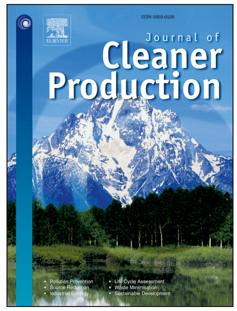

Implementation at a city level of circular economy strategies and climate change mitigation – the case of Brussels

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TITLE

Implementation at a city level of circular economy strategies and climate change mitigation– the case of Brussels

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Material footprint

ABSTRACT

Within the framework of the 2015 Paris Agreement and the increased acceptance of circular economy (CE) principles of national and local governments, it is essential to study the potential effect on climate change of CE-strategies implemented on an urban scale. The present research quantitatively assesses the potential impact of these strategies on primary material footprint (MF) and carbon footprint (CF) of households in areas an urban area, using the case of Brussels Capital Region (BCR), Belgium. Because the CE-strategies are linked to consumption domains, this assessment first calculates both footprints of consumption domains using a city-level input-output analysis and discusses the relationship between the footprints. The findings show that the carbon footprint of BCR in 2010 was 22Mt CO_2-eq. or 20.3 t/cap. The material footprint of BCR in 2010 was 31Mt or 29.5 t/cap. Important insights are that BCR relies on its hinterland for 98% of its primary materials and 83% of the region's greenhouse gas emissions (GHGs) are emitted outside of its territory. The household consumption domains of food, housing and transport were identified as hotspots in both footprints. Within these domains, we calculated and discussed the potential impact on both footprints of CE-strategies on consumption or production of food, mobility and housing. Results from this case show that with these strategies Brussels could mitigate 25% of its CF and 26% of its MF, 18% of its CF and 26% of its MF, and 7% of its CF and 10% of its MF, respectively. The methodology and insights could therefore support authorities and policy-makers to effectively develop coherent and consistent action plans on consumption domains to improve resource efficiency and reduce the GHGs, simultaneously.

1. INTRODUCTION

Climate policies call for producers and consumers to reduce their climate change impact (European Environment Agency (EEA), 2015). For a long time, climate change policies were solely focused on the reduction of energy use, increasing energy efficiency or using renewable energy sources (Eurostat, 2016). The use of fossil-fuel based energy is indeed a high contributor to GHG-emissions (EEA, 2013), so societies strive for solutions such as low carbon-intensive energy sources and energy-efficiency improvements, essentially on the production side (Reinders et al., 2003).

However, it is unlikely that energy-related improvements on the production side will be sufficient to reach the climate change goals (EC, 2010). For example, a high share of energy use is indirectly caused across production chains by household product consumption (Jones and Kammen, 2011; Reinders et al., 2003). We argue that productive activities are triggered by consumption needs and therefore climate change mitigation strategies should also focus on the consumption side.

This observation is particularly relevant for urban areas where economies have become service-based and are mainly consumption nodes, making cities one of the key areas in tackling global climate change. Also because cities host more than half of the world population and they are responsible for three quarters of global energy consumption although most productive activities are located outside of their territories (IPCC, 2014) (Batty, 2008). Thus, the environmental impact of cities should not only be measured through the productive activities taking place on their territory, but through the combination of both their productive and consumption activities. This includes productive activities that are not taking place locally, but are induced by cities' consumption activities (Ramaswami et al., 2012; Satterthwaite, 2008).

A number of publications have studied the environmental effect of cities. These analyses considered direct or territorial flows examining the territorial flows inside a cities' border (Alfonso Piña and Pardo Martínez, 2014; Hillman and Ramaswami, 2010; Kennedy et al., 2015), indirect or (global) upstream flows of production activities linked to the consumption side (Chen and Chen, 2015; Dias et al., 2014; Wiedmann et al., 2015) or both (Caro et al., 2015; Minx et al., 2013; Wiedmann et al., 2015). These studies consider different flows and different footprints depending on the purpose and data availability, although in most cases only one flow is considered. Yet it is essential to better understand the relationship between flows (and their associated footprints) as proposed policies for one flow could have undesired effects on others. In addition, the obtained results often characterise urban environmental effects from a descriptive approach which, at best, identify the environmental hotspots of consumption and/or production activities.

The main focus of the paper (work flow visualised in Figure 1) is to measure to which extent CE-strategies in the city of BCR can enable climate change mitigation and understand what is their effect on the material footprint. CE-strategies consist in keeping materials and products circulating (i.e. to preserve resources) in a closed loop, reducing the extraction of raw materials, and, to a certain extent, avoid processing and manufacturing steps (Deloitte, 2016). Based on a previous article and on 2007 data (Athanassiadis et al., 2016), the carbon footprint of Brussels consumption was 4.4 times higher than the territorial GHG-emissions in Brussels (Belgium). This suggests that a key driver of energy use and of its associated GHG-emissions is urban consumption, triggering impacts through globally spread production chains. The present research adds to the case of Brussels the different contributions of the household consumption domains to the carbon and primary material footprint. Which consumption domains trigger most of these hinterland impacts? Also, to go beyond the footprint analysis and to explore the link between the impact of CE-strategies on GHG emissions, strategies are developed to estimate potential benefits. The goal of the strategies is to provide insight to which extent the implementation of CE-strategies can enable climate change mitigation. For each scenario, it was also assessed whether its potential for reducing the carbon footprint is of comparable size to its potential of reducing the material footprint. Therefore, this research explores how these strategies (e.g. including repair, reuse, remanufacture and recycle) which are principally aimed at reducing the material footprint, can also mitigate local and global climate change.

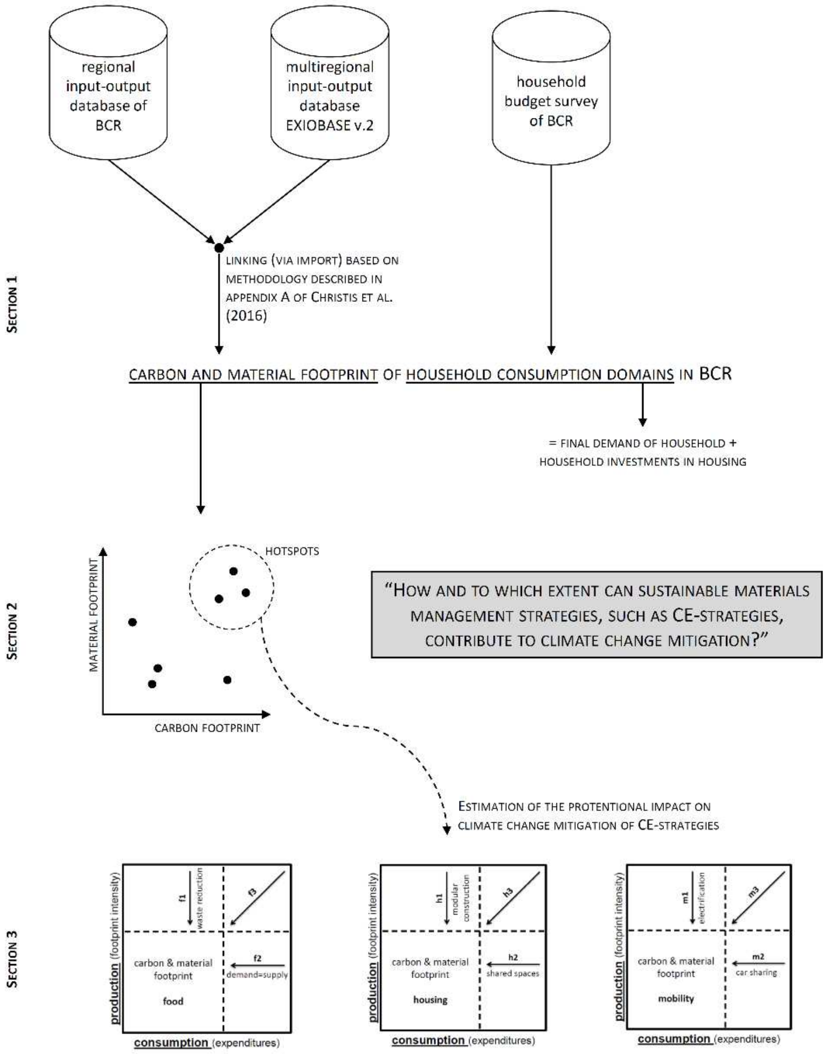

Figure 1: Work flow scheme.

Following on this is the main research question: 'How and to which extent can sustainable material management strategies, such as CE-strategies, can have a positive impact on climate change?'. The main research question is visualised in **Error! Reference source not found.**. Within this research the purpose to illustrate and compare the potential impact of production chain improvements compared to the potential impact of changing consumption behaviour thanks to CE-strategies.

2. METHOD AND MATERIALS

In this section the method and materials used to measure the material and carbon footprint of Brussels and to estimate the mitigation potential of the CE-strategies is outlined. In a first step, this paper explains the boundary of this study, the characteristic of the Brussels case and estimates its carbon and material footprint for 2010. This step addresses the environmental effects of cities' production and consumption activities, using input-output analysis (top-down approach). In Athanassiadis et al. (2016), we illustrate that this methodology is valid to estimate a city's footprint, especially with a focus on measuring indirect impacts and comparing them with local impacts. Both the footprints are decomposed in a local city-level and global hinterland impact (Lenzen and Peters, 2010). In a second step, the link and overlap between both footprints is analysed and discussed. Using a two-dimensional plot, the footprints are visualised to identify their relation and overlapping hotspots. Next, CE-strategies are linked to these hotspots.

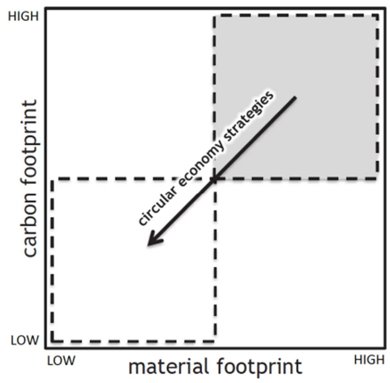

Figure 2: Figure supporting the main research question 'How and to which extent can CE-strategies enable climate change mitigation?'.

To assess the environmental sustainability of a city comprehensively, a clear boundary definition is required. In this paper, we use the consumption perspective based on the residential concept. This includes all consumption aspects carried out by Brussel residents over one year and measure its environmental impact, including the global indirect environmental counterparts (Chen et al., 2016). This approach excludes commuters and tourist activities in Brussel and includes non-Brussels purchases by Brussel residents.

The Brussels case covers the Brussels Capital Region (BCR). The city covers 161.4 km² and in 2010, hosts 1,089,538 inhabitants and generates a GDP of 67,746 million euros, or 18.5% of Belgium's GDP out of which 89.6% is generated in the tertiary sectors (IBSA 2014). The largest GDP is generated in financial institutions, holdings (headquarters), administration and education. Less than 10% of BCR's GDP is generated in manufacturing activities (incl. construction).

The primary material footprint, measured by the raw material consumption indicator (EC, 2016), estimates the global primary material use associated with urban consumption activities. It represents the global amount of used extraction to provide products for final demand of its citizens. The carbon footprint measures the global GHG-emissions emitted in value chains linked to products consumed by citizens' final demand calculated using the IPCC guidance (IPCC, 2014). Following the emission typology of Lebel et al. (2007), these footprints include direct emissions and deemed emissions (i.e. embedded emission of imported products), but exclude responsible and logistic emissions (i.e. embedded emissions of exported products). The exclusion of exports (i.e. responsible and logistic emissions) allows the focus on the consumption perspective.

Following Eurostat's definition, a city's final consumption is the sum of household consumption, non-profit institutions serving households, consumption of governments and gross capital formation. Due to the high residential density in BCR and the quasi-absence of manufacturing activities, this research will narrow its focus to household consumption and the household part in gross capital formation, allowing a more direct link to the CE-strategies later on. The gross capital formation includes acquisitions minus disposals of fixed assets, both tangible assets (e.g. buildings, machinery, etc.) and intangible assets (e.g. software, artistic originals, etc.) (Eurostat, 2008). Part of the gross capital formation are investments in housing with the purpose to provide accommodations to households. To provide a more complete assessment for the household footprints, the footprints of the investments in housing for households are added to the household footprints. This household investment is derived as a share of investments in dwellings in the total gross fixed capital formation, which is based on investment statistics from the National Bank of

Belgium. One reason of solely focusing on households is that their consumption can be categorised into consumer needs and directly linked to CE-strategies. These consumer needs, which can locally be steered by policies through changing or shifting expenditures, trigger global production activities and their associated likewise global impacts.

The footprints are calculated using an input-output analysis (Eurostat, 2008; Miller and Blair, 2009). This analysis approximates the environmental impacts due to final demand via the inclusion of its complete upstream network of production chains. The general formula, based on the Leontief inverse, is $\hat{\mathrm{e}}_{\mathrm{coef}} \times \mathrm{L} \times \hat{\mathrm{f}}$, with:

- $\hat{\mathrm{e}}_{\mathrm{coef}}$: diagonalized extension vector containing e.g. primary material use and carbon emissions;
- L: Leontief-inverse $\mathrm{L} = (\mathrm{I} - \mathrm{A})^{-1}$ with $\mathrm{A} = \mathrm{Z} \times \hat{\mathrm{q}}^{-1}$, Z the matrix containing the interindustry deliveries and I an identity matrix; and
- $\hat{\mathrm{f}}$: diagonalized final demand vector.

Here, f is restricted to household consumption specified by consumption domains (COICOP-classification). The methodology makes use of a city-level input-output table, which is linked to multiregion input-output tables covering the rest of the global economy. The method describing the linking of a regional database to a world model is described in Christis et al. (2016). By combining a local input-output model and a multiregion input-output model, the analysis is based on the available local data, adapted to the local economic characteristics, and includes global sectoral data. For open economies, footprints are determined both by local and global specific characteristics (Christis et al., 2016). The IO-models used are:

- The city IO tables of BCR (2010 data), compiled by the Belgian Federal Planning Bureau, details 124 sectors (Federal Planning Bureau, 2016). The monetary tables contain an inter-industry matrix Z, a final demand matrix F and a value added matrix K. Expenditure accounts for Brussels are gathered from the Household Budget Survey (HBS) (FPS Economy, 2015). This dataset (1978; 1999-2010; 2012 data) provides revenues, expenses and assets (in EUR) per capita, per household and totals for the Brussels Capital Region. Expenditures are subdivided based on the COICOP-nomenclature (Classification of Individual Consumption According to Purpose). The extension data in city IO tables are often lacking or available on an insufficient level of detail. In case coefficients on the city level are not available, a possible solution is to use national coefficients from (multiregion) IO tables. As the city IO tables of Brussels contain no extensions, the extension data (converted into coefficients) of Flanders, a neighbouring region of Brussels, were used instead. This choice only has implications for the estimation of territorial activities, as activities abroad use the data provided in multiregion IO tables.
- Exiobase version 2 (2007 data, industry-by-industry tables) is a global EE-MRIO database produced in the context of the project 'Compiling and Refining of Economic and Environmental Accounts' (CREEA). The database covers 200 products and 163 industries for 43 countries and 5 rest-of-world regions. The extension tables include 15 land use types, employment broken down by three skill levels, 48 types of raw materials and 172 types of water use. BCR is indirectly included in the Exiobase 2 database via Belgium. (Tukker et al., 2013) (Wood et al., 2015).

The CE-strategies used in this research are based on the cost reduction potential, which estimates the reduction potential in total annual cash-out costs per household. These scenarios are based on the ReSOLVE framework (Ellen MacArthur Foundation et al., 2015). This recently developed framework provides strategies for the main household consumption domains. The ReSOLVE framework includes several principles of a CE: Regenerate (e.g. shifts to renewable energy and materials), Share (e.g. second-hand markets), Optimise (e.g. performance and efficiency improvements), Loop (e.g. recycling and remanufacturing), Virtualise (e.g. e-readers) and Exchange (e.g. product as a service systems) (Ellen MacArthur Foundation et al., 2015). The paper compares several scenarios that focus on the three consumption domains being the most promising, as they represent the highest share on both the CF and MF: food, housing and mobility[1]. For every consumption domain a shift in the production network is compared to a shift in fulfilling consumer needs (Figure 3). Their combined effect is included as an additional strategy. The strategies as well as the associated numeric assumptions are listed in Table 1. As the IO-analyses are based on linear relationships between expenditures and emissions, doubling the percentage would double the impact. Table 1 describes the most probable action, as an example, for each of the scenarios. The numeric assumptions correspond to monetary reduction on either the production or consumption side.

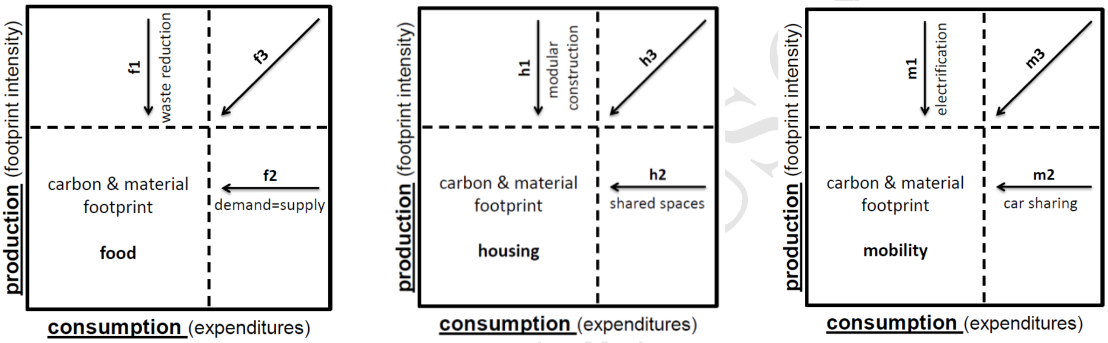

Figure 3: Representation of the mitigation scenarios in the household consumption domains of food, housing and mobility via strategies focusing on production, consumption and a combination of both.

Table 1: Defined scenarios in the consumption domains of food, housing and mobility and their associated numeric assumptions, categorised by the ReSOLVE framework.

consumption domain \ scenarios	**production**: changing the footprint-intensity of products	**consumption**: changing the expenditures on products	**Combination:** combined effect of production and consumption
food	**f1**: efficiency and waste reduction improvements (e.g. closed nutrient loops) in the supply chain of food products (optimise, loop, regenerate) *-15% of all monetary inputs to the food manufacturing (NACE Rev. 2:*	**f2**: consumption adopted to needs (e.g. digital solutions matching supply and demand, adopted quantity per package) and improved diets, no excessive consumption (optimise) *-15% of all expenditures on food products (COICOP-group 01.1)*	**f3**

[1] For example, Jones and Kammen (2011) focus on transportation, housing and food. The composition of the carbon footprint varies considerably across 28 metropolitan regions: 15-30% for housing, 20-40% transportation and 10-30% for food. Moore et al. (2013) show that the largest components of the ecological footprints are food, transportation and buildings, based on a case for Metro Vancouver. The study by Ellen MacArthur Foundation (2015), applying the ReSOLVE framework, estimates the cost reduction potential of the above mentioned consumption domains: mobility with a cost reduction potential of 60-80%, food with a potential of 25-40% and buildings with a potential of 25-35%.

	divisions 10 and 11)		
housing	**h1**: modular constructions and reuse of construction materials (optimise, loop)	**h2**: shared multifunctional spaces and mixed-use buildings (share)	**h3**
	-15% of all monetary inputs to the construction sector (NACE Rev.: division 41-43), except energy inputs	*-15% of all expenditures on investments in construction products (COICOP-division 04b)*	
mobility	**m1**: electrification of the car park (regenerate)	**m2**: increased car sharing reducing individual car ownership (share, exchange)	**m3**
	-6% expenditures on fuels and monetary shift from fossil fuels (COICOP-class 07.2.2) to electricity (COICOP-class 04.5.1)	*-40% expenditures on new vehicles (COICOP-class 07.1.1)*	

3. Results

3.1 Detailing the carbon and material footprint of Brussels

The carbon footprint (Figure 4) of BCR in 2010 is 22Mt CO_2-eq. or 20.3 t/cap, including both production and the use phase. 17% of these GHG-emissions are emitted on BCR's territory and another 12% are emitted in the rest of Belgium (RoB). 71% of BCR's carbon footprint takes place outside Belgium (RoW), stressing the globally spread impact of the BCR's consumption. To put these figures in perspective, total territorial emissions of BCR are 5.5 t/cap which implies that GHG-emissions from the local consumption perspective are 3.7 times higher in comparison to the territorial GHG-emissions.

The material footprint of BCR in 2010 is 31Mt or 29.5 t/cap (Figure 4). Only 2% of the primary materials used in the production chains of goods and services for BCR's final demand originate from BCR's territory. A small share (around 12%) is produced or excavated in Belgium (RoB). Again, the results show how BCR profoundly impacts the environment globally to satisfy its local consumption activities, as 85% of the primary materials used originate from outside Belgium (RoW). In fact, the territorial production and excavation of primary materials is limited to 0.2 t/cap compared to a consumption perspective of 29.5 t/cap. The mass composition of the material footprint by the four major primary material groups is: 45% non-metallic minerals, 23% biomass, 20% fossil energy carriers and 11% metals.

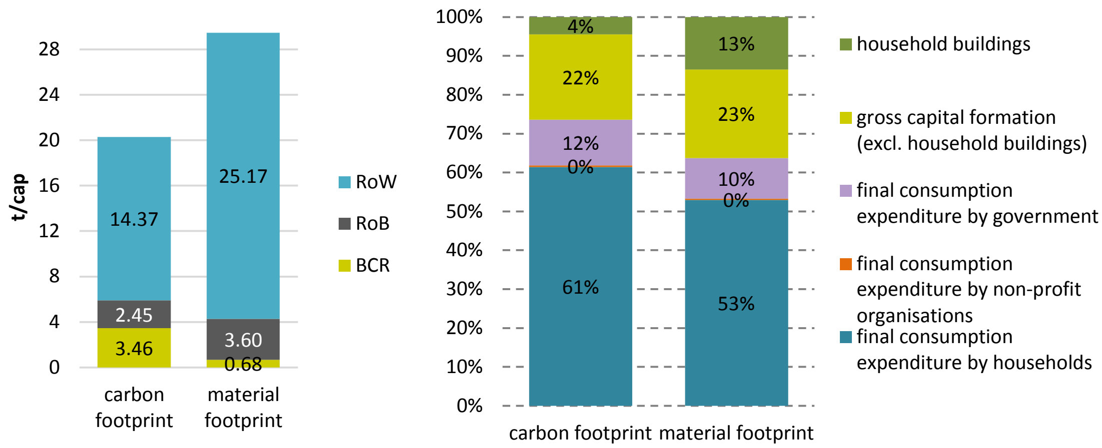

Figure 4: The material and carbon footprint of Brussels Capital Region (BCR) by origin (left) and by final demand category (right) (2010; RoB: rest of Belgium, RoW: rest of world)

When disaggregating the carbon footprint and the material footprint by final demand category, 61% and 53% respectively are caused by household consumption (Figure 4). Another 4% of the carbon footprint and 13% of the material footprint are determined by investments in buildings accommodating households. Its considerable impact supports the reasoning to be included in the final consumption expenditures by households. The maintenance and energy use of housing is part of the household expenditures as well. So, the total BCR's household consumption, including the investments in housing, has a contribution of 66% in the total BCR's carbon footprint and 59% in the total BCR's material footprint. The remainder of the footprints are mainly related to government consumption and other investments.

3.2 Hotspot analysis

The relationship between the material and carbon footprint is explored by plotting the scatterplots in **Error! Reference source not found.**. The scatterplot shows both footprints, in tonnes per capita, for all 12 COICOP-divisions (01 to 12) and the additional consumption domain household investments in housing (04b). The correlation between the material footprint and the carbon footprint of these divisions is 0.6473 (Pearson correlation coefficient), revealing a relatively strong positive correlation. This high correlation can be partly explained by the use of primary fossil energy carriers. Fossil energy carriers are part of (20%) the material footprint and have a correlation coefficient of 0.9845 with the carbon footprint, revealing a perfect positive linear relationship. This could have been expected as there is a direct relation between both footprints: energy-related greenhouse gas emissions (carbon footprint) are a result of fossil energy carriers use (material footprint). In addition, further downstream the manufacturing/processing/production chain of material into products increases both the cumulative material and energy input along the production network. Across the consumption domains the correlation of the carbon footprint with biomass, metals and non-metallic minerals is lower, 0.2393, 0.5942 and 0.4186, respectively. These lower coefficients indicate that the relationship between material footprint and carbon footprint, on the level of the different COICOP subcategories, is not that straightforward. In addition, it shows that a reduction of the material footprint will not necessarily result in a reduction of the carbon footprint.

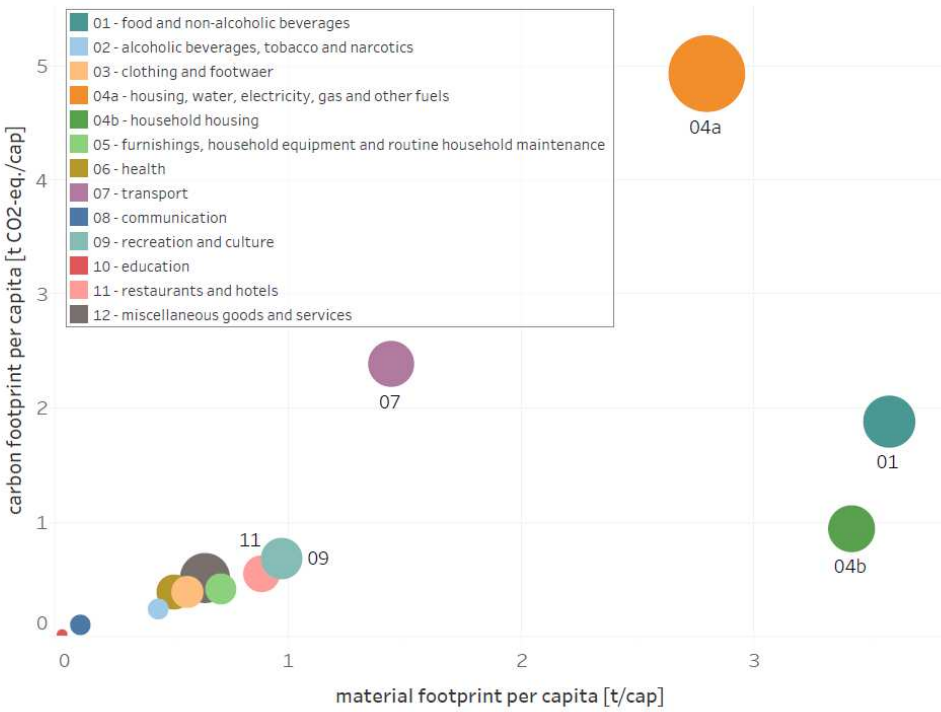

Figure 5: The relationship of material and carbon footprints of BCR's household consumption. The size of the circles is proportional to expenditures per capita.

The three household consumption domains that have both a high carbon and material footprint in the BCR are: food and non-alcoholic beverages (01), housing (incl. construction of household housing), water, electricity, gas and other fuels (04) and transport (07). The energy-related consumption domains, housing, water, electricity, gas and other fuels (04a) and transport (07) have the highest carbon footprint of 4.6 and 2.3 t/cap, respectively. They also have a considerable material footprint of 2.8 and 1.4 t/cap, respectively. The consumption domains of food and non-alcoholic beverages (01) and construction of household housing (04b) have the highest material footprints of 3.6 and 3.4 t/cap respectively, with a carbon footprint of, 1.8 and 0.9 t/cap respectively. The three consumption domains combined (food, housing and transport) make up for 75% of the BCR's households carbon footprint and 70% of the BCR's households material footprint. Table 2 provides the numerical values for all 12 COICOP divisions of BCR's households material and carbon footprint.

*Table 2: The material and carbon footprints of BCR's household consumption. *Investments in household housing are no real household expenditures, as those payments are spread across multiple years via mortgage or rentals, which are part of 04a. The category is added to include the footprint of the construction of housing, which is not part of 04a.*

COICOP	**household expenditure**	**CF**	**MF**	**CF/cap**	**MF/cap**
	million euros	*kt CO2-eq.*	*kt*	*t CO_2-eq./cap*	*t/cap*
01 – Food and non-alcoholic beverages	2,116.80	2,054.74	3,900.19	1.89	3.58
02 – Alcoholic beverages, tobacco, drugs	332.46	264.60	475.84	0.24	0.44
03 – Clothing and footwear	791.98	429.14	615.53	0.39	0.56
04a – Housing, water, electricity,	4,589.96	5,370.56	3,046.64	4.93	2.80

gas and other fuels					
04b – Household housing	*(1,708.99)**	1,034.72	3,724.51	0.95	3.42
05 – Furnishings, household equipment and routine household maintenance	744.23	455.49	775.07	0.42	0.71
06 – Health	957.05	424.71	551.60	0.39	0.51
07 – Transport	1,644.60	2,595.58	1,570.98	2.38	1.44
08 - Communication	325.38	110.58	114.54	0.10	0.11
09- Recreation and culture	1,335.58	747.71	1,061.82	0.69	0.97
10 - Education	89.30	22.68	23.15	0.02	0.02
11 – Restaurants and hotels	1,043.80	600.49	964.54	0.55	0.89
12- Miscellaneous goods and services	1,949.54	558.89	699.57	0.51	0.64
TOTAL	**17,629.67**	**14,669.89**	**17,523.98**	**13.46**	**16.09**

The identified hotspots are further disaggregated to the level of groups and classes. **Error! Reference source not found.** provides more detail about the three household consumption domains of food, housing and mobility. The consumption domain food (01) is decomposed into food (01.1), which is further subdivided into 9 COICOP-classes (01.1.1 to 01.1.9), and non-alcoholic beverages (01.2). The two classes that both have the highest carbon footprint and material footprint and that slightly stand out from the others are animal products: meat (01.1.2) and milk, cheese and eggs (01.1.4). As the expenditures in these categories are similar to the other food classes, their higher footprints are caused by a high material and carbon intensity of the underlying production networks. The consumption domain of housing (04a) is decomposed into 5 groups of which the group 'electricity, gas and other fuels' 04.5 is further subdivided into different energy sources: electricity, gas and liquid fuels. The consumption domain of investments in household housing (04b) stands out, especially because of its high material footprint. Not surprisingly, as the construction processes are material intensive. The gas consumption (04.5.2) is accompanied by a high carbon footprint. It is the result of both a high expenditure (natural gas is the main source of heating in BCR) and a high carbon intensity of both the production process and the use phase. 36% of the GHG-emissions of gas consumption appear at the consumption stage. Also, the consumption of electricity (04.5.1) and liquid fuels (04.5.3) generate a considerable carbon footprint. The consumption domain transport (07) is decomposed into 10 (aggregated) COICOP-classes. The carbon and material footprint of transport is almost completely determined by the consumption of fuels (07.2.2). The footprint of the purchase of vehicles (07.1.1-07.1.3) is ten times smaller compared to the footprint of the household consumption of fuels.

Figure 6: The material and carbon footprint for food, housing and mobility of BCR's household consumption.

Figure 7 rearranges the detailed information to illustrate the link between both footprints and the direct use of energy and other consumption. 43% of the carbon footprint and 13% of the material footprint are direct related to energy use, leaving a considerable share related to product consumption which in turn illustrates why CE-strategies are relevant to mitigate GHG emissions.

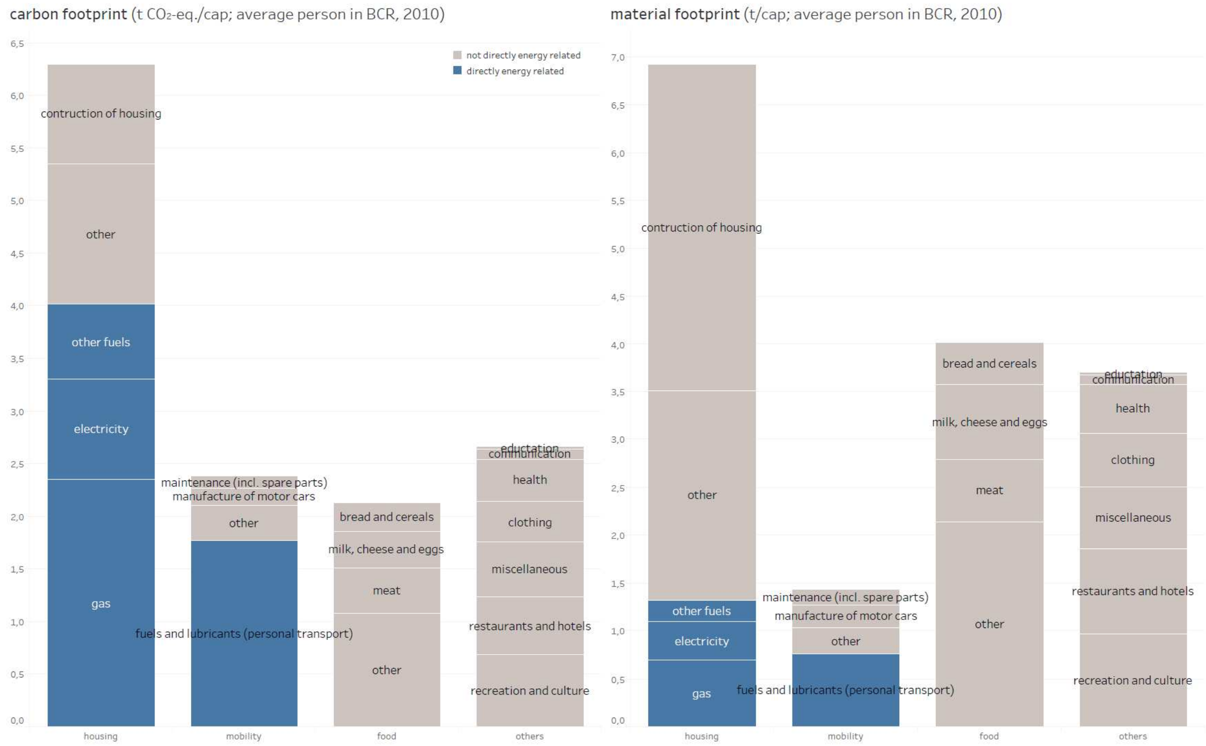

Figure 7: Detailed overview of the main consumption categories determining the carbon and material footprint per capita in BCR (2010)

3.3 Scenario analysis

The estimated impact of the scenarios on both footprints is listed in Table 3. The scenarios f2 and h2 result in a reduction of 15%, which is equal to the modelled reduction in expenditures. In fact, reduced demand directly and linearly reduces its embedded impact. Of course, this assumption does not take into account potential rebound effects. Rebound effects could lead to, given equal income, increased expenditures in other consumption domains such as traveling that might be more carbon- and material-intensive leading in increased impacts. Scenario m2 only effects the expenditures on new cars, which are only a small part of the consumer needs for mobility. For example, scenario m2 does not change the demand for maintenance or repair services and fuel usage. The impact of the scenarios f1, h1 and m1 is not equal to the assumed impact on production, because the CE-strategies impact only partly the production network. So, improvements in the production network are not equally transferred to a reduced consumption footprint. The effect of scenario m3 is the sum of the effect of scenarios m1 and m2, but this is not the case in h3 and f3 due to an overlap in the potential impact of the assumed CE-strategies.

Table 3: Carbon footprint and material footprint mitigation based on CE-strategies.

consumption domain	**carbon footprint** *t CO2-eq./cap*	**material footprint** *t/cap*	**scenario**	**CF reduction** *in %*	**MF reduction** *in %*
			f1	-12.3%	-12.8%
food	1.89	3.58	**f2**	-15.0%	-15.0%
			f3	-25.5%	-25.9%
			h1	-3.7%	-13.0%
mobility	5.88	6.22	**h2**	-15.0%	-15.0%
			h3	-18.2%	-26.0%
housing	2.38	1.44	**m1**	-4.5%	-3.2%

	m2	-2.7%	-6.6%
	m3	-7.1%	-9.8%

By analysing Table 3 it becomes visible that scenarios that address consumption needs have a higher impact on both carbon and material footprint mitigation. In addition, the proposed CE-strategies f3, h3 and m3 on food, mobility and housing could simultaneously reduce 51% and 62% of BCR's households carbon and material footprint, respectively. The scenarios show only a substantial territorial emission reduction for BCR in the mobility scenario m1 and resulting thereof m3. The mobility scenario m2 and the other scenarios have no substantial territorial impact for BCR, as the effected production activities are located elsewhere. With (very) limited supply of primary resources, the reduction effect on primary material extraction is also found outside the BCR territory.

4. Discussion

The present section discusses the findings and limitations of this research within the framework of urban environmental policy-making and climate change mitigation. Future research pathways are also described.

The current research provides a number of insights based on the BCR case that could support the city of BCR to better understand how their CE-strategies could have an impact on local climate change mitigation. By considering both direct and indirect flows for BCR, it is possible to further underline its strong linkages and dependence with a global production network. In fact, BRC relies of its global hinterland for 98% of its primary materials and 83% of BCR's GHG are emitted outside of its territory. In fact, despite the efforts BCR is making to implement environmental policies, their effects remain local and might only relate to an insignificant part of their total footprints. Similarly, BCR urban policies have a limited impact on production (as it is located outside its boundaries), so in order to effectively address circularity and climate change, their focus should shift more to consumption. This observation can only be extended to wider range of cities sharing similar characteristics than BCR. While an urban policy could influence local productive activities, due to the globalised and open character of the world economy, a large share of urban footprints would still be unaffected.

At this stage, without a coherent local and global mitigation plan for production activities, only consumption based policies at an urban scale would have an observable effect. This observation for BCR is backed up by results from Table 3 as scenarios f2, h2, and m2 are consistently more effective than their production based counterparts. Therefore, environmental police in a city like BCR, which are large consumption nodes with limited production activities and limited resources, should focus on sustainable consumption. In BCR, local initiatives on consumption can have a considerable impact in reducing global carbon emissions . For example, food consumption adopted to consumer needs, adopted quantity per package, shared multifunctional spaces and mixed use of building, car or ride sharing, etc. These findings are essential for urban environmental policy-making as it implies that more complex and comprehensive strategies need to be implemented to ensure a reduction of different urban footprints.

These results are consistent with the observation made above although they consider a linear effect on footprint mitigation and they do not consider any rebound effect. Nevertheless, it is important to underline that different consumption products from the same economic sector may have different "production recipes" which implies that the results from the analysed CE-scenarios might yield non-linear results. In addition, input-output analysis results about indirect impacts often hide great uncertainties. When combining both these limitations, the footprint reduction potential becomes considerably less certain and in the future an uncertainty interval should be added to make our insights more accurate. Furthermore, as rebound effects from circular economy strategies were not included in this research, the reduction impacts could considerably change the insights of the current study. Approaches to include these rebound effect can be found in Thomas and Azevedo (2013) and Hertwich (2005). As some CE-strategies in cities are still relatively new or small, it is difficult to estimate the relationship between CE-policies and its potential rebounds. To reduce potential future rebound effects it becomes crucial to already start monitoring and analysing the changes in consumption and production patterns after implementing CE-strategies.

A finding from this research triggering further research is that, except from fossil energy use, the carbon and material footprint of BCR are not directly related. Due to the highly intertwined effect of global environmental challenges such as resource scarcity, biodiversity loss, air and water pollution, etc. it will become necessary to identify and propose solutions that cover, at least, both footprints simultaneously. To do so, it could be relevant to look even further in detail into which expenditure elements cause the highest combined footprint (e.g. which type of meat products, which type of economic activities or land use, etc.). Additional research comparing the relationship of footprints between cities could also enable to understand whether the observed relationship is unique to BCR or is common for global cities. Comparing the relationship across a wider sample could enable to draft more comprehensive urban environmental strategies.

This paper illustrates the use of input-output analysis to measure the effect of applying CE-strategies at a city scale on climate change. In other words, it supports the understanding how it becomes possible to reduce both local and, by extension, global climate change through closing (or cycling) material flows and reducing the material footprint of cities. The results of Table 3 indicate the possibility to substantially reduce the carbon footprint of a city and its climate effects via CE-strategies focusing on households consumption. In addition, the current scenarios provide a first understanding of the potential effect of policies but also allow to propose more relevant ones. For instance, CE-strategies focusing on transportation should integrate the (footprint intensity of) fuel consumption by households. Car sharing (asset sharing) without reducing the volume of person-kilometres would only have a limited effect on the total carbon and material footprint.

From a methodological point of view, it has to be underlined that environmental extensions for Brussels IO tables originate from another Belgian Region as no sufficient data for Brussels are available. Also, the exclusion of investments in housing in the footprints of households is a major underestimation, especially in relation to the material footprint. Although this paper makes a correction for household footprints by including the investments in housing, still these footprints describe only a part of the total consumption footprint of a city: for example excluding government spending and other non-housing investments. Another aspect that could provide a more complete picture would be to complement the consumption-based results of Table 2 and 3 with territorial-based results. This could also reinforce the importance of consumption policies, as well as further express the dependency of urban economies on global supply chains and their impact on global climate change. Therefore further research is required on the difference between geographic regions, income distribution and demographics.

It is also important to highlight that while at this stage the proposed CE-strategies are essentially focusing on reducing the material footprint and by extent aiming to reduce the carbon footprint. Yet, the most efficient strategies to reduce carbon footprint should still focus on energy use reduction. Due to the use of fossil fuels, their impact on carbon footprint and climate change is much more direct. The proposed paper targets this energy use indirectly by minimising production activities that use energy. Nevertheless, it is important to mention that in the long run, if a larger share of the energy use is provided through renewable sources, further reducing the carbon footprint becomes more difficult and reducing the material footprint would become a major component for urban sustainability.

5. Conclusion

Within the framework of the Paris Agreement and the increased acceptance of CE-principles from national and local governments, it is essential to study the effect of CE-strategies on local and global climate change mitigation. This study focusses on the urban scale, as cities are major consumption nodes triggering global production chains. The present research assesses and discusses the relationship between the material and carbon footprint of theBCR in order to identify hotspots. The identified hotspots give guidance to policies to focus on those consumption needs with a high impact. While energy improvements can have an impact on all consumer needs, CE-strategies need often more focus and influence only one (or only a part) of these consumer needs. Several CE-strategies on both consumption and production are considered aiming to decrease both footprints in an effort to illustrate the mitigation potential of a city on global climate change. The findings from this research support authorities and policy-makers to develop an action plan to improve resource efficiency and reduce the emissions of greenhouse gases.

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