Indus. Ecol.* 11 117–31