Creating sustainability benefits by planning for integration of garden cities in the urban scale

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Abstract
Nowadays, more than half of the world's population lives in urban areas, and in the following years urbanization is expected to keep its upward trend. The morphological attributes of an urban area (density, land uses, building types and respective emissions, transport infrastructure etc.) can significantly affect its performance in all three sustainability aspects: environmental, economic, and social. Therefore, a holistic view is crucial in urban planning, so that all aspects are taken into consideration and the correct balance between all of the integrated features is achieved.

Contemporary garden cities are characterized by moderate density, with a variety of low-rise building types and services, private gardens and wide, planted roads, so that the air can freely circulate, and solar light can penetrate the houses. The sense of belonging that is created in such configurations, where residents are not getting stacked in small areas, together with the provision of green areas in proximity create the appropriate conditions for a sustainable community. In the Swedish context, garden cities are directly related to wood constructions, thus the main construction material is wood which is a sustainable material with a low carbon footprint.

This paper focuses on a life cycle assessment comparison of the carbon footprint between two imaginary urban-form configurations: a contemporary garden city and a dense compact city, both built in a suburban area in Stockholm. Two sensitivity analyses are provided to examine a different set-up scenario and the effect of using different materials in the building types of the compact city. Furthermore, the paper proposes a city planning configuration where an interchange between high density city centres and adequately dense garden cities is applied, thus succeeding a sustainable, multidisciplinary urban planning system that will be able to meet the needs of both the present and the future generations.

Introduction
The contemporary high rate of urbanisation[1] creates some of the most complicated environmental issues. Cities are complex systems and they are created by, and for, human beings, who, in their turn, have heterogeneous needs and preferences. Thus, the task to seek efficient ways to mitigate climate impacts in urban areas has been proven challenging (Jenks, et al., 1996). The increasing demand for housing, together with the high costs in the city centre and different residential preferences, has led to the phenomenon of urban sprawl, which has been assumed to create unsustainable cities, in all three sustainability aspects – environmental, social, and economic. (Shakibamanesh & Daneshpour, 2011).[2] The negative consequences of urban sprawl to sustainability has led to the development, and major acceptance, of the compact city model, which gained popularity after the publishing of the report "Our common future" (World Commission on Environment and Development,

1. 55 % of the global population live in urban areas, and by 2050 this proportion is expected to increase to 68 %. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

2. "… unplanned, uncontrolled, and uncoordinated single use development that does not provide for a functional mix of uses and/or is not functionally related to surrounding land uses and which variously appears as low-density, ribbon or strip, scattered, leapfrog, or isolated development" (Nelson & Duncan, 1995).

1987), and, particularly after being suggested from literature in the 1990's as a model which could promote sustainability (Shakibamanesh & Daneshpour, 2011).

With the two, from a density point of view, opposite urban configuration scenarios that are described, an interesting question is how a middle-density configuration, like a modern garden city, would affect sustainability. Swedish contemporary garden cities are characterised by moderate densities, with a variety of housing types, a mix of low-rise homes and services, private gardens and planted roads, allowing solar light to penetrate the houses (Andersson, 2016). Taking these characteristics into consideration, a garden city can be seen as an urban form providing benefits of both the previously mentioned compact city model and urban sprawl; a combination of the "advantages of the most energetic and active town life, with all the beauty and delight of the country" (Howard, 1898).

This paper is examining the garden city's sustainability performance in comparison to the compact city's performance, with a focus on the carbon footprint from the residential sector in both configurations, while most of the other sustainability aspects (environmental and social) are also assessed.

LITERATURE REVIEW

The benefits of the compact city model have been analysed in many studies (referred to in (Shakibamanesh & Daneshpour, 2011), however often in comparison to the disadvantages of urban sprawl. Some of their main findings are: reduced car dependency and energy demand, provision of efficient public transportation, reuse of existing infrastructure and lower land consumption, strengthening of urban vitality and quality of life, preservation of green areas and creation of an active economic environment (Shakibamanesh & Daneshpour, 2011). However, in the mid 1990's, the contribution of the compact city model to sustainability was questioned as adverse impacts could emerge, like overcrowded areas, reduced access to open areas and daylight, deteriorated life quality, increased risk for deteriorated air quality (Breheny, 1992) and, finally, unsatisfied residents, as people would rather live in low-density areas (Gordon & Richardson, 1997) & (Bramley, et al., 2009).

The discussion clearly indicates the complexity of the problem and the reason why the relation between urban form and sustainability has been characterized as "one of the most hotly debated issues on the international environmental agenda" (Jenks, et al., 1996).[3] The aspect of urban form that is most frequently discussed is density (Bramley, et al., 2009). This is because the most common comparison performed in literature is the one between urban sprawl and the compact city, the two urban area configurations with opposite density characteristics. According to (Seto, 2014), "urban density is […] a necessary – but not a sufficient – condition for low carbon cities". High population density clearly implies high built density. The last one though, is not inextricable to high-rise constructions (Seto, 2014).

However, there are multiple aspects, other than urban density, that can and do affect the sustainability performance. E.g. layout, distribution of green areas, provision of facilities and services, variety of building types (physical characteristics, life cycle carbon footprint) and transport infrastructure (Jenks & Jones, 2010) are all important for the sustainability performance of a city. For example, according to (Cervero, 1996), a mixed land use inside the neighbourhood can positively affect residents' walking and cycling preference. This can result in a possibly stronger influence in the neighbourhood's sustainability performance than urban density (Cervero, 1996). Concerning buildings, until recently, energy savings were mainly approached by optimizing the operational energy consumption, as this had been the main contributor to the building's energy demand throughout its lifecycle (Vlassopoulou, 2019). However, nowadays, all building life cycle stages have an increased importance, since operational energy demand has significantly been reduced through the optimizations that have been applied. Therefore, the total building energy, from cradle to grave, should be discussed when assessing sustainability (Gustavsson & Joelsson, 2010). In this context, the need to choose the most sustainable construction materials has increased. EU (European Commission, 2011) and the (IPCC, 2007) state that the increased use of wood materials could entail a significant measure to mitigate climate change. Many studies have shown that wood-frame buildings require less energy and emit less CO_2 than concrete or steel-framed ones, since wood products require less energy to be manufactured (Lehmann, 2013) & (Sathre & Gustavsson, 2009).

Regarding transport infrastructure and travel habits, according to (Duncan & Hartman, 1996), sustainable urban transportation is the one that can limit emissions and waste to the amount that can be absorbed by each area. Cars are a main contributor to not only emission of fossil fuels but also to land use consumption, noise and congestion. According to an empirical research, the streets' design can affect traveling habits even more than urban densities, in examined traditional neighbourhoods (Seto, 2014). Furthermore, there is an interrelation between all the different elements of urban sustainability. For example, the development of urban sprawl – with extremely low densities – was eased by an increased car ownership. Urban sprawl, in its turn, has led to the creation of need for private vehicles to enable the commute towards facilities, services and shops (Jenks & Jones, 2010). It is, therefore, interesting to examine how the sustainability performance of a middle density urban configuration (a garden city) can differ from the respective of the currently considered as the most sustainable urban form, the compact city model. The garden city, provided that it is carefully designed, and its principles are properly applied, has been proved that it creates "long-term usable environments with large spatial qualities" (Åkesson, 2008).

Methodology

Attempting to answer such a broad and complex question requires several constraints, assumptions, and tools. Firstly, for the scope of this study, a sustainability certification tool for neighbourhoods has been used since sustainability performance of an urban area involves many interrelated aspects that cannot easily be distinguished. The chosen tool is City-Lab for districts (SGBC, 2019), a sustainability certification scheme developed by SGBC in collaboration with a large number of municipalities, contractors, consultants and other

3. Urban form: the "morphological attributes of an urban area at all scales" (Williams, et al., 2000).

Table 1. Basic values for the urban form scenarios.

	Compact city	Garden city
Number of housing units	18	476
Number of apartments	1,746	1,280
Number of residents	5,940	3,806
Density factor (residents/ha)	92	59
GAF	0.56	0.52
Public green area/resident	61	32
Types of housing units	1 block of 4 multi-storey concrete buildings	2 types of detached single-family houses, semi-detached 2-storey houses and 4-storey wooden multi-family buildings

stakeholders.[4] In the analysis presented in this paper CityLab has been used as a framework for indicators that have been assessed, as it focuses on performance and it consists of a large but still limited number of indicators both for environmental and social sustainability, hence simple to use (Vlassopoulou, 2019). Evaluating the sustainability performance in relation to CityLab's indicators required comparable data for the two urban configurations, which was not readily available from existing neighbourhoods in Sweden.

Therefore, it was decided that an area of 646,000 m^2 in Sundbyberg should be considered as an "empty" area, which was used to assume the set-up of either a compact city-like neighbourhood or a garden city-like neighbourhood.[5] Representative residential building types were chosen for each of the two urban forms, based on the contemporary most common building material and building types in Sweden. For the compact city multi-storey buildings concrete building frame were chosen, while for the garden city low-rise buildings made of wood were chosen. The compact city's multi-storey buildings were chosen to be represented by multiple identical concrete buildings, in particular several Blå Jungfrun blocks.[6] That is, blocks consisting of four contemporary four to six floor passive house buildings each, with a concrete building frame and an occupancy of 330 residents in each block (SvenskaBostäder, 2009). The garden city scenario was planned with a variety of low-rise wooden housing types. The building types used are two types of 1½ storey single-family houses – namely HOME#601 and TRANAN[7], one type of two-storey semi-detached houses[8] and the low-rise multifamily buildings Föreställningen.[9] The garden city scenario has been designed so that 30 % of its residents live in the wooden multi-storey buildings (with an occupancy of 54 residents/building), while the rest of the area's citizens live in the detached and semi-detached houses up to two floors (with an occupancy of four residents/home). Then, to make the comparison as objective as possible, it was decided to use the same Green Area Factor (GAF) for both of the urban area scenarios.[10] The GAF was for both of the urban forms set to be at least 0.5. It was also decided to include a basic level of services, facilities and transport infrastructure for the scenarios' respective number of residents according to the standards of CityLab for urban areas.

For the calculation of the number of residents in each of the two urban form scenarios an iterative process has been used. In this process, the remaining land area after the attribution of the mentioned basic facilities in the neighbourhood has been adjusted to the maximum fitting number of accommodation units (Vlassopoulou, 2019). All the main characteristics of the two compared urban form scenarios are presented in Table 1. Table 2 shows the main characteristics of the residential buildings, together with the number of residents that each building type accommodates in the respective neighbourhood scenario. Figure 1 illustrates the comparative land-use consumption in the two urban form scenarios. The public green spaces that are not included neither in the green spaces within the property areas, nor in the requirements of CityLab for public green spaces are referred to as "Extra green spaces". These are used to achieve the GAF required (higher than 0.5).

The comparative evaluation of the sustainability performance of the two urban form scenarios, based on CityLab indicators, has been performed either quantitatively or qualitatively, using a systematic synthesis of literature and/or statistics, municipality data or calculation tools (Vlassopoulou, 2019). The indicators assessed are security and trust in the neighbourhood, meeting places (public free space and public green space specifically), range of services, travel habits, energy demand in buildings, climate impact from buildings and transport infrastructure and biodiversity. A particular focus was set on the carbon footprint from the residential sector, which was assessed using the Life Cycle Assessment (LCA) methodology. In recent years, a rapidly increasing focus has been put on assessing the overall contribution of a building's life cycle CO_2 emissions, as the building sector is one of the most significant contributors to the environmental sustainability of an urban form.[11]

4. SGBC: Sweden Green Building Council.

5. Sundbyberg: municipality neighbouring Stockholm, with a suburban character.

6. The Blå Jungfrun block is geographically located in the suburb Hökarängen in Stockholm, it was built by the contractor Skanska.

7. HOME#601 is manufactured by Trivselhus and TRANAN by Fiskarhedenvillan.

8. The semi-detached houses are manufactured by OBOS.

9. The multi-family house Föreställningen is manufactured by Derome.

10. GAF: Green Area Factor is an indicator representing the percentage of all the green areas in a landscape, with varying weighting factors for different types of vegetation. Incentive for "covering a certain percentage of the parcel in vegetation" (Tung, 2014).

11. Building and construction sector account for 39 % of all global carbon emissions, while operational emissions are responsible for 28 %. (WorldGBC, n.d.)

Table 2. Housing units in the two urban form scenarios and their characteristics. The first four rows represent the garden city's housing units and the last row represents the compact city's housing units.

Name of housing unit	Atemp (m^2)	Living area (m^2)/person	Property area (m^2)	Number of apartments	Number of residents
HOME #601	157	37	700	192	768
TRANAN	176	43	500	192	768
OBOS (4 apartments in a semi-detached houses)	488	30	1 000	282	1 126
Föreställningen (4-storey wooden building)	1 636	23	1 700	29	1 144
Blå Jungfrun block (4 concrete multi-storey buildings)	11 003	25	8 760	97	5 940

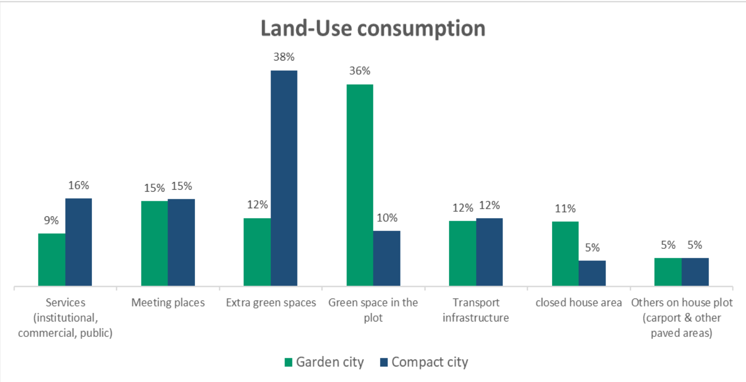


Figure 1. Comparative land-use consumption of the two urban form scenarios.

LCA METHODOLOGY

The residential buildings that represent the compact city scenario in this study – Blå Jungfrun – have been chosen for two reasons. Firstly, they are considered being representative of the common multi-storey concrete buildings built today (Liljenström, et al., 2014), and secondly, they were already analysed in detailed LCA studies, the results of the most recent of which (Malmqvist, et al., 2018) are used unaltered in this study. For the LCA results of the garden city scenario to be comparable with those of the compact city scenario, the same assumptions and limitations are considered. Therefore, the LCA stages analysed for the garden city's residential buildings are A1–3, A4, A5, B6[12] and C1–4, as shown in Figure 2. An exception is the B1 phase, which is not included in the new calculations, despite the fact that they were included in (Malmqvist, et al., 2018), the reason for this is that is that its contribution was considered negligible. Concerning the building parts included in the calculations, again, in accordance with the calculations in (Malmqvist, et al., 2018), the whole building is assessed; foundation, floor, roof, exterior and interior walls, windows and doors and electrical equipment. LCA stages A1–3 are calculated with the software BECE (Basic Energy and CO_2 Emissions for buildings) (Wallhagen, et al., 2011), while for the stages A4–5, B2,4, B6, C1–4 manual calculations were conducted. These were based on data from the respective manufacturing companies, and information found through a literature review. In some cases, approximations were used based on the LCA data of the different building systems analysed in (Malmqvist, et al., 2018). The assumptions made are presented in Table 3. It should be noted that the study has a strong local character (Sundbyberg, Stockholm) and that when "garden cities" and "compact cities" are mentioned, these refer to garden and compact city-like neighbourhoods, respectively.

Results

Most of the sustainability indicators which have been used for the comparison of the sustainability performance of the two urban configuration scenarios have mainly been qualitatively assessed in regards to the comparative basis of this study. Regarding the indicators "meeting places" and "range of services", the minimum requirements provided by CityLab has been used as a base for the planning of the two urban form scenarios.[13] Hence, both scenarios offer a basic level of meeting places as well as public services and commercial and institutional facilities, which are representative for the respective number of their residents. A differentiation is noticed in the extent of public spaces, which is substantially larger in the compact city scenario.[14]

12. For heating and electricity of the buildings the following have been assumed (based on current praxis in Sweden): compact city's buildings use district heating with an emission factor of 62 g $CO_{2\text{-eq}}$/kWh and electricity with an emission factor of 102 g $CO_{2\text{-eq}}$/kWh. The multifamily building of the garden city uses geothermal heat pump and solar panels, while the single-family and semi-detached houses use exhaust-air heat pumps, which is the dominating heat source in new Swedish single-family houses.

13. A minimum of 15 % of the area should be allocated for public open spaces, a minimum of 5 % of the area are should be allocated for green public space and available for public and at any time, a minimum of 30 m^2 should be allocated for outdoor space provided per child in preschool facilities and, at least, a basic level of various forms of services should be provided.

14. The public spaces are so large in the compact city scenario provided that the planning has been focused on maintaining a specific amount of open vegetated areas (keeping the required GAF with on-land open green spaces).

Production phase (A1-A3)			Construction Phase (A4-A5)		Operational Phase (B1-B7)							Final Phase (C1-C4)				Other Environmental Information (D)
A1 - Raw material supply	A2 - Transport to the factory	A3 - Manufacturing	A4 - Transport to the construction site	A5 - Construction-installation Process	B1 - Use	B2 - Maintenance	B3 - Repair	B4 - Replacement	B5 - Refurbishment	B6 - Operating Energy Use	B7 - Operating water use	C1 - Dismantling, Demolition	C2 - Transport	C3 - Waste Processing	C4 - Waste Disposal	D - Potential for reuse and material and Energy recovery
X	X	X	X	X		X		X		X		X	X	X	X	

Figure 2. Life cycle stages as defined in the European standard EN 15978:2011. The phases assessed in this study have been marked with an 'x' at the bottom line in the figure.

Table 3. Assumptions used in the LCA calculations. Source: Vlassopoulou, 2019.

Stage	Assumptions	Reason	Reflection
A1-3	Emissions per m^2_{Atemp} from the electrical equipment for the single-family houses: 13,9kg CO_{2-e}/m^2A_{temp}	Calculations for the attached house	The value can differ for the detached houses, but the highest emissions come from the heat-pump, which is approximately the same for all.
	Emissions per m^2_{Atemp} from the electrical equipment and elevator for the multi-family houses: 15,6kg CO_{2-e}/m^2A_{temp}	Value used for Blå Jungfrun LCA	Quite good assumption
A4	GHG emissions from diesel transportation: 87 g CO_{2-e}/MJ diesel	Typical value and the one used for Blå Jungfrun LCA	Typical although recent data show a lower emission factor
	MJ/tonkm based on (1)	Good approximations and same considerations for Blå Jungfrun	Same assumptions for all the dwellings so the compared value is close to the actual one.
	Distances calculated: from the suppliers to the factory and from the factory to the construction site (Sundbyberg)	The real distances could be provided; therefore these were the ones calculated.	The transport distances depend on the construction site's location in relation to the factory's and the supplier's location. Many differences can occur.
	Transport of construction equipment and material losses during transport assumed negligible and therefore not included	Same for all the dwellings (Blå Jungfrun and all the garden city's buildings)	A good assumption, as all houses considered in the garden city come to the construction site in modules. Probably an underestimation of the Blå Jungfrun's emissions.
A5	A5.1: the same value as for Lindbäcks construction (2)	Prefabricated buildings with wooden envelope, coming in modules. Spills per m^2 can be assumed to be the same	Fairly good assumption
	A5.2: "hjul och band grävmaskin" for excavation and "mobilkran" for the house assembly using (3) for the detached and attached houses. Same value as for Lindbäcks construction (2) for the multi-storey wooden building	Approximate data from a construction company of single-family houses (Älvsbyhus). Same reason as for A5.1 for the multi-storey building.	Probably the emissions could be a little higher for the low-rise houses, assuming any other service vehicle, but not significant change
	A5.3-5: not included for the detached and attached houses. Same value as for Lindbäcks construction (2) for the multi-storey wooden building	Effect considered negligible due to prefabrication and simple construction of the single-family houses. Same reason as for A5.1 for the multi-storey building.	Fairly good assumption
B2,4	Painting of façade, windows and doors every 10 years and replacement of windows and doors every 30 years for the detached and attached houses. Same value as for Lindbäcks construction (2) for the multi-storey wooden building	Most significant and carbon intensive requirements, according to a construction company of single-family houses (Älvsbyhus). Same reason as for A5.1 for the multi-storey building.	Probably a bit low value due to ignorance of other possibly necessary measures for the low-rise houses.
	Replacement of the electrical equipment is not considered for the detached and attached houses.	Lack of detailed data	Underestimation of the B2-4 emissions of the low-rise houses.
B6	Electricity emission factor: 102g CO_{2-e}/kWh	Same value used for Blå Jungfrun LCA	For the sake of comparison. However it is high with regards to the recent emission values of Nordic el mix (4)
C1-4	C1: according to (5)		Good assumptions
	C2: according to (6) and (7)		Good assumptions
	C3: according to (5)		Good assumptions

1. (E2B2, 2018), 2. (Malmqvist, et al., 2018), 3. (Erlandsson, 2013), 4. (Stockholms stad, 2020), 5. (Erlandsson & Pettersson, 2015), 6. (Larsson, et al., 2016), 7. (E2B2, 2018).

As for security levels, national survey statistics have been used combined with theoretical aspects regarding security in urban forms. According to the statistics, (NTU statistics, (2007–2018)) neighbourhoods with single-family houses fulfil the assessment criteria for security while this is a challenge for neighbourhoods with high rise constructions. Additionally, it is argued (Dempsey, et al., 2011) that the sense of community and sense of place in the neighbourhood to a large extent affect the quality of the place and the security and trust levels that residents experience (Dempsey, et al., 2011). It has been found in several research projects mentioned in (Smith, 2011), that aspects such as adequate amount of public spaces, minimum travel distances to facilities, aesthetically pleasant buildings and moderate housing densities can increase people's attachment to the neighbourhood which leads to positive feelings for the community (Smith, 2011). On the contrary, high density built environments, with noise, overcrowding, and lack of green space, result in lower levels of satisfaction. However, the larger possibilities of working places inside the community in dense areas increase the experienced security and the general satisfaction levels, as this reduces the need for mobility (Smith, 2011). Another related aspect is the financial security and the long term residencies that owned properties can offer. In these contexts, people tend to become more attached with the neighbourhoods and thus more satisfied (Smith, 2011). Consequently, aspects such as security and trust in the neighbourhoods, depend highly on socioeconomic criteria, such as marital status, gender, ethnicity, financial status, age and education. Thus, factors not directly related to the physical characteristics of an urban form (Jenks & Jones, 2010).

Concerning travel habits and climate impact from transport infrastructure, one of the most important issues that affect the sustainability performance of an urban form is the use of personal vehicles. The more the cars in an urban form the larger roads are needed for the transport system to be effective, and more fuels are consumed. These lead to reduced space for other uses in the area, increased emissions from the construction of additional transport infrastructure and increased emissions from fuels used. Trying to find differences in the materials and land occupied from transport infrastructure in the two assessed urban forms, has been proven challenging in the neighbourhood scale. Different materials and planning processes can be applied, depending on planning demands, the surrounding environment, economic issues and regardless of whether the neighbourhood is built up as a compact or a garden city – even if the layout of the roads in the two urban forms is usually different. Therefore, in this study it is assumed that in both urban forms the same materials are used for road construction and maintenance, as well as that the transport infrastructure is occupying the same land area. Based on this assumption, the comparative analysis is about the climate impact of transport infrastructure per person. In this context, it is reasonably the compact city that causes lower carbon emissions per person, as the carbon footprint is divided with a larger number of users.

Regarding mobility habits, one of the most discussed advantages of the compact city is that it can offer efficient public transport systems, supported by the high population density that they serve, and shorter distances, which can reduce the need for car-use (Woods & Ferguson, 2014). This is commonly used as an argument to promote the compact city model as the most sustainable one. However, according to (SKL, 2016), 50 residents per hectare is a sufficient population density for a public transport system in an urban area, and, as seen in Table 1, the garden city scenario supports a density of 59 residents per hectare. What is more, the use of private vehicles within the neighbourhood depends not only on the percentage of residents using them, but also on the number of residents in the neighbourhood. This means, that in the compact city scenario, even if a smaller percentage of residents uses private vehicles, a significant decrease in the distances travelled per person is needed to compensate for the increased population in the neighbourhood (Woods & Ferguson, 2014).

Another aspect that emerges is the extent to which the building types and population density of the two assessed urban forms may affect car ownership shares in the neighbourhood. According to a carried out by Spacescape (Spacescape, 2018) an increased number of single-family houses leads to an increased number of cars and longer distances travelled by car, even though this is mainly related to the different lifestyle and to the free-of-charge and easily available parking spaces such areas provide. This is also confirmed by (Naturskyddsföreningen, 2020), where the direct relation between increased car use and provision of parking spaces is presented. Here it should be noted that only car ownership is studied and not the number of car journeys. Finally, socioeconomical aspects (education, work nature and workplace, income, marital status, etc.) have a significant influence on travelling and mobility habits (Naturskyddsföreningen, 2020; Spacescape, 2018).

Consequently, even though the contribution of the compact city to a more effective public transport is not questioned, it might be reasonable to say that in the comparison between the compact city scenario and the garden city scenario, it is not only the building types or the population density that causes the differences, but also socioeconomical aspects, planning processes, and the extent to which mixed land use (including work spaces) is provided within the neighbourhood.

Biodiversity and stormwater management have not been directly assessed in this study, but the requirement for a GAF of at least 0.5 creates the conditions for provision of several ecosystem services in both urban forms. Carbon sequestration, stormwater interception, climate regulation and biodiversity potential are directly affected by the availability and the type of vegetated surfaces (Tratalos, et al., 2007). However, even if both assessed urban forms provide the same share of green spaces, these areas have different functions, and the basic difference is the fact that the garden cities have a large share of private gardens, while the compact cities mostly have large public green areas. The difference in the ecosystem services provided by the two studied urban forms is not easily assessed. The way people manage their private gardens is crucial for the provision of an environment that can support a variety of plants and biodiversity (Upplands Väsby, 2016), and the quality of the public green space offered in compact cities is strongly related to a number of factors, such as location, physical environment, a possible planning that isolates the green areas from the built-up land, etc. (C.Y., 2004).

As for the buildings' energy demand, all of the residential buildings that are included in this study are assumed to be low-energy buildings (high energy performance, even though not all have the same energy requirements per m^2) Hence, the energy use from the residential sector in both urban forms is considered as sustainable.

Finally, for the focus area of this study– climate impact from the residential sector – a significantly larger and more thorough quantitative analysis has been performed, using LCA for all of the buildings, as mentioned in the methodology section. In Figure 3, the graphs depict the carbon footprint from the residential sector for the whole neighbourhood scenarios, as well as the carbon footprint per square meter and per resident in the two analysed urban form scenarios. Firstly, for the carbon footprint per year in the whole neighbourhood, the garden city scenario is performing better, which is unquestionable since it accommodates significantly less residents. A more objective way of comparison, however, is the differentiation of the carbon emissions per square meter and, mainly, per capita in the two examined urban forms. Results from the study (Figure 3) shows that the garden city scenario performs better in all the LCA phases, with approximately 40 % lower carbon emissions than the compact city scenario, both in terms of emissions per m^2 and per person.

The LCA results for each building type of the garden city are presented in Figure 4. In this graph, only, the electrical equipment is not included in the amount of carbon emitted for the production phase, for any of the houses[15]. Looking at the two

15. This is because electricity and ventilation equipment emissions are only calculated for stages A1–3 in the LCA. Emissions for their maintenance and end-of life management are not included in this analysis due to lack of data. Therefore, in this graph only, also the emissions from A1–3 stages are excluded.

detached houses – first two depicted columns (HOME#601 and TRANAN) in Figure 4 – it can be observed that there is an inversely proportional relation between the produced emissions during the production phase and those during the operational phase. Moreover, the semi-detached house is performing better overall, and this can be explained by the fact that its apartments are comprised of common walls, reducing both the material required and the energy demand during the operational phase. As far as the wooden multi-storey building is concerned (last column in Figure 4), even if the carbon emissions from the production, construction-installation and maintenance-replacement stages are higher than those of the single-family houses, the emissions from the energy use during the operational phase are much lower. This can be explained both due to the fact that multifamily houses have a lower share of climate shell area per m² building than a single-family house and due to the different energy supply systems that are applied. The energy supply used for the detached and semi-detached houses is air-source heat pumps, which is the dominating heat source in new Swedish houses of these kinds. For the multi-family building, energy is assumed to be supplied by a geothermal heat pump and solar panels, which is a common choice for new buildings in this category in Sweden.

Sensitivity analysis

ALTERNATIVE PLANNING (DENSIFICATION) OF THE COMPACT CITY-LIKE NEIGHBOURHOOD

One of the basic constants in this study is the provision of the same extent of green areas in both the urban form scenarios, which is achieved by maintaining a GAF higher than 0.5. Here it is assessed how the results of the compact city's sustainability performance can be affected by replacing some of the common green areas with green roofs, covering 70 % of the buildings' roofs. (Although green roofs can be installed in combination with PV, this has not been chosen due to the increased investment that would have implied.) By implementing this alteration, the compact city can be densified to give room for more residential buildings, accommodating even more people. However, less meeting places for recreational and other services are then provided per person, and increased emissions are noticed from the residential sector (see Figure 5). In this scenario positive impacts from the green roofs, such as stormwater management and increased insulation (Bengtsson & Lind, 2017), as well as negative impacts, such as increased emissions from the materials and the possible need for structural strengthening of the buildings, have not been assessed. Regarding the transport sector, transport infrastructure emissions per person are reduced, due to the increased number of residents, but traffic-related emissions are increased, for the exact same reason. Even if densification is assumed to be related to reduced distances travelled, it is also related to an increased number of residents. This means that to reduce the net distances travelled in the area, there should be a significant decrease in the average distances travelled per capita to compensate for the increased population. (Woods & Ferguson, 2014).

Nevertheless, a new scenario, called "densified city", has been created for which the land-use and characteristics are illustrated in Figure 5. A different land allocation is provided, to adjust for the densification that is examined in this new scenario.

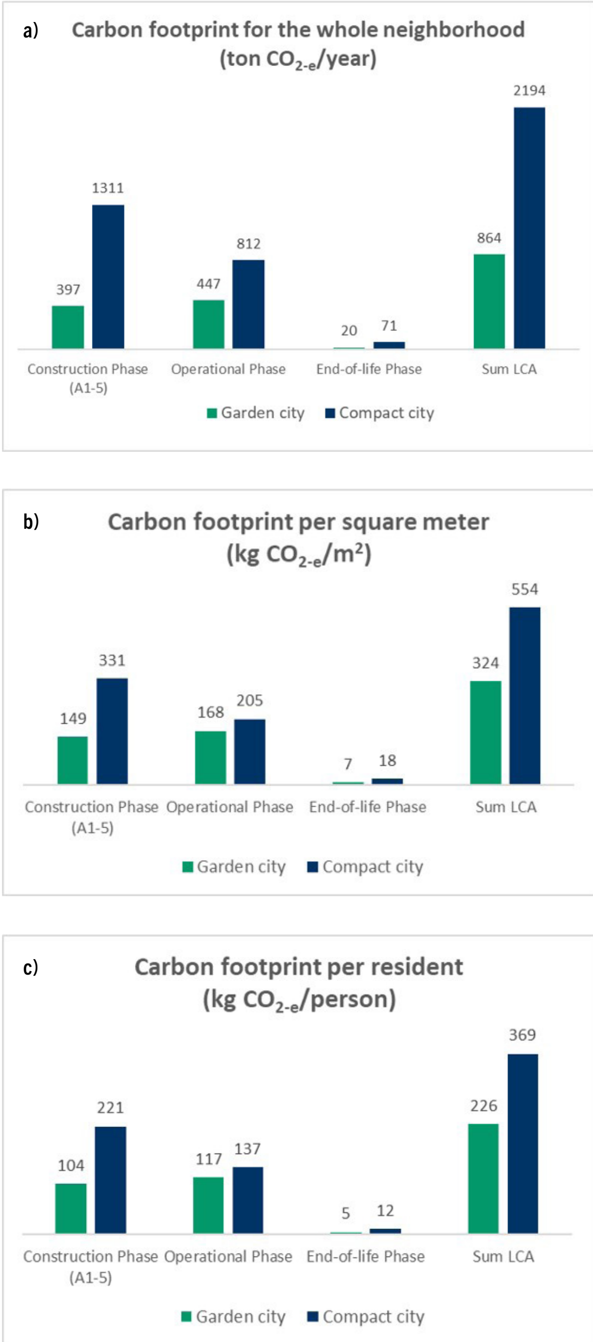


Figure 3. Carbon footprint from the residential sector in the whole neighbourhood (a), per m² (b) and per capita (c).

The carbon footprint per square meter from the residential sector, as well as per capita, remain equal to the compact city scenario's values, as exactly the same buildings are used for the residential sector. However, when the carbon footprint for the whole neighbourhood is assessed, the results are significantly worsened due to the densification (see Figure 6). However, this is balanced by the increased number of residents. It can be noted that in a comparison with the garden city scenario the densified city scenario accommodates 2.1 times more residents but emits 2.9 times higher carbon equivalent emissions from the residential sector.

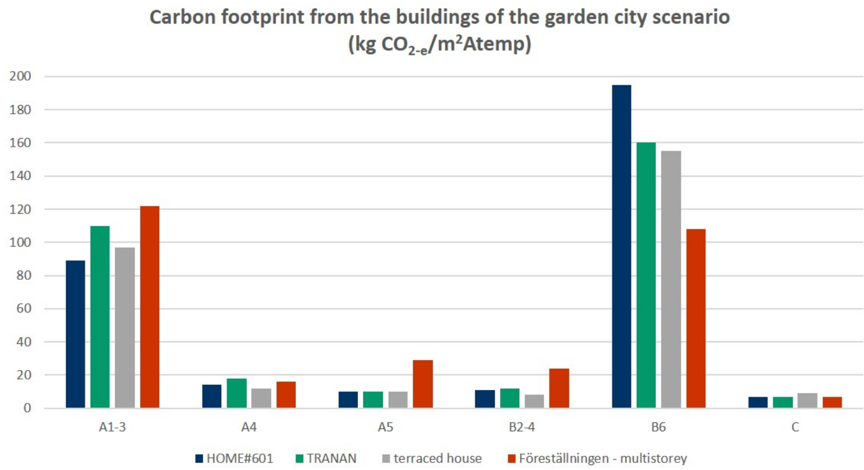
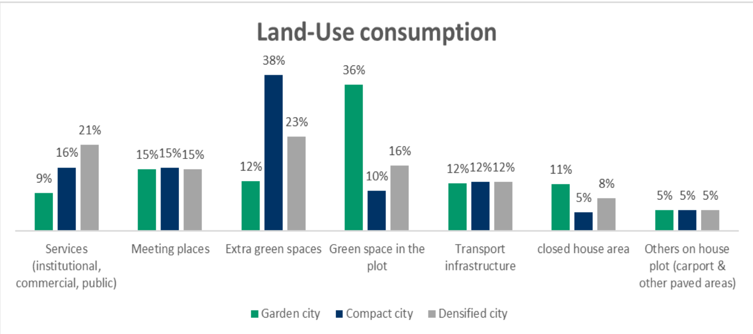


Figure 4. Carbon equivalent emissions per m² for the LCA stages assessed for the building types in the garden city scenario.



	Compact city	Garden city	Densified City
Number of housing units	18	476	30
Number of apartments	1746	1280	2910
Number of residents	5940	3806	9900
Density factor (residents/ha)	92	59	153
GAF	0,56	0,52	0,53
Public green area /resident	61	32	31
Types of housing units	1 block of 4 high-rise concrete buildings	2 types of detached single-family houses, attached 2-storey houses and 4-storey wooden multi-family buildings	1 block of 4 high-rise concrete buildings

Figure 5. Land-use consumption (left) and main characteristics of the densified city scenario (right), in relation to the two other assessed urban form scenarios.

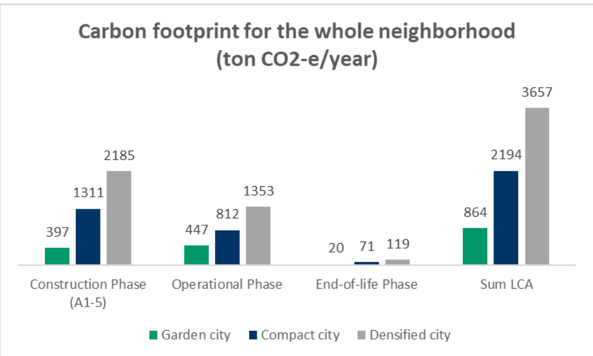


Figure 6. Carbon footprint for the densified city scenario in relation to the other two assessed urban forms.

ALTERNATIVE MATERIAL IN THE BUILDINGS OF THE COMPACT CITY-LIKE NEIGHBOURHOOD

A question that may emerge is what if the compact city scenario buildings' constructions were changed to another type of material. The results of replacing wood with concrete are shown below.

Firstly, it is examined how the compact city scenario would perform if it would be designed with wooden constructions instead of concrete. In the (Malmqvist, et al., 2018) report, Lindbäcks building was designed to the same reference house as for Blå Jungfrun's construction, occupying the same space and providing the same area (A_{temp}), as well as accommodating an equal number of residents.[16] The wood framed multi-family dwelling shows a significantly better performance than the concrete-framed one. Figure 7 shows a comparison between the carbon footprint results per capita in the "wood-compact" neighbourhood scenario, the garden city scenario and the compact city scenario. Here, the advantages of using wood constructions are clear, as the total carbon emissions per capita in the com-

16. Lindbäcks system: a system for prefabricated volume elements made of wood.

pact city would be reduced by 20 %. However, the garden city scenario still performs better, with approximately 24 % lower emissions per capita.

Using a more climate-friendly concrete type

The Blå Jungfrun construction was chosen as a reference house, as it is considered representative for the common multi-storey concrete buildings that are built today (Liljenström, et al., 2014). However, technology is constantly evolving with new materials and methods being introduced to the market. Hence simulation of applying a more climate-friendly concrete type in the Blå Jungfrun construction has been made.[17] This other type of concrete has a part of the Portland cement (which is a carbon intensive material) replaced by fly ash and slag as alternative binders. The alternative concrete type chosen in this study is the one used in different parts of a new building in Gothenburg (Riksbyggen's Brf Viva).[18] The results (Figure 8) show that the carbon emissions per capita from the production phase of the residential units would be reduced by 16 %, while the total emissions would be reduced by 8 % when using this more climate friendly concrete recipe for the compact city scenario.

Conclusions

The high urbanization rates of our times require continuously new residential developments. Moreover, the socioeconomic differences and preferences create a need for a variety of housing types and housing tenures, a need which nowadays often is neglected. These two aspects can easily lead to "allowing growth to occur in a haphazard and inefficient fashion" (Shakibamanesh & Daneshpour, 2011), which can be interpreted as the urban sprawl phenomenon. The negative consequences that it results in strengthen the already commonly held opinion that the compact city model creates the most sustainable results. According to a survey presented in a report from the Swedish National Board of Housing, Building and Planning (Boverket, 2014) approximately 70 % of the Swedes want to live in single-family or semi-detached houses. The current urban area configurations do not provide the conditions to meet the desires of the people. One of the results of this discrepancy is that a lot of new houses tend to be built in insufficiently planned areas, creating a need for expensive and environmentally unfriendly infrastructure and increased travelling distances. Furthermore, in Scandinavia a 'second home' tradition is observed, underpinning the fact that compact urban developments can create a need for 'compensation travelling', depending on socioeconomic criteria. (Haaland & Konijnendijk, 2015).

The outcome of this study is that there is no "one size fits all" concept when planning for sustainable urban areas, since the sustainability of an urban form depends on a large variety of factors. From the results of this study it has been observed that the garden city model can provide advantages in areas where the compact city model is limited and vice versa. This means that planning for an integration of garden city-like neighbourhoods in the urban scale could provide a number of benefits in the sustainability performance of the future urban areas. Sustainability is mainly about meeting the needs of the present, without compromising the needs of future generations to meet their needs. Thus, the goal should not be to meet the needs of an increased population and its related transports by investing – both financially and in terms of resources and emissions – with large infrastructure projects. The aim should be to build resource-efficient, smart, satisfying the citizens' needs and creating the necessary conditions to connect areas with efficient transit systems (Vlassopoulou, 2019).

Figure 9 shows the suggested city planning. The outer circle represents the external boundaries of the city, parts with dot-pattern represent garden city-like neighbourhoods and plain parts represent compact city-like neighbourhoods. The large bold circles represent multiple city centres; these could mitigate traffic congestions, pollution, and residency demand in the central city centre. A variation between high-density areas with multi-storey buildings and lower density garden cities would allow for the provision of choice of housing and diversity. With such a planning all city centres are linked to each other through public transport, encouraging the detachment from private car use (Vlassopoulou, 2019). Figure 9 (right) presents the intersection at one main road of the suggested city.

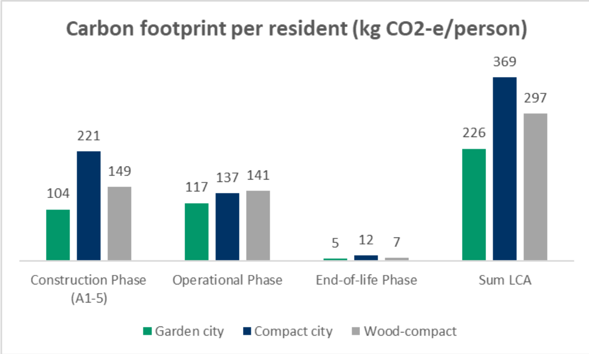


Figure 7. Carbon footprint from the wood-compact city, in relation to the other two assessed neighbourhood scenarios.

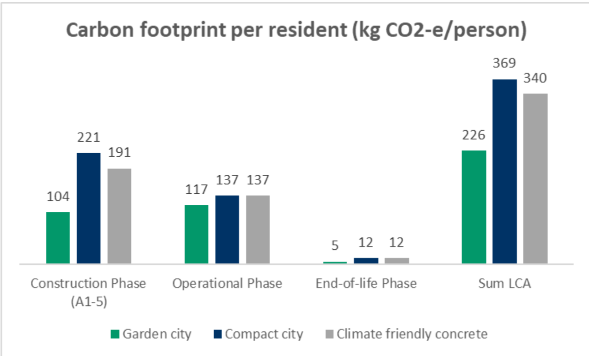


Figure 8. Carbon footprint from the compact city scenario built with a more climate-friendly concrete recipe, in comparison to the other two assessed neighbourhood scenarios.

17. With an exception for the VST-wall system, which was designed without changing the concrete recipe.

18. A detailed analysis was performed in (Kurkinen, et al., 2015) for various building frame alternatives for Brf Viva.

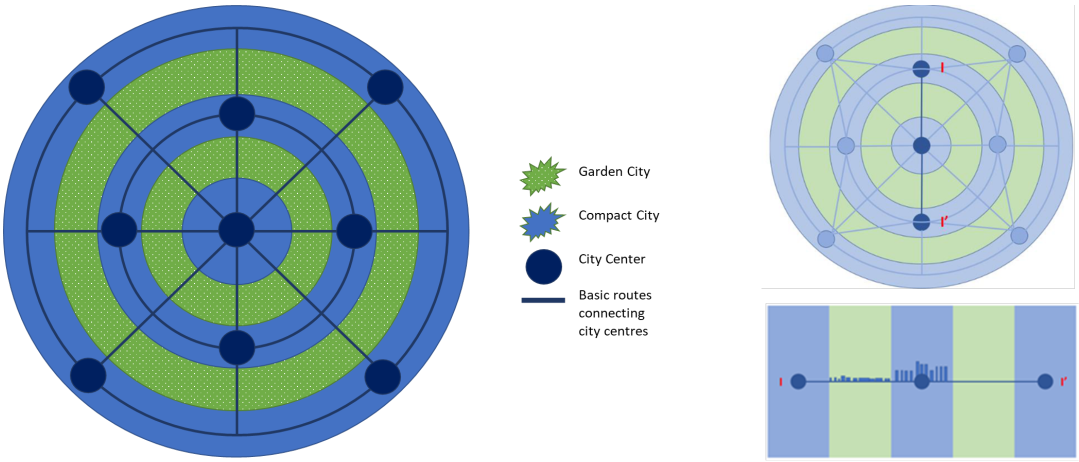


Figure 9. Illustration of the suggested city planning with a variation between garden city- and compact city-like neighbourhoods (left) and marking of the intersection I-I' for the depiction of how the two urban forms are varying inside the city (right). (Vlassopoulou, 2019.)

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