Supplementary Information

Decoupling density from tallness in analysing the life cycle greenhouse gas emissions of cities

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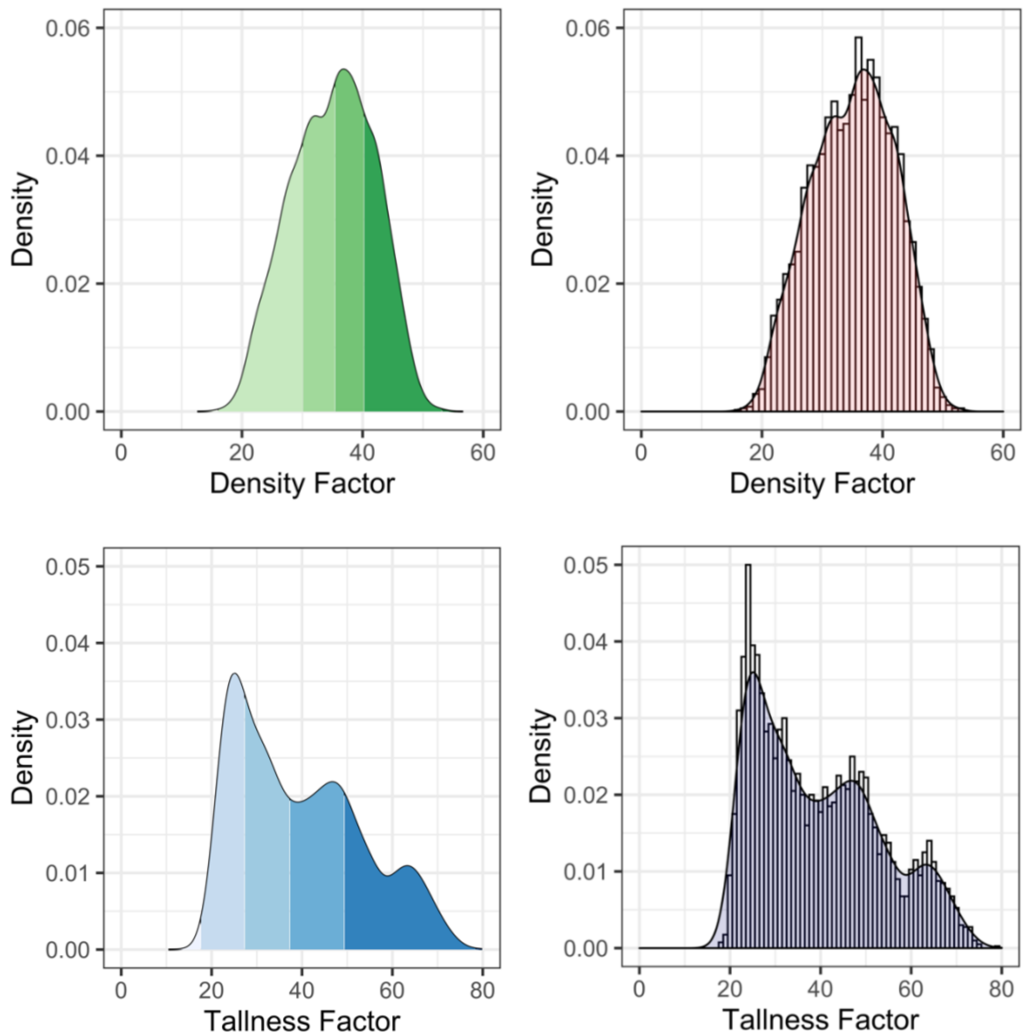
Supplementary Discussion: Urban Typology Definitions

Supplementary Figure 1 shows the histograms of all simulated environments. The data were separated into four quartiles for both density and height. The upper quartiles were then denoted as high-density and high-rise (density factor greater than 40.2 and tallness factor greater than 49.3), while the lower quartiles were denoted as low-density and low-rise (density factor less than 30.1 and tallness factor less than 27.2). The middle two quartiles are considered mid-rise or mid-density and are not included in the discussion of this study.



Supplementary Figure 1. Histogram and kernel-density estimates for the tallness and density factor of all simulated urban environments.

Supplementary Methods 1: Primary Data Collection from Existing Urban Environments

In this research we distinguish between four urban typologies which are populated by five building typologies. These are defined as follows:

Supplementary Table 1 – Building and urban typologies developed for and used in this research

Building typologies	**Urban typologies**
Non-domestic low-rise (NDLR)	High density, high-rise (HDHR)
Non-domestic high-rise (NDHR)	Low density, high-rise (LDHR)
Domestic low-rise (DLR)	High density, low-rise (HDLR)
Domestic high-rise (DHR)	Low density, low-rise (LDLR)
Terraced or semi-detached houses (House)	

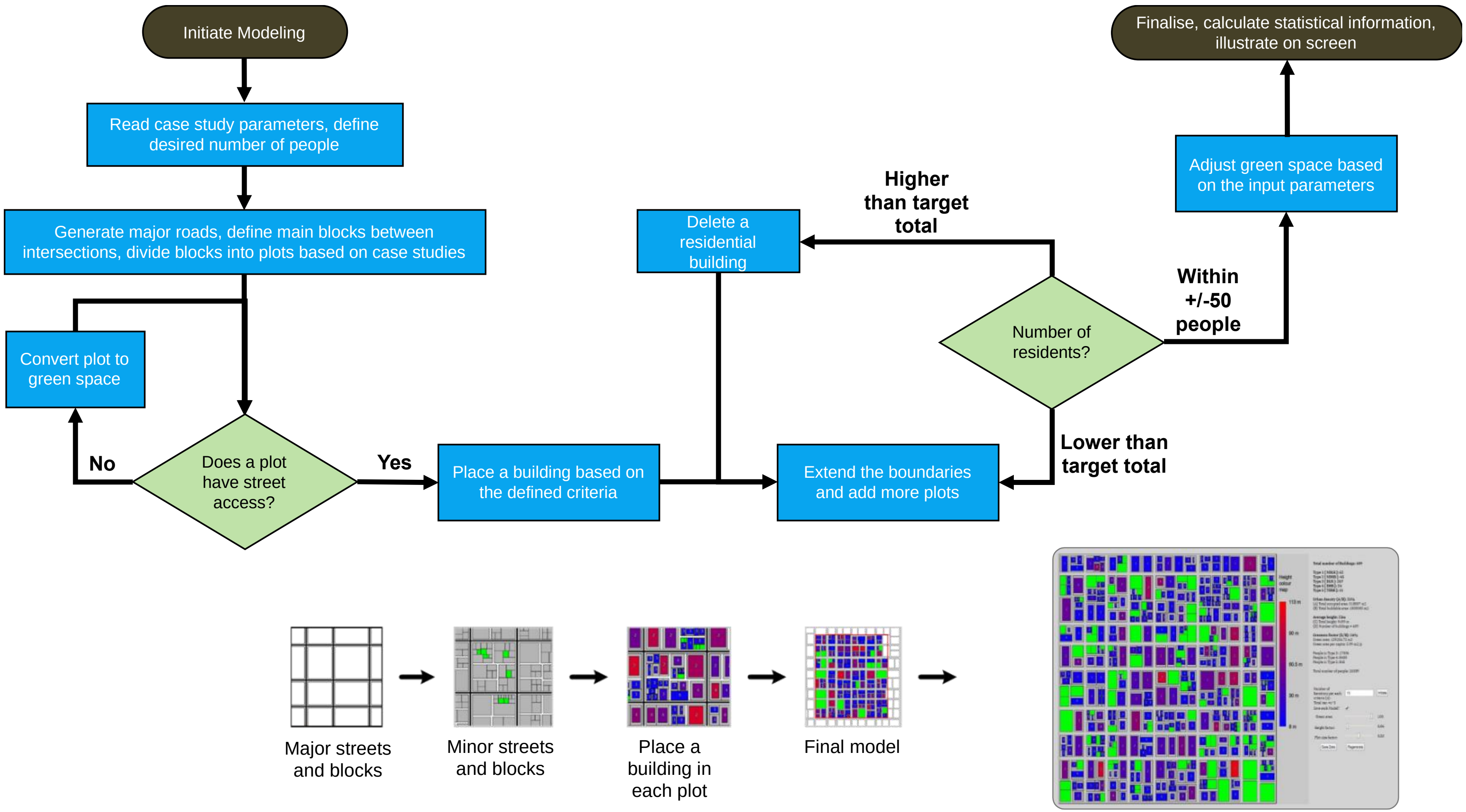
The case studies used to develop the parametric model were chosen based on building type and number of stories. The building types chosen to represent the building stock were non-domestic low rise, non-domestic high rise, domestic low rise, domestic high rise and terraced housing. Low rise was anything below five stories while high rise was above 20 stories. Five case studies were chosen for each building type from various UK cities (London, Edinburgh, Glasgow, Manchester, Leeds, Sheffield, and Birmingham) resulting in 25 case studies in total. These data were then used to cross-check other buildings in Berlin, Oslo, Stockholm and Vienna to make our analysis relevant to the broader Europe. Buildings in built up areas of the city were chosen to obtain realistic neighbouring characteristics, i.e. information about the surrounding area. The buildings were found and analysed using Google Earth and measurements were taken from the remote satellite imagery and street view. Where needed, site visits have been carried out to double check elements about which doubt remained from the satellite imagery. The building parameters and neighbouring constraints were determined to ensure realistic scenarios from the parametric model.

From remotely sensed satellite imagery, the following building parameters were found or calculated: number of stories, storey height, total height, perimeter, building envelope area, building footprint, total floor area, volume of the structure, and façade material. For the terraced housing building type, only two storey housing was chosen and the number of homes in each terrace was noted. To determine the neighbouring constraints, a square kilometre was drawn on Google Earth with each building at the centre and the following parameters were noted: number of blocks, number of green spaces, average block perimeter, average block area, average green space perimeter, average green space area, average street width, average main road width, average distance to surrounding buildings, and width and depth of the building plot (including gardens, driveways, etc.). The population densities for the different building types, i.e. number of people per square meter of floor area, were obtained from the literature. The data from these case studies are provided in Supplementary Information S4 and S5 and in raw form in S8.

To determine the embodied energy of the buildings, the following parameters were used: number of doors, number of windows, area of doors, area of windows, area of window frame, area of walls, area of insulation, and façade area. The windows and their frames were assumed to be glass and aluminium respectively, and the walls were made from either concrete or brick except for non-domestic high rise where curtain wall, fully glazed façade was assumed. Based on these parameters, and the mass of each material per square meter, the total mass of glazing, aluminium, concrete or brick, and insulation was calculated. Using the embodied carbon coefficients provided by Monahan and Powell[1] and corroborated by the ecoinvent database, the total embodied carbon for each material was calculated. Note that the embodied carbon for the materials in non-domestic high rise buildings was taken directly from Pomponi and Moncaster[2]. Operational energy values, in kWh/m^2 of floor area per year, were taken from government statistics. The operational carbon over an assumed 60 year lifespan of the buildings was calculated by applying carbon conversion factors from DBEIS[3], considering the decarbonisation of electricity at a rate of 6.4% per year for the 60 years. All data and sources pertaining to the embodied and operational analyses are provided in Supplementary Information S6 and S7.

Supplementary Methods 2: Methodological flowchart of the simulation process

The following figure shows the logical process adopted by the model to populate urban environments according to input criteria and real-world constraints.



Supplementary Figure 2 – methodological flowchart of the simulation process

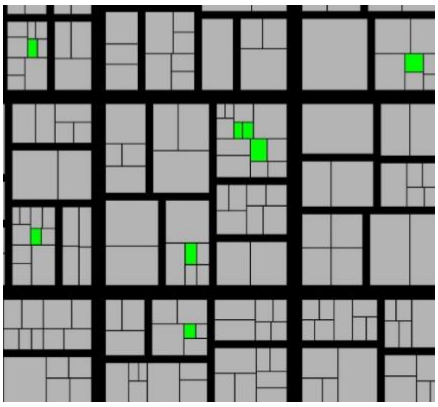
In the following, we explain in detail the sampling and stochastic process used for the genesis of synthetic urban environments for both scenarios.

To begin, 1000 building are randomly sampled from each building type. These samples were generated as uniform distributions collected from the case studies previously described and their distributions are summarised in Supplementary Table 2.

Supplementary Table 2. Geometric constraints used by the programme.

	Building Width [m]		**Building Depth [m]**		**Building Height [m]**	
Building Type	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Non-Domestic Low Rise	12.9	44	18.2	62.6	12.7	35
Non-Domestic High Rise	21.7	70	35.3	114.7	35	118
Domestic Low Rise	7.3	35	16	37.7	11	35
Domestic High Rise	16.4	31.6	24.4	4709	35	82
Terraced Houses	50	180	11.4	36.8	8	9.9

To generate blocks and plots, the whole land area is first divided into main streets and then divided into minor streets. Each block is then divided into small plots of land as shown in Supplementary Figure 3. Major and minor streets width are derived from as-measured streets in the case study cities with mains streets ranging between 13 and 16 m and minor streets having a fixed width of 7 m. The depth and width of blocks was sampled from 80 m, 100 m, 120 m, 160 m, and 200 m. If a plot does not have access to a street, then it is assumed to be a green space (e.g., Supplementary Figure 3). Additionally, the population size that can be supported by a synthetic urban environment is calculated using the coefficients in Supplementary Table 3.



Supplementary Figure 3. Division of block and plots by major and minor streets.

Supplementary Table 3. Floor area per-capita depending upon building type.

Building Type	Floor area per person [m^2]
Non-Domestic Low Rise	10.5
Non-Domestic High Rise	10.5
Domestic Low Rise	36
Domestic High Rise	36
Terraced Houses	46

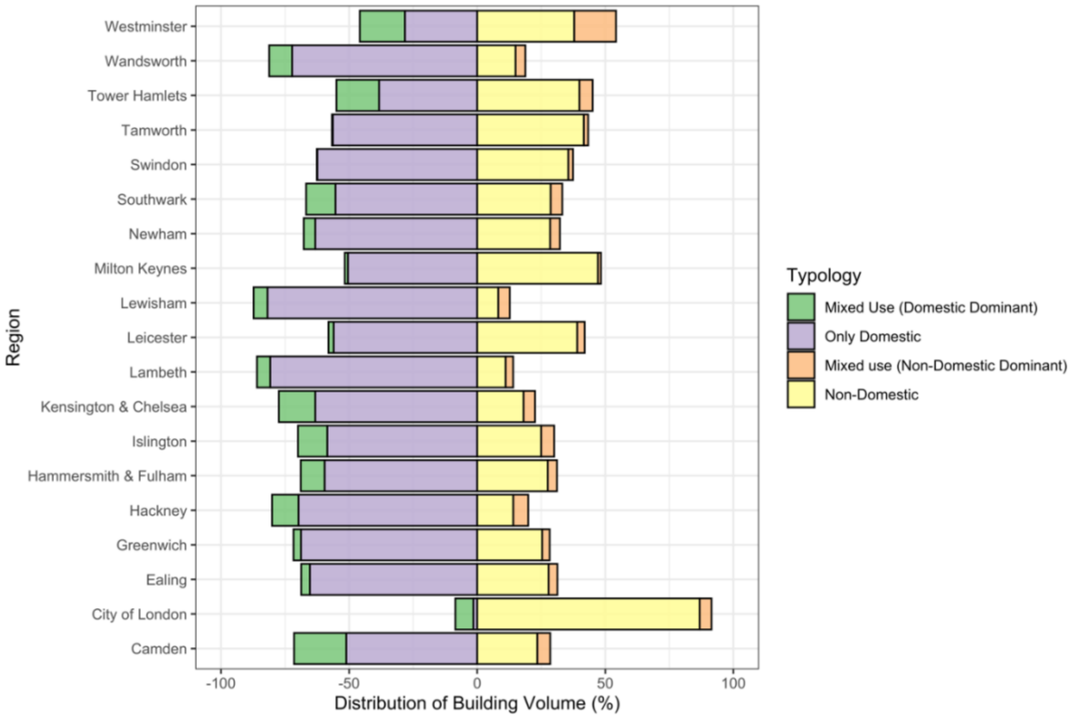
The methodology used for both scenarios is nearly identical, with minor variations between each. To place a building into each plot of land, the programme runs through randomly selecting all the buildings generated previously based on the following criteria:

- The height of building should be close to the desired height assigned for the model (0 for very low rise, 1 for very high rise with 0.5 being the separator between low and high rise).
- The model should select from buildings with heights that are within ±5 m of the desired height.
- Building footprint should fit within the size of the plot.
- The number of non-domestic high rise buildings should not exceed 25 if the target height factor is less than 0.5, 80 if it is between 0.5 and 0.85, and 200 if it is greater than 0.85. This selection is based upon trial and error until the simulation achieves a realistic scenario. Likewise, for the low-rise environments, the number of high-rise buildings are reduced in a similar fashion.
- The distance between an adjacent plot and a building should be:
  - At least 5 m from each side, yet no more than 20 m for a high-rise building.
  - If low-rise, there is no minimum spacing between buildings, but no greater than 20 m.
  - If no building can be found based upon this criterion, then the plot is converted to a green space.

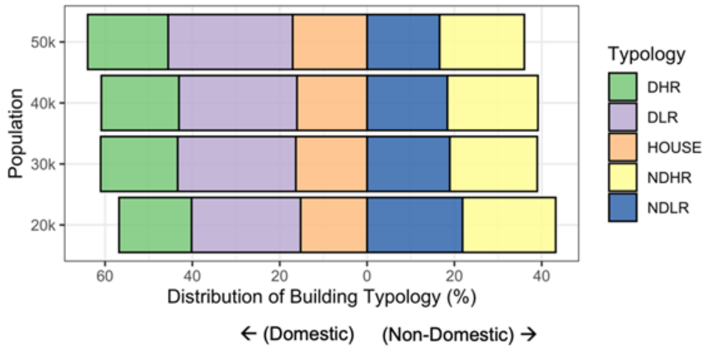
Once every plot was filled with buildings/green space, the greenness of the model is checked and adjusted to the desired greenness factor. If more green space is required, plots are randomly converted to green space to be within the proximity of the desired greenness factor gathered from our primary data collection to reflect real urban environments. Once the simulated environment has been populated, various calculations are performed to calculate the total footprint area, the buildable area, the LCGE, and, for Scenario 2, the total number of people supported.

For Scenario 1 (Fixed Population), minor changes are made to the simulation. First, the simulation begins with an area of 400 x 400 m which is populated with buildings (as previously described). If the total number of people supported is less than the desired number, then an additional 50 m is added to each side of the space and the simulation repopulated. This process is repeated until the desired number of people supported is achieved. If the number of people is higher than the target value, the algorithm searches for domestic buildings to remove (one-by-one) until the target population is achieved (within a tolerance of 50 people).

To ensure our synthetic urban environments would align well with reality, we did an analysis of the share of domestic versus. non-domestic buildings between the results in our model and primary observations from London carried out by Evans et al.[4]. Results are shown in Supplementary Figure 4.



(a)



(b)

Supplementary Figure 4. Comparison of the domestic vs. non-domestic buildings share between real world (a) and our synthetically generated (b) urban environments. With the exclusion of the City of London (which is indeed an exceptional borough), non-domestic buildings in an urban environment range between 20-50%. Our model places non-domestic buildings in a share of 30-40% which is well aligned to the evidence from the 'real world'.

Supplementary Methods 3

The supplementary method includes input data for the calculations performed to produce the results contained in this article and it can be freely, permanently, and publicly accessed via the following DOI on Mendeley Data Repository: http://dx.doi.org/10.17632/kj3zn5nx6b.1

Supplementary Note

The supplementary note includes UK case studies on buildings and neighbouring constraints as well as confirmatory EU case studies that have been used to support the findings presented in this article and it can be freely, permanently, and publicly accessed via the following DOI on Mendeley Data Repository: http://dx.doi.org/10.17632/kj3zn5nx6b.1

Supplementary References

1. Monahan, J. & Powell, J. C. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy & Buildings* **43**, 179–188 (2011).
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3. DBEIS. *Energy Consumption in the UK 2018 update (Table 3.04)*. (2018) doi:10.1073/pnas.1423686112.
4. Evans, S., Liddiard, R. & Steadman, P. Modelling a whole building stock: domestic, non-domestic and mixed use. *Building Research & Information* **47**, 156–172 (2019).