Modeling the carbon footprint of urban development: a case study in Melbourne

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Abstract: It is estimated that urban areas account for 60-80% of global energy use and are responsible for the emission of more than 70% of global greenhouse gases. Since most future population growth is expected to be in urban areas, one main question regarding urban planning is how new urban communities should be developed in order to minimise resource consumption and greenhouse gas emissions. This research will develop a spatially explicit model to simulate the carbon footprint of urban growth under three different development scenarios: 1) the horizontal (the business as usual (BAU) scenario), 2) vertical (Le Corbusier’s ‘Radiant City’ scenario), and 3) the mixed scenario. The intention of the research is to 1) assist in identifying the ideal spatial composition and configuration of suburban communities with potential to consume less resources and produce less greenhouse gas emissions; 2) propose an alternative approach to greenhouse gas emission control at the neighbourhood level; and 3) inform planning and design actions aimed at realising low carbon development.

Keywords: Carbon footprint; sustainability; urban planning; Melbourne.

1. Introduction

In order to limit the increase of future global warming to 2°C, it is necessary to stabilise the atmospheric concentration of CO₂ equivalent at no more than 450 ppm. To achieve this, it is necessary for all countries to implement actions to contribute to the reduction of GHG emissions from 2010 to 2050 (Güereca et al., 2013). To cope with global climate change challenges, regional and local level environmental impact measurements are important in decision making for city and regional planning (Chen, 2014). Human activities superimposed on the natural environment have caused many important transitions in our society (Galli et al., 2012; The Royal Society, 2014). Consequently, numerous natural hazards—for example drought, flood, and urban heat island—cause social, economic, and environmental problems (Mezosi et al., 2014). In order to systematically measure the impacts of human activities on the natural environment, many tools and frameworks have been developed (Barnosky et al., 2012; Borucke et al., 2013; Galli et al., 2012; Steen-Olsen et al., 2012; Wackernagel, 2014) and many studies have been undertaken to better understand environmental pressures associated with the
material flows of energy, water and other goods and services used to satisfy human needs for water, energy, food, shelter and transportation (Chavez and Ramaswami, 2013; Jha et al., 2013; Ramaswami et al., 2012). Among all these tools and frameworks, the consumer responsibility approach uses footprints as indicators of the total direct and indirect effects of a product or consumption activity.

Carbon footprint is the environmental pressure from greenhouse gas (GHG) emissions, which is characterised by a consumption-based perspective able to track human pressure on the surrounding environment, where pressure is defined as appropriation of CO$_2$ uptake and GHG emissions. Conventional carbon footprint is the total CO$_2$ emitted directly or indirectly by a certain activity or the CO$_2$ accumulation during a product life cycle (Galli et al., 2011, 2012; Larsen and Hertwich, 2010; Wiedmann and Minx, 2008), where carbon footprint is used as a measure of greenhouse gas (GHG) emissions embodied in the consumption and is usually measured using CO$_2$ equivalent (tonne). However, this definition cannot be used to quantify CO$_2$ emissions for different land use types. In this study, carbon footprint is quantified as ‘CO$_2$ land’ by applying the carbon footprint concept used by Global Footprint Network (GFN), which is similar to ecological footprint as measured using Global Hectare (Chen, 2014). The aim of this study is to analyse the carbon footprint of three different urban development scenarios in order to identify the ideal spatial composition and configuration of suburban communities to reduce resources and greenhouse gas emissions.

2. Project site and methods

2.1. Project site – The Caroline Springs growth area

The Caroline Springs growth area is selected to analyse its carbon footprint under three development scenarios. This urban growth area includes four suburbs 25km west of Melbourne – Caroline Springs, Burnside, Burnside Heights and Taylors Hill, which were developed on greenfield land since the 1990s. At the 2011 Census, Caroline Springs had a population of 20,366. It is fast-growing and the anticipated population will exceed 25,000 people in 2015. Coupling the population growth is the rapid housing development. As one of the designated urban growth areas (UGAs) by Melbourne 2030 (DOI, 2002), today Caroline Springs is one of the major growth regions in Melbourne’s western suburbs (Figure 1).

Figure 7: Caroline Springs is located at the urban growth boundary speculated in Melbourne 2030.
2.2. Methods

Time series of remote sensing imageries are collected for digital land use and cover change characterisation. GPS data and other higher resolution aerial photos are used for ground truth purposes. Statistical data and demographic data from the Australian Bureau of Statistics are collected for the analysis in the later stage, coupling the carbon footprint outputs from the GIS-based simulation model. The final stage of the study is to compare the carbon footprint of the 3 different scenarios and their carbon balance effect i.e. is the site a carbon source or sink and how large is it (Figure 2). The implications of the study are discussed in light of informing future urban planning practices aiming at realising low carbon city design. Given the data and tools used in the study, the method itself is innovative as it is the first attempt to create a spatially explicit account of carbon footprint at the neighbourhood level.

![Spatially explicit methodological framework](image)

Figure 2: The spatially explicit methodological framework employed in carbon footprint simulation.

3. The three scenarios

As noted above, if Caroline Springs grows as projected by 2030, thousands of additional people will require housing over the course of the next two decades. If these people are to be housed in freestanding homes then 8,000 homes are required. As seen in Figure 1, there is land available for homes set out at an average density of 10 homes per hectare in the current western Melbourne metropolitan area.

3.1. Horizontal scenario (Business As Usual: BAU)

In this scenario, to accommodate most of the predicted population increase, Caroline Springs would simply continue to build low-density suburbs the way it currently does in the western metropolitan
Melbourne region. The BAU plan for Caroline Springs growth area is characterised by low to medium density single family housing development with a town centre built in the middle of the site (Figure 3a). The BAU scenario applies a set of design guidelines conceived to ensure that our suburbs are well crafted at the human scale but it doesn't, and nor can it be expected to, substantively challenge suburban orthodoxy. Supporting around 20,366 people (2011 census), the current urban footprint of Caroline Springs is 285,000 hectares. The average density is 10 dwellings per hectare (the average density in many European cities is 250 dwellings per hectare, often more).

Figure 3: The three scenarios of urban development in Caroline Springs urban growth area: (a) BAU; (b) vertical scenario; and (c) mixed scenario.

### 3.2. Vertical scenario

The vertical scenario uses a density 10 to 50 times that of conventional suburbia. The theoretical basis for the vertical scenario lies in Le Corbusier’s ‘Radiant City’. This utopian ideology of urban master plan using the ‘Towers in the park’ concept was perceived to have certain influence on the urban planning of many contemporary cities including New York City (Schulz, 2015). Though radical, strict and nearly totalitarian in its order, symmetry and standardisation, the Radiant City proposed principles had an extensive influence on modern urban planning and led to the development of new high-density housing typologies (Merin, 2013). The Radiant City was to emerge from a tabula rasa: it was to be built on nothing less than the grounds of demolished vernacular European cities. The new city would contain prefabricated and identical high-density skyscrapers, spread across a vast green area and arranged in a
Cartesian grid, allowing the city to function as a ‘living machine’ (Schulz, 2015). As mentioned above, the Caroline Springs growth areas have been developed on ‘greenfield’ land since the 1990s, thus providing an ideal opportunity to test the carbon footprint of the vertical scenario using the urban planning concept described in Le Corbusier’s ‘radiant city’ ideology. The plan under the vertical scenario for Caroline Springs growth area is characterised by high-density high rise development with vast landscape reserved as green space or parks (Figure 3b).

### 3.3. Mixed scenario

The mixed scenario combines the ideal ‘Towers in the Park’ concept with the typical existing growth pattern in Australian suburbs. Under this scenario, high rise residential development is scattered among the low or medium density developments. Some innovative ideas such as Food City (Weller, 2012), which involves increased density suggest that the remaining low-lying land on the site can be utilised for high-tech organic agricultural production (Figure 3c). This idea leads to a third, Car Free City, a system of public transport which can be built into greenfield areas and retrofitted through our existing suburbs. The mixed scenario represents the potential for low carbon city development as it provides more flexible housing choices (thus higher level of affordability). It is also a more environmentally friendly approach as well as economically progressive strategy because under this scenario environmental and ecological concerns are considered against other social and cultural issues such as economic desirability and associability of living in an urban region, which are detrimental to urban life. The carbon footprint of this scenario therefore will have profound influence on the planning of future cities.

### 4. Results

#### 4.1. Spatially explicit modelling of carbon footprint

In this study, the carbon footprint is estimated by calculating the balance between the source and sink factors using land cover data based on each of the development scenarios. Carbon fluxes and emissions of each land use type are mapped using GIS-based spatially explicit modelling. A literature survey reveals that no previous spatially explicit study at suburb scales has been made. Therefore this study is the first attempt to quantify carbon footprint at the neighbourhood scale in an explicit manner. The carbon footprint per person was calculated as:

\[
CF = \sum_{i=1}^{n} CF_i
\]

(1)

Where: \( CF \) is the total carbon footprint of the site; \( i \) is individual land use category; \( n \) is the total number of land use categories (\( n = 8 \) in this study - 1) Residential, 2) Industrial and commercial, 3) Civic and institutional, 4) Agricultural, 5) Forest, 6) Grassland, 7) Wetland, and 8) Transport); \( CF_i \) is the individual land use type on the site.

Considering the fact that there are different sub-types in each land use category (e.g. different housing densities under the residential category, or different tree densities under the forest category), \( CF_i \) is calculated as:

\[
CF_i = \sum_{j=1}^{k} CF_j \times E_j \pm A_j
\]

(2)
Where: $j$ is individual land use sub-type; $k$ is the total number of sub-types in one land use category; $CF_j$ is the carbon footprint of the land use sub-type $j$ for the land use type $i$; $E_j$ is the equivalence factor for cross site comparisons, which deals with situations where the carbon sequestration or emission rate for the same sub-type of land use may be different for different project sites; $A_i$ is the adjustment factor considering local ad hoc events (such as a local bushfire) that may affect the carbon sequestration or emission of the site.

Integrating Equations (1) and (2), CF is calculated using Equation (3) as follows:

$$CF = \sum_{i=1}^{n} \sum_{j=1}^{k} CF_{ij} \times E_j \pm A_i$$

In this study, carbon footprint information is adapted from published average carbon flux (see Table 1 for details).

### Table 1: Average carbon sequestration or emission rates for different land use types

<table>
<thead>
<tr>
<th>Land use type</th>
<th>Carbon Footprint ($\pm$ t C ha$^{-1}$ yr$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>+ 120</td>
<td>Floyd, 2012</td>
</tr>
<tr>
<td>Commercial and industrial</td>
<td>+ 894.9</td>
<td>Rothberg, 2011</td>
</tr>
<tr>
<td>Civic and institutional</td>
<td>+ 60.4</td>
<td>Alvarez et al., 2014</td>
</tr>
<tr>
<td>Agriculture$^c$</td>
<td>- (1.5-2.4)</td>
<td>IPCC, 2000</td>
</tr>
<tr>
<td>Forest</td>
<td>- (2.5-7)</td>
<td>Valentini et al., 2000</td>
</tr>
<tr>
<td>Water</td>
<td>- (0.2-0.4)</td>
<td>IPCC, 2000</td>
</tr>
<tr>
<td>Grassland, park, open space</td>
<td>- (0.7) - (+0.2)</td>
<td>Parton et al., 1995; Chen et al., 1999</td>
</tr>
<tr>
<td>Wetland, riparian lowland</td>
<td>- (0.4-0.8)</td>
<td>IPCC, 2000</td>
</tr>
<tr>
<td>Transport</td>
<td>+ 29.3</td>
<td>Zhang et al., 2014</td>
</tr>
</tbody>
</table>

$^a$ Assuming no leakage outside the project boundaries and no emissions from carbon stocks in the soil; $^b$ + denotes carbon source, and – denotes carbon sink; $^c$ CO$_2$ fertilisation effect in agriculture land is considered (at current rates of increase of CO$_2$ in the atmosphere) to be 0.036 t C ha$^{-1}$ yr$^{-1}$ (van Ginkel et al., 1999)

### 4.2. Carbon footprint of the three urban development scenarios

The plans for the three development scenarios were digitised in GIS and used as input data for Equation (3) to simulate the carbon footprint under each scenario. Ancillary data such as remote sensing imagery and GPS readings are used to improve accuracy in digitising site-specific land use types such as industrial and commercial land use, and civic and institutional land use. Model outputs are presented in terms of spatial distribution patterns and annual carbon footprint for the entire suburb and for dwelling units.

#### 4.2.1. Spatial pattern of carbon footprint

The carbon footprint for each scenario is simulated and mapped using ESRI ArcGIS package. Results show that for all three scenarios, carbon footprint along the Kororoit Creek area is lower, due to the fact that the water area, wetland, and vegetated riparian zones are net carbon sinks. However, activity centres and high-density residential areas have the higher carbon footprint due to intensive consumption of energy and resources. Based on the simulation results, the vertical scenario has the
lowest carbon footprint (526,167 t C per ha per year), while the BAU scenario has the highest carbon footprint (603,533 t C per ha per year).

Figure 4: Carbon footprint of three development scenarios for Caroline Springs urban growth area (left: BAU; middle: vertical scenario; and right: mixed scenario).

4.2.2. Total carbon footprint and average carbon footprint per dwelling unit

In terms of average carbon footprint per dwelling unit, the vertical scenario has the lowest value, while the BAU scenario again has the highest footprint, indicating the BAU scenario’s carbon and environmental performance leaves considerable scope for improving sustainable urban growth and management. Total carbon footprint for the suburb, number of dwelling units, and carbon footprint per dwelling units under the three scenarios are summarised in Table 2.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total net carbon footprint (t C per ha per yr)</th>
<th>Total dwellings</th>
<th>Average carbon footprint per dwelling (t C per ha per yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU</td>
<td>603,533</td>
<td>17,150</td>
<td>35.2</td>
</tr>
<tr>
<td>Vertical</td>
<td>526,167</td>
<td>17,496</td>
<td>30.1</td>
</tr>
<tr>
<td>Mixed</td>
<td>587,126</td>
<td>18,010</td>
<td>32.6</td>
</tr>
</tbody>
</table>

As evidenced by this study, the vertical scenario, in which high-density housing development consumes less land with a larger portion of land on the site used for agricultural or other productive land uses, has the lowest footprint. The agricultural and productive land uses can assimilate carbon in the atmosphere. The removal of carbon dioxide from the atmosphere by forests and other vegetation also provides an important carbon sink. Thus, development based on land clearing (such as greenfield development) must be carefully considered in order to minimise the carbon footprint of urbanisation. However, the validity of the vertical scenario is yet to be tested on unique sites integrating and balancing the value of the people in the place, design culture, and public affordance.
5. Discussion

5.1. Development scenarios and the flavour of urban culture

In Australian cities like Melbourne, which is a quintessential suburban city, the liveability and life style is largely “radicalised” around the low density suburb. Although climate change, global warming and other pressing issues have been affecting citizens’ lifestyles, it is not likely that Australian citizens will soon accept the urban lifestyle similar to those of the Asian cities – where the majority of the population live in high rise apartments. Therefore, the priority in the next few decades is to promote and facilitate the mixed scenario. In the second phase, the high density vertical scenario may be considered and tested in some pilot study cities. Considering its potential to decrease the carbon footprint of cities, the mixed scenario and vertical scenario have been planned or built at small-medium scales around the activity centres in established suburbs or have been planned to be built around new town centres in Melbourne (Figure 5). In the future, this practice could be adopted and used widely in Melbourne’s urban growth frontier given other urban issues - such as social problems generally associated with high-density residential land use in areas of relatively low natural and cultural amenity - are sufficiently tackled and well-integrated in design and planning. To a certain degree, development following all the three scenarios will co-exist in Melbourne.

Figure 5: Mixed-use residential, retail and office development for North Melbourne (source: buchan.com.au).

5.2. Data quality and modelling techniques

Since the simulation is based on geocoded spatial data in GIS, the quality of input data has considerable influence on the outcomes of the study. The carbon footprint data were sourced from a literature survey from various sources and for different time frames, which may contribute to errors and increase discrepancy. Data with high quality in terms of both spatial and temporal resolutions is highly desired in order to maximise the reliability of the findings. In this study, basic land use information is the primary data used to drive the model. Details and further disaggregation of sub-types within each major land use type will improve the reliability of the model outputs. Unfortunately, many of these datasets are currently not available at neighbourhood scale, which probably explains why studies alike are rare.
At national or regional scales, carbon accounting studies heavily rely on statistical data, which are generally useful to guide national policy making aimed at emission reduction. However, national reduction goals are to be realised through local actions such as urban planning, design and development, which are always taken at much finer (e.g. city suburb or neighbourhood) scales. Additionally, national level carbon footprint accounts ignore spatial heterogeneity, which leads to ecological fallacy in analysis. Therefore, spatially explicit carbon footprint accounting at finer scales is critical to the realisation of the ambitions of carbon-neutral cities and the implementation of low carbon development. Unfortunately there are few efforts being made in this regard so far, although similar studies have been made in water and land use footprint (Phisher and Bayer, 2014; Norman, et al, 2012). We expect this paper to fill the gap in the carbon footprint literature by applying a novel approach to account carbon footprint at the suburban neighbourhood scale.

5.3. Further improvements to carbon footprint accounting

The model demonstrated in this paper would benefit greatly from improvements to the data used in determining the carbon footprint of urban areas/development scenarios. Data typically used in life cycle assessment (LCA) can be used to provide a more detailed, and potentially reliable, analysis of carbon footprint. This may include both spatially disaggregated national average environmentally-extended input-output data (Wiedmann et al., 2014) and industry sourced process data, providing information on carbon emissions for materials, transport modes and building typologies used in the different urban development scenarios. GIS-based carbon accounting at broad scale can be integrated with LCA assessment at building or block level to construct city-wide carbon footprint assessment in a spatially explicit manner. The implication of such studies on city and regional planning is profound and priorities should be given to these emerging interdisciplinary fields in the future.

6. Conclusion

Understanding the relationship between urban density and carbon emissions is essential for low carbon development. This paper has demonstrated a model for analysing the carbon footprint of urban developments based on land use. A suburban area located in Melbourne, Australia, was used as a case study for which three development scenarios were analysed in order to identify the type of development resulting in the lowest carbon footprint. It was shown that the vertical development scenario offers the best opportunity to reduce greenhouse gas emissions in urban areas. This analysis and the findings provide useful evidence and guidance for the planning and design of low carbon communities, which collectively will help to make the dream of low carbon cities a reality.

Acknowledgements

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References


