# Measuring residential building density at the scale of the urban block

## OSMuf: a Python library for quantifying urban form from OpenStreetMap

Nicholas James Owen Bristow

MA in International Planning and Sustainable Development, University of Westminster

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# Abstract

Urban development that is compact and makes efficient use of land is seen as essential to creating sustainable cities. London's commitment to deliver new housing without breaching its political boundary or encroaching on the green belt requires redeveloping and intensifying existing urban areas. Density ratios are often used to control urban development yet there remains little comparable data on what constitutes 'good' density, nor even a consensus on how to measure it. Even well-established density ratios produce widely differing results depending on how they are applied.

This paper investigates London's recent decision to drop its Sustainable Residential Quality Density Matrix and to move towards managing development with urban design guidance and site-based measures of building density. This is contrasted with the City of Buenos Aires' recent decision to reject similar plot-based measures due to their unintended and undesirable consequences for urban form. Empirical studies establish that there are fundamental flaws with applying generic density ratios to sites or plots in the expectation that it will generate consistent urban form.

These findings motivate the development of an improved method for measuring urban form that focusses uniquely at the scale of the urban block. Viewed at this scale, the linear nature of residential buildings reveals a strong correlation between residential building capacity and the frontage length of an urban block.

Freeing density measurements from land title boundaries makes it possible to assess urban form purely from physical mapping data. OSMuf, an open-source software library developed for this purpose is explained and demonstrated. It uses OpenStreetMap as its data source. Preliminary results generated by applying the new tool onto four sample areas support the earlier findings that residential building capacity is more strongly related to frontage length than land area.

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I would like to thank my family for being there for me all the way through this process and especially Melina without whose unfailing love and support this research would simply not have been possible.

Nick Bristow, August 2019

# Declaration

I declare that all of the material contained in this thesis is my own work.

"Having arranged for the necessary thoroughfares, the minor roads should be laid out to afford the requisite frontages for the average number of houses which are to be placed on each acre."
(Tudor Walters Report, Local Government Boards for England and Wales and Scotland, 1918)

## Contents

# Abbreviations

| Abbreviation | Term |
|---|---|
| CABA | City of Buenos Aires *(Ciudad Autónoma de Buenos Aires)* |
| CAD | Computer Aided Design |
| EDA | Exploratory Data Analysis |
| ESDA | Exploratory Spatial Data Analysis |
| FSI | Floor Space Index |
| | Floor Area Ratio |
| | Plot Ratio |
| | Built Potential |
| | *Factor de Ocupación Total* |
| GEA | Gross External Area |
| GIS | Geographic Information System |
| GLA | Greater London Authority |
| GSI | Ground Space Index |
| | Site Coverage |
| | Site Utilisation Factor |
| | *Factor de Ocupación del Suelo* |
| INSPIRE | Infrastructure for Spatial Information in Europe |
| LPA | Local Planning Authority |
| MAUP | Measurable Areal Unit Problem |
| N | Network Density |
| NPPF | National Planning Policy Framework |
| NUA | New Urban Agenda |
| ODI | Open Data Institute |
| ONS | Office for National Statistics |
| OS | Ordnance Survey |
| OSM | OpenStreetMap |
| PAR | Perimeter to Area Ratio |
| PIL | Private Issue Land |
| PTAL | Public Transport Accessibility Level |
| PySAL | Python Spatial Analysis Library |
| SDGs | Sustainable Development Goals |
| SEC | Smallest Enclosing Circle |
| SHLAA | Strategic Housing Land Availability Assessment |
| SHMA | Strategic Housing Market Assessment |
| SPG | Supplementary Planning Guidance |
| SRQ | Sustainable Residential Quality |
| UK | United Kingdom |
| UN | United Nations |
| UTM | Universal Transverse Mercator |
| VGI | Volunteered Geographic Information |

Note: Different terms that refer to the same concept are grouped under a single abbreviation.

# Definitions

| Term | Definition |
|---|---|
| Block / Urban Block / Net Urban Block / Street Block | An island of land of private ownership or public amenity surrounded by land dedicated to public highway. Typically subdivided into multiple plots. |
| Building block plan | Conzen's equivalent to Building Footprint. |
| Building Footprint (m2) | The GEA of a building at the ground floor only. |
| Building Density | Measures quantity of building against a Reference Area. The two building density ratios used in this study are FSI and GSI. |
| Cut-off angle | The angle between the ground and a line joining the base of one façade to the roofline of the façade opposite – used as an approximation for access to daylight |
| Dwelling Density (u/ha) | The ratio of number of dwellings (or residential units) to a Reference Area. |
| Floor Space Index / Floor Area Ratio | The ratio of the total built floor area (measured to the outside of external walls) to the Reference Area. |
| Frontage | The line where private land meets the public highway. |
| Gross Density | Ratio of something to a Reference Area that includes public highway and potentially other public spaces (e.g. gross urban block, neighbourhood). |
| Gross External Area (m2) | The sum total of a building's floor area measured to the exterior of its external walls at all storeys. In this study of urban form, basement storeys are ignored. |
| Gross Urban Block | An extension of the Net Urban Block to the centreline of the surrounding streets. It includes land dedicated to the public highway. |
| Ground Space Index / Site Coverage | The ratio of the sum of the building footprints to a Reference Area. |
| Net Density | Ratio of something to a Reference Area excluding public highway and potentially other public spaces (e.g. plot, site, net urban block). |
| Net Residential Area | The area of a plot or Net Urban Block adjusted to the proportion of the total building GEA used for residential purposes. (e.g. 1ha net urban block; 9,000m2 residential GEA, 1,000m2 commercial GEA = 0.9ha net residential area). |
| Network Density (m/ha) | The ratio of the linear length of highway to Reference Area. As the measure includes public highway this is a gross density ratio. |
| Physical Mapping | Maps that record physical things (e.g. buildings, streets, fences, hedges, streams etc.). |
| Plot | An individual piece of land under private ownership. |
| Population Density (p/km2) | The ratio of the resident population to the Reference Area. Commonly reported as people per square kilometre rather than hectare. |
| Reference Area | The area of land used for calculating density ratios. Common reference areas include the Plot, Site, Net Urban Block, Gross Urban Block, neighbourhood, etc. |
| Residential Density | A range of density ratios that specifically apply to residential building types rather than commercial, industrial etc. Typically this might be Dwelling Density, Population Density, and Residential Building Density. |
| Site | In the UK, the total area of land affected by a planning application – may be considerably larger than an individual plot. See 'The plot or the site?' p.19. |
| Tare Space | Berghauser Pont & Haupt define Tare Space at a variety of scales. In this study Tare Space is public space that is not used for highway (e.g. parks, squares, playing fields etc.). |
| Urban Form | The shape of the combined sets of elements, the streets, the blocks, the buildings and the open space. |

# 1 Introduction

## 1.1 The compact city and measuring density

The United Nations' (UN) Sustainable Development Goals (SDGs) and the New Urban Agenda (NUA) encourage sustainable urban development of "adequate densities and compactness" (United Nations, 2015, 2017, p. 19). Preventing urban sprawl is credited with improving public transport viability (Cervero & Kockelman, 1997), reducing energy consumption (Breheny, 1995) and making more efficient use of land (Williams, 2009). Yet the truth of these assertions remains equivocal (Burton, 2000; Neuman, 2005). Ever increasing density is also blamed for social segregation and a lack of affordable homes (Bowie, 2017a; Edwards, 2018).

However, sustainability is not the only motivation for compact development. London faces a crisis of housing supply and affordability (Mayor of London, 2018b) but Greater London's political boundary and the green belt limit the city's capacity for outward growth (Bowie, 2017b). Increasing the density of existing urban areas is seen as the only means of providing more housing within the capital (Mayor of London, 2017c). In an attempt to focus attention on quality of life rather than rising numbers of dwellings per hectare London intends to introduce new measures of density. Focussed on urban form they are driven by a belief that 'good design' will facilitate higher residential density levels than those recommended by current policy (Mayor of London, 2017c) yet they remain wedded to site-based density ratios.

Internationally, tracking progress against the SDGs and NUA is hampered by a lack of globally comparable metrics (Ritchie, Roser, Mispy, & Ortiz-Ospina, 2018; Valencia et al., 2019). There is no definition of what makes a city 'compact', no agreed method for measuring it (Burton, 2002) nor even a common agreement of what makes an area 'urban' (Angel et al., 2005; Valencia et al., 2019). As the World Bank notes "there has been relatively little comparative work classifying differences in the specific morphological dimensions of different urban forms, such as shapes, levels of centrality, density, and differences in shares of open space within built-up areas" (Mason & World Bank, 2017b, 2017a).

A case-study of Buenos Aires' recent revision to its *Código Urbanístico* and its rejection of measuring building density against plot area identifies a fundamental flaw in applying generic area-wide density ratios to individual sites or plots.Their new method for defining residential building capacity in relation to the perimeter of the urban block emphasises the linear nature of residential buildings and the importance of corner plots. It has the additional benefit of enabling building density to be assessed purely from physical mapping, opening a path to implementing international comparison of urban form from crowd-sourced open-data.

Following Geoff Boeing's work on OSMnx, an open source library for quantitatively analysing highway networks from OpenStreetMap (OSM) data, a new Python library is implemented. Called OSMuf, it measures urban form from OSM. It is tested on a selection of study areas and its preliminary results are discussed and compared with the findings of the case-study and simple spatial models.

## 1.2 Research focus

The research focus is on identifying a set of metrics for quantifying urban form with a particular focus on the relationship between the street network and residential building capacity.

The chosen method for measuring urban form is based primarily on Berghauser Pont and Haupt's SpaceMatrix while the implementation follows Geoff Boeing's work on OSMnx (Boeing, 2017c). The method and the implementation are combined into a new Python library that measures and visualises measures of urban from OpenStreetMap data.

## 1.3 Value

With sustainability and housing pressures driving an international focus on city compactness, a simple, reliable, openly accessible method for measuring and comparing urban form is needed. Flaws in the application of existing density metrics combined with limited openly available geographic data hamper meaningful evidence-based discussion and accurate policy responses. Based on crowd-sourced open-data and open-source software, this research offers an improved method for measuring urban form and its implementation in an open-source software library.

## 1.4 Aim and objectives

The aim of the study is to establish a reliable internationally applicable method for measuring urban form with a focus on the relationship between residential building density and street network density. A second aim is to test its implementation in open-source software, using crowd-sourced open-data.

The objectives are:

- To review existing methods for measuring density.
- To investigate how cities use them to manage development.
- To define an improved method for measuring urban form.
- To implement it using open-data and open-source software.
- To test the validity of the approach by applying the method onto four study areas.
- To make some preliminary observations about the relationship between streets and residential buildings.

## 1.5 Hypothesis

The initial hypothesis is that street network density directly affects residential building density and that London's existing planning policy, which focusses on dwelling density measured against site area, not only obscures this relationship but actively works against it.

## 1.6 Research questions

1. Why do existing site based density metrics produce inconsistent results?
2. How does street layout affect residential building density?
3. How might residential density measures be adapted to make them more consistent and to re-establish the link between street layout and urban form?
4. Can a method for generating internationally comparable measures of urban form be implemented using crowd-sourced open-data and open-source software?
5. Do the preliminary results from the software implementation support the findings from the case study?

# 2 Methodology

## 2.1 Research approach

This is a study of the quantitative analysis of urban form. It is based on two research traditions, typo-morphology and deductive, quantitative research (Berghauser Pont & Haupt, 2009). It has its roots in quantitative geography (Batty, 2016; Harris, 2016) and its philosophical world view is post-positivist. As an exploratory study, it adopts qualitative methods where required to link to contemporary urban design thinking and planning policy.

## 2.2 Research design

The background for the study and the research problem lie in a detailed review of London's existing planning policies related to site-based measures of residential density and its proposal to move to design-led capacity studies and site-based measures of building density and urban form.

An academic literature review establishes the theoretical and conceptual framework for addressing it and helps to define a core set of metrics for quantifying urban form. Some of the texts are quite old but they are important as they include concepts that have dropped out of contemporary thinking but which would help to address contemporary problems.

A qualitative case-study of Buenos Aires approach to urban form challenges hypotheses implicit in London's current approach to managing urban development with site-based density ratios. These qualitative findings are backed up by spatial modelling and empirical observation.

Exploratory Spatial Data Analysis (ESDA) and data science techniques are then used to investigate correlations between key urban metrics in sample study areas and whether they support the findings of the case study. To do this a new open source software library is developed to quantify crowd-sourced open mapping data. New ratios are identified that might be used to create a more robust evidence base for decision making in relation to urban form.

Finally, explorative abstract modelling is used to investigate the particular relationship between street network density and residential building density in isolation from the effect of other variables inherent in real-world data.

## 2.3 Research methods

### *2.3.1 Case study*

London does not have a history of using building density ratios (in London referred to as Site Coverage and Floor Area Ratio – GSI and FSI respectively) to guide residential development. In contrast, Buenos Aires does. By chance, at the same time that London is proposing to introduce building density ratios Buenos Aires has decided to remove them. A case study investigates Buenos Aires' motivations behind this decision and explores the implications for London's proposed changes. It also situates the subsequent method for measuring urban form in real-world policy and decision-making. Three empirical studies back-up the case study's findings and establish the case for the rest of the research.

### *2.3.2 Spatial analysis*

Rey (2015) defines three components of spatial analysis:

- Mapping and geovisualisation
- Exploratory spatial data analysis
- Spatial modelling

***Mapping and geovisualisation***

Mapping and geovisualisation are techniques for analysing geospatial data by representing spatial data graphically to reveal patterns and relationships that would otherwise be difficult to identify in the raw data (Singleton, Spielman, & Brunsdon, 2016).

***Exploratory Spatial Data Analysis***

Tukey defined Exploratory Data Analysis (EDA) as "any method of looking at data that does not include formal statistical modelling and inference" (1977, p. 61). Exploratory Spatial Data Analysis (ESDA) is an extension of this to geospatial data (Anselin, 2005). Limitations on the scope of this work mean that the samples cannot be taken as representative of a wider population and so no formal statistical analysis is performed. Instead, Exploratory Spatial Data Analysis techniques are used to identify initial findings suitable for further research. Univariate and multivariate graphical techniques are used to look for patterns and correlations between metrics extracted from sample areas of physical mapping data.

***Spatial modelling***

When investigating real world spatial data the effects of one variable may be hidden among the many that vary in each sample. Spatial modelling creates and analyses simplified representations, which reduce the number of variables helping to isolate the ones being studied.

### *2.3.3 Data collection*

The data for this study come from OSM a crowd-sourced map of the physical world. OSM was founded in 2004 and is judged to be one of the most successful collaboratively maintained open data sets in the world (Open Data Institute, 2018). It is an example of volunteered geographic information (VGI) (Goodchild, 2007).

The World Bank, the Open Data Institute (ODI) and others are investigating the use of OSM for urban development, planning and tracking progress against the SDGs (Chakraborty, Wilson, Sarraf, & Jana, 2015; Clark et al., 2016; Firth, 2017; Haklay, Antoniou, Basiouka, Soden, & Mooney, 2014; Open Data Institute, 2018; OpenStreetMap contributors, 2019). There are also initiatives to encourage its adoption by national governments with an example in Zanzibar (Haklay et al., 2014; World Bank, 2019).

There are various benefits of using OSM as a data source:

- It stores building, land use and highway network data.
- It has global coverage with a broadly consistent data format.
- The underlying vector geometry and attributes are available for download and use under an Open Database License (OpenStreetMap Foundation, 2012).
- It is low cost – communities and individuals can contribute to it and download data from it at no cost apart from their time and access to an adequate computer and the internet.
- As OSM's adoption grows the burden of adding and maintaining data is shared more widely and the quality improves.
- OSM has well-tested tools allowing users to modify and add data where missing.

Two concerns frequently raised when working with OSM data are completeness and quality. No map is ever complete. The United Kingdom's (UK) Ordnance Survey requires that "some 99.6% significant real-world features are represented in the database within six months of completion" (Haklay, 2010, p. 685). OSM's completeness varies greatly by element and by location.

***Highways***

OSM's global highway network data was judged 80% complete in 2017 (Barrington-Leigh & Millard-Ball, 2017). More recently a team from Oxford University combined it with data from Google Maps to map global accessibility published in the journal Nature (Weiss et al., 2018).

***Buildings***

Building information in OSM is much patchier. Various academic studies have tried to quantify its completeness and accuracy. Microsoft licensed its high-resolution Bing aerial imagery for use by OSM in 2010 (Microsoft, 2010). By way of example, in 2012 building footprints in two federal states in Germany were assessed as ≈25% complete but with a strong heterogeneity in their geometric modelling (Hecht, Kunze, & Hahmann, 2013). The data were found suitable for assessing building typologies and urban character areas (Fan & Zipf, 2015; Hijazi et al., 2017). A more recent study of Lombardy, Northern Italy assessed completeness there at ≈57% and accuracy as comparable with official maps at a scale of 1:5000 (Brovelli & Zamboni, 2018).

***Land use***

Two studies using OSM to assess land use were found but both explored methods for generating land use information that was not directly mapped in OSM (Brinkhoff, 2016; Grippa et al., 2018). The author's experience is that land use data in OSM remains crude. However, there is a growing consensus within the community on how it should be mapped.

**Further considerations**

OSM is a physical map – it does not map land ownership boundaries. OSM is a community project. Engagement with the community is fundamental to successfully contributing to and using its data.

Despite OSM's building and land use data being patchy, the workflow for adding or amending them is straightforward and consistent around the world. This means that while OSM cannot currently be used as a bulk source of building and land use data in the way that it is for highways (Boeing, 2017a; Weiss et al., 2018), a workflow for comparing international built form from small neighbourhood-size samples can be established in the knowledge that the necessary data can be added where it is missing.

### 2.3.4 Sample selection

The OSM community recommends that mappers are familiar with the areas that they work on (OSM Wiki Contributors, 2019). This is particularly important when adding information such as street names, etc. that cannot be ascertained from aerial or street view photography. On this basis, the sample areas selected are areas that the author is personally familiar with. They were also selected because they have particular characteristics that lend themselves to comparison of urban form. It is perhaps the nature of the ESDA process that the influence of some of these characteristics only became evident as the study progressed. They are summarised in the following table:

| **Place** | **Streets** | **Blocks** | **Buildings** |
|---|---|---|---|
| Clerkenwell, London | Irregular, 'organic' | Irregular shape, range of sizes, some very small | Terraced houses or shallow plan apartment buildings consistently 4-5 storeys high |
| Colegiales, Buenos Aires | Rigid square or rectangular grid | Very regular shape, 2 or 3 fixed sizes | Typically either terraced houses of up to 2 storeys or deep plan apartment buildings up to 14 storeys high |
| Welwyn Garden City | Irregular, high proportion of cul-de-sacs | Very large and very irregular shape | Short terraces of 2-storey houses |
| Bromley, London | Very long residential streets | Regular shape; large | 2-storey detached houses |

### 2.3.5 Method for quantifying urban form

The final method for analysing urban form used by the study comes out of the literature review and is described in the findings. Broadly, it is a simplification and modification of Berghauser Pont and Haupt's 'SpaceMatrix'. It looks at the same three key ratios: Ground Space Index (GSI), Floor Space Index (FSI) and Network Density (N) but applies them uniquely at the scale of the urban block. Both net measurements (excluding public highway) and gross measurements (including public highway) are generated and measures of frontage length and frontage density are introduced. Combined with observations on the limits of residential building plan-depth this gives an alternative explanation for the correlation that Berghauser Pont and Haupt found between street network density and building density which they explored uniquely in terms of relative area (2009). The modifications reinforce the link between their work, Unwin's and Martin and March's – as suggested by Steadman (2014).

## 2.4 Research tools

### *2.4.1 Geographic Information System*

Due to the small sample sizes, all of the metrics in this study could have been generated in a standard desktop Geographic Information System (GIS) application. Digital tools for analysing geospatial data have been used since the 1970s (Tomlinson, 1974). Contemporary programs such as QGIS or Esri's ArcGIS provide an easy to use interface for analysing geospatial data and OSM data is available for download in compatible file formats (Figure 1).

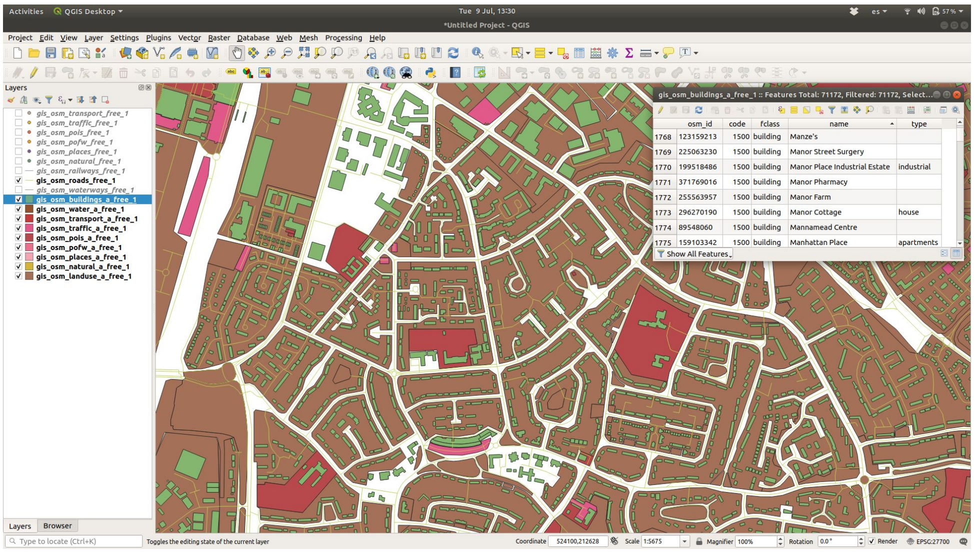


Figure 1: QGIS with OSM data for Welwyn Garden City downloaded from geofabrik.de (Bristow, 2019)

### *2.4.2 Open-source software for spatial analysis*

More recently, open access to datasets that are extremely large, very detailed, rapidly changing and often messy has encouraged the use of new tools capable of cleaning, processing and analysing this data. Much of it has a spatial component and this has led to a new methodological approach called Spatial Data Science (Anselin, 2015). These tools take a different approach from the point-and-click interfaces of standard GIS packages. For reasons of efficient use of computing resources they tend to have a text-based interface and they rely on code-based tools that, while more opaque to new users, offer greater flexibility and the opportunity for scripting new analysis methods rather than having to rely on the ones that come built in to a software application. These text-based tools also facilitate recording and repeating the process in digital notebooks that combine documentation and executable code in a single interface and do not have to rely on a description of where to click and when (Kluyver et al., 2016)(Figure 2).

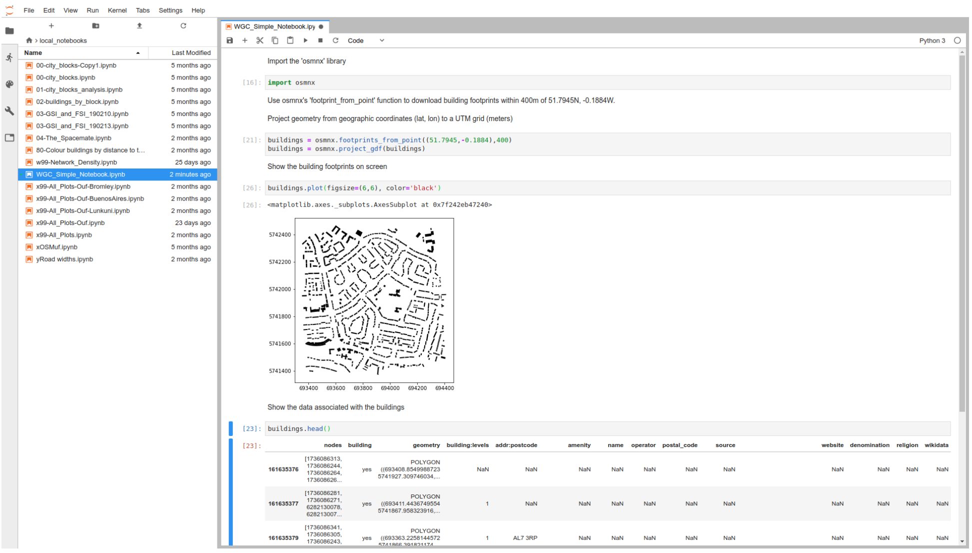



Figure 2: Jupyter notebook showing buildings from the same area in Welwyn Garden City (Bristow, 2019)

The notebook approach is also helpful for people new to programming and exploratory work because it is interactive – each line of code can be run individually and a summary result displayed. If a modification to the code is needed this can be done and the cell run again. Once a sequence of commands have been tried and tested in a notebook they can be collected as predefined methods and stored in a library enabling their consistent use across multiple notebooks.

The library developed during this study is called OSMuf (OSM urban form) and is available at https://github.com/AtelierLibre/osmuf. It builds on OSMnx adding functions for quantifying urban form and built density. Modifications were also contributed directly to OSMnx to extend its building module to work with other polygon-based geometries such as land use areas and urban block outlines and to enable it to process multi-polygons.

### *2.4.3 OSMnx*

This study has in a large part been inspired by the work of Geoff Boeing on OSMnx (Boeing, 2017b, 2017c). OSMnx is an implementation of primal graph analysis in a Python library. There are two main approaches to quantifying highway networks – primal and dual graphs (Porta, Crucitti, & Latora, 2006a, 2006b). The dual approach is topological, exemplified by Space Syntax. It looks at network configuration and disregards Euclidean distance. But, for a study on measuring urban form, the topographic primal network approach is more useful due to its retention of "geographic, spatial, metric information essential to urban form and design that dual representations discard" (Boeing, 2017c, p. 127).

Boeing has spoken of his motivation for developing OSMnx coming from the limited sample size of previous studies of road networks and the realisation that he could vastly expand the sample size by using OSM data and a programming language approach (Cornell Systems Engineering, 2019).

Figure 3: Centrality (Boeing, 2000 https://geoffboeing.com/2018/01/urban-street-network-centrality/)

## 2.5 Ethical considerations

The Big Data revolution is seen as driving a move towards data-defined rather than data-informed decision making. It is tempting to view crowd-sourced open data mapping of the physical world and quantitative analysis as objectively measuring and analysing the world as it actually is, free from value judgements and subjective interpretation. This is to ignore its role as part of a much larger framework of cultural, social, legal, fiscal and political limitations and expectations (Kitchin, 2016). Even the simple act of mapping is fraught with ethical implications – adding informal settlements to a map can be a force for good, supporting claims for land-rights and access to public services, or it might be a source of suffering if it is used as a tool for targeting evictions.

If anything, in fulfilling its aim of developing an improved method for quantifying urban form, this study reveals with greater clarity the dangers inherent in deciding where to draw a boundary and also in relying on single quantitative measures. Unquestioningly relying on site-based density ratios without understanding their interaction with land ownership divisions, culturally and legally defined building types and political decisions related to urban boundaries obscures the complex interactions between them.

# 3 Background: London's approach to density

London's approach to guiding development with density ratios and its implementation in planning policy.

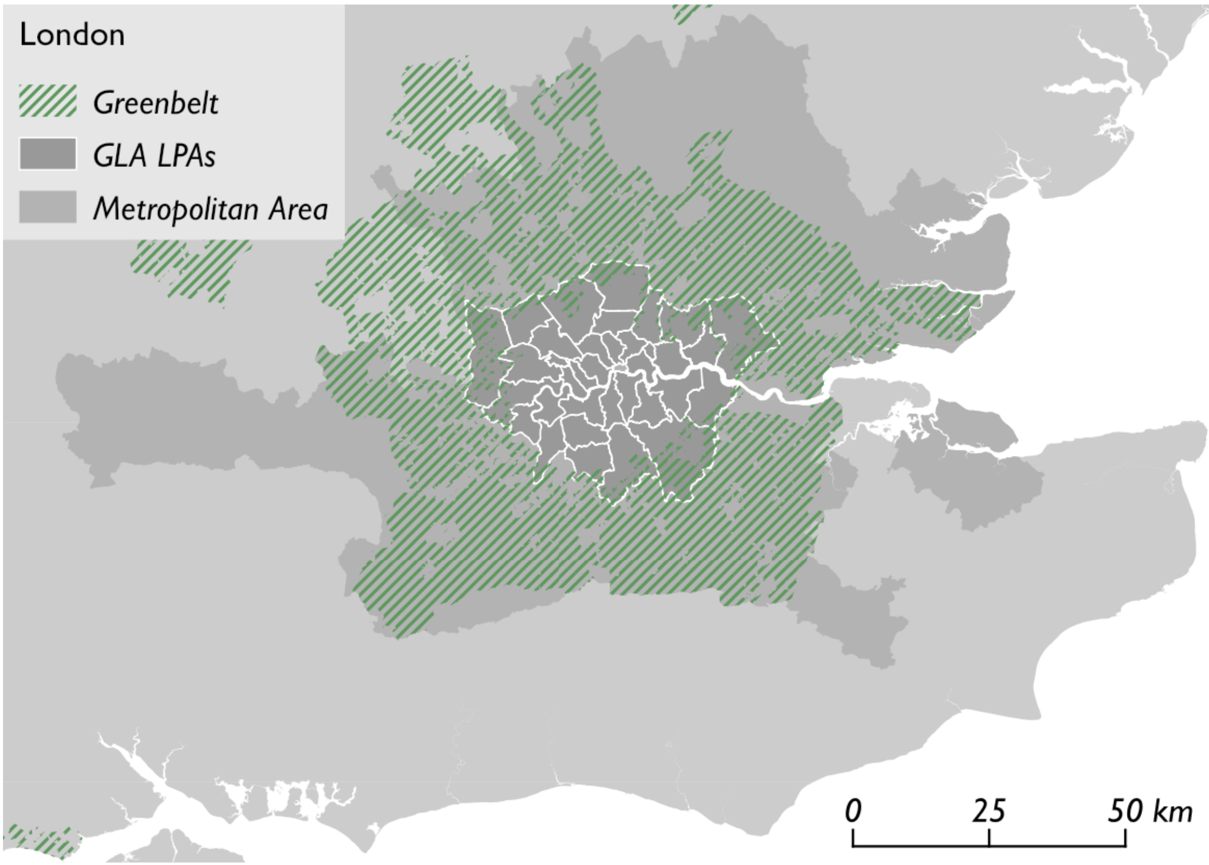



Figure 4: Map of London showing the area administered by the GLA, its wider metropolitan area and the extent of the green belt (Bristow, 2019. Source: ONS, data.gov.uk)

## 3.1 Population, housing need and planning policy

In 2017 London's metropolitan area was home to 14 million people (Eurostat, 2018). London has a relatively low population density with a maximum of 20,000 people per square km (p/km$^2$), in comparison, areas of Paris and Madrid exceed 30,000p/km$^2$ (Mayor of London, 2018a). In 2015 the population of Greater London, the area controlled by the Greater London Authority (GLA), was estimated to have reached its previous 1939 peak of 8.5 million people. It is expected to grow to 10.8 million by 2041(Mayor of London, 2017d).

The UK operates a two-stage discretionary planning system (Booth, 2007). The plan making stage defines national, regional and local planning policy. The development management stage assesses planning applications against this policy framework on a case by case basis (Department for Communities and Local Government, 2015).

Under the terms of the National Planning Policy Framework (NPPF), strategic policy-making authorities are responsible for establishing the requirement for housing in their local area and for demonstrating how that need can be met over the lifetime of their plan (Ministry of Housing Communities and Local Government, 2019). In London the GLA is the strategic policy-making authority and it produces the London Plan in collaboration with the London Boroughs (or Local Planning Authorities (LPAs)). They in turn draw up their local development plan documents (Ministry of Housing Communities and Local Government, 2019).

## 3.2 The London Plan evidence base

In carrying out its responsibility to ensure that there is an adequate supply of housing to meet London's housing need, the GLA prepares two documents:

The Strategic Housing Market Assessment (SHMA) estimates London's current and future housing need over a ten year period based on demographic projections. This is an aggregate need across the Greater London area. Based on the anticipated population of 10.8 million by 2041, the GLA's 2017 SHMA estimated that 66,000 new homes need to be built every year over the next 10 years (Mayor of London, 2017b).

The Strategic Housing Land Availability Assessment (SHLAA) assesses the supply of land available to accommodate this need. To produce the SHLAA the GLA puts out a 'call for sites' asking landowners to bring forward sites suitable for development in the next ten years. The GLA makes an initial assessment of their residential capacity before asking the boroughs to adjust them based on their local knowledge. The GLA reviews these adjustments before agreeing each borough's housing target and aggregating the results to compare London wide supply with need (Mayor of London, 2017d).

While there are many factors involved in the process, this demonstrates that London's density targets are primarily a result of dividing anticipated population growth by the area of land available - they are not based on an idealised assessment of what constitutes 'good' density.

Commitments by successive Mayors to accommodate all growth within Greater London's political boundary and without encroaching on green belt land means that London is restricted to delivering this future housing by redeveloping existing urban land at higher density and indeed the 2017 SHLAA notes that 98% of London's new housing is already delivered on brownfield sites (Bowie, 2018; Mayor of London, 2017d, 2017b).

## 3.3 Density in the existing London Plan

In order to guide where these new homes should be located, the London Plan includes a Sustainable Residential Quality (SRQ) density matrix (Figure 5). The matrix was born out of work done by Llewelyn-Davies in the late 1990s with the explicit objective of examining "to what extent and how, might London accommodate additional dwellings while maintaining urban quality and fostering sustainable development" (Llewelyn-Davies, 1998, p. 5). It sets out dwelling density thresholds for application at the scale of an individual site (ARUP, 2016). The density thresholds in the matrix are used by both the GLA and Local Planning Authorities (LPA) during the Plan Making and the Development Management stages of the planning process.

| Setting | Public Transport Accessibility Level (PTAL) | | |
|---|---|---|---|
| | 0 to 1 | 2 to 3 | 4 to 6 |
| Suburban | 150–200 hr/ha | 150–250 hr/ha | 200–350 hr/ha |
| 3.8–4.6 hr/unit | 35–55 u/ha | 35–65 u/ha | 45–90 u/ha |
| 3.1–3.7 hr/unit | 40–65 u/ha | 40–80 u/ha | 55–115 u/ha |
| 2.7–3.0 hr/unit | 50–75 u/ha | 50–95 u/ha | 70–130 u/ha |
| Urban | 150–250 hr/ha | 200–450 hr/ha | 200–700 hr/ha |
| 3.8 –4.6 hr/unit | 35–65 u/ha | 45–120 u/ha | 45–185 u/ha |
| 3.1–3.7 hr/unit | 40–80 u/ha | 55–145 u/ha | 55–225 u/ha |
| 2.7–3.0 hr/unit | 50–95 u/ha | 70–170 u/ha | 70–260 u/ha |
| Central | 150-300 hr/ha | 300–650 hr/ha | 650–1100 hr/ha |
| 3.8–4.6 hr/unit | 35–80 u/ha | 65–170 u/ha | 140–290 u/ha |
| 3.1–3.7 hr/unit | 40–100 u/ha | 80–210 u/ha | 175–355 u/ha |
| 2.7–3.0 hr/unit | 50–110 u/hr | 100–240 u/ha | 215–405 u/ha |

Figure 5: SRQ density matrix, London Plan (Mayor of London, 2016)

The appropriate density for a particular site is selected based on its Public Transport Accessibility Level (PTAL) and character setting (suburban, urban or central). By encouraging higher-density development around transport interchanges and town-centres it is seen as consistent with contemporary preferences for polycentric and compact city planning ideals. To identify a site’s PTAL and character setting two maps are made available. Transport for London’s PTAL map (Figure 6) lays a 100m x 100m grid over London and gives each cell a score based on how easy it is to access public transport from that cell (Transport for London, 2019).

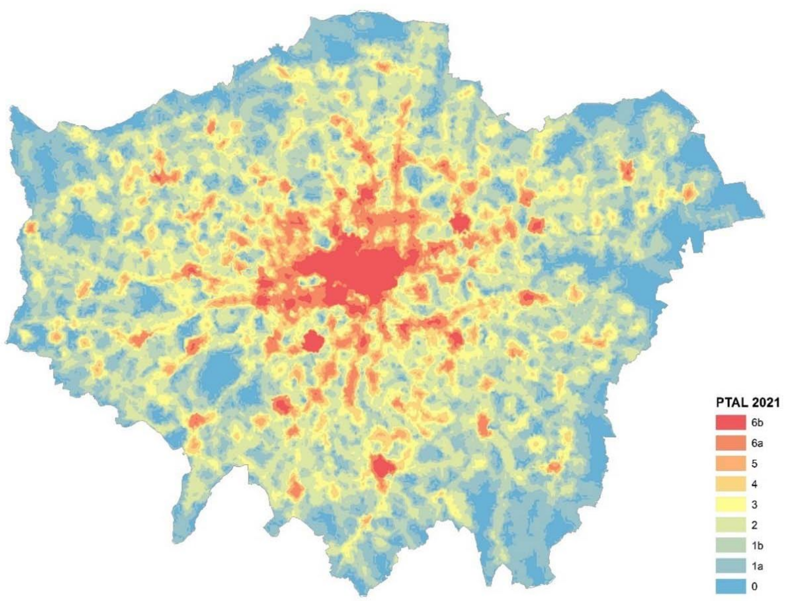



Figure 6: Map of London's Public Transport Accessibility Level 2021 (TfL, 2019)

The GLA's character map (Figure 7) represents the distribution of public services such as education and health based on the assumption that they are clustered in greater number in central or urban character areas.

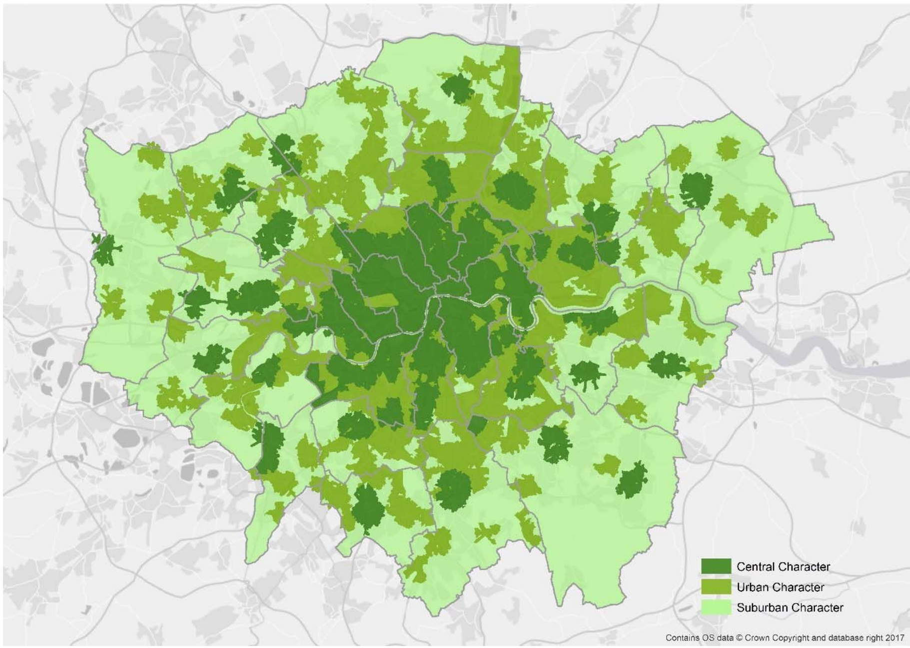



Figure 7: Map of central, urban, suburban character areas in London (ARUP, 2016)

## The plot or the site?

A complication when applying residential density thresholds in the London context is that the area they are measured against is not simply the building plot. Instead, density is assessed against the site.

The site encompasses the entirety of the land necessary for carrying out a development. In small schemes this may include areas of land beyond the ownership of the applicant such as areas of highway needed for access. In large schemes it might include land that will become public highway in the future. It is also complicated by Section 106 obligations by which a developer may be required to contribute to the local area by upgrading estate landscaping or a nearby playground. These additional areas would be included inside the red-line site boundary and so would affect the density calculations.

The author's personal experience from working on an estate regeneration scheme is that improvements to the wider estate's landscaping could be interpreted as having doubled the site area that would have been directly attributable to new building thereby reducing its reported residential density by half.

> *The application site should be edged clearly with a red line on the location plan. It should include all land necessary to carry out the proposed development (e.g. land required for access to the site from a public highway, visibility splays, landscaping, car parking and open areas around buildings). A blue line should be drawn around any other land owned by the applicant, close to or adjoining the application site.*
> (Ministry of Housing, Communities and Local Government, 2014)

> *This refers to the 'red line' planning application site boundary. It generally includes the development's housing, non-residential uses in mixed-use buildings, ancillary uses, internal access roads and car and cycle parking areas. It also generally includes the on-site open spaces (including those that are publicly accessible), children's play areas and gardens* (Mayor of London, 2017a)

## 3.4 Density research projects

In January 2016, as a result of the ongoing shortfall of housing delivery within the capital, the GLA commissioned six research projects on housing density to inform a full review of the London Plan (Mayor of London, 2016). The research conclusions were reported in a topic paper (Mayor of London, 2017c) and the key findings for the purpose of this paper are summarised here:

- 50% of development in London was at a density above the appropriate range in the matrix, 25% was double the maximum, 15% was below.
- Density outcomes in London are the result of market forces, conditioned by national policy (a restriction on greenfield development added to the existing green belt constraint in the Wider South East), and interactions between developers and local planning authorities.
- The primary density measure should be habitable rooms or bedrooms per hectare, it would be desirable to also monitor dwellings and sq. meterage (floor area ratio)
- **Variations in where a site boundary is drawn hamper meaningful comparisons of site densities. Thus, multiple measures of density such as floor area ratio [in addition to dwelling density etc.] give a better metric by which to understand the built form of a development.**
- Minimum density standards should be retained to encourage higher density in appropriate locations so as to provide additional housing and reduce dependence on the private car.
- There is no case for maximum density levels, since perceptions of density are subjective.

At around the same time that the research projects were commissioned, the Mayor's Design Advisory Group noted that "Whilst there is plenty of guidance and experience on how London should plan and design at densities of up to the top range of the Density Matrix of 405 units per hectare, there is very little to guide us beyond that. With developments being proposed in London reaching densities over 3,000 units per hectare, policies need to be updated and research undertaken to better understand the challenges and opportunities of building at such high densities" (Prasad, Allies, Scott, & Powell, 2016, p. 42). This statement is problematic not only for the very high density quoted (3000 d/ha) but also for its failure to define either the actual number of homes or the area they were being assessed against.

## 3.5 The draft new London Plan

The outcome of the density review process has ultimately been the removal of the SRQ density matrix from the 2017 draft London Plan in favour of a 'design-led approach' to density. In practical terms this means the removal of both minimum and maximum site density thresholds in anticipation that, freed from these restrictions, a greater quantity of housing will be delivered. To mitigate the potential consequences of removing the numeric controls, the GLA's intention is that a greater focus on urban design will ensure that people's quality of life is protected. It does mean however that boroughs will have to adopt a design led approach to assessing site capacity at the plan making stage as well as the design management stage.

## 3.6 Housing Design Supplementary Planning Guidance

Due to concern that borough planning authorities lack the skills and capacity to effectively implement these new London Plan housing design policies the GLA decided that it needed to replace the existing Housing Design Supplementary Planning Guidance (SPG) (Mayor of London, 2017a) with a new one. The GLA approved funding for this work in May 2018.

Consultants tendering for the work were asked "to produce a guide for determining the appropriate density of new development on a site (implementing Policies D2, D6 and H1B.2 in the draft London Plan) at the plan-making and application stages" (Mayor of London, 2018c) This should provide enough urban design guidance to council planning officers to allow them to carry out design-based site capacity assessments. It would also provide "best practice examples of higher-density housing typologies to fulfil the Mayor's ambition for good growth" (ibid.).

As part of the winning consultant team, involved during production of early drafts, the author was tasked with writing urban design guidance for large housing sites (0.25 hectares and above). This was primarily targetted at council planning officers at the initial plan making stage.

The author carried out a review of current and withdrawn UK urban design guidance (CABE & DETR, 2000; Homes & Communities Agency, 2014; Llewellyn Davies et al., 2007; Llewelyn-Davies & Alan Baxter & Associates, 2001; studio | REAL, 2007) and identified multiple conceptual gaps and ambiguous definitions that would make it hard to provide concise measures of good urban design. The literature was found to be nearly silent on the relationship between street layout, urban block size and residential density.

This lack of clear guidance on the relationship between residential density and streets, and the GLA's observation that "Variations in where a site boundary is drawn hamper meaningful comparisons of site densities" (Mayor of London, 2017c, p. 3) are extremely challenging when trying to draft urban design guidance for large sites that ultimately will still be assessed with site-based density measures – just more of them. These challenges prompted this research.

# 4 Literature review

This section reviews academic approaches to measuring city density and explores key texts related to urban form and building density.

## 4.1 Density

Cities measure density as part of their evidence base for decision-making. It helps them assess whether areas have an adequate provision of housing, jobs and public services for the current and future population. It helps keep development at a similar size and scale to its neighbours. It helps define where future development should be focussed (Gordon, Mace, & Whitehead, 2016). Boyko & Cooper (2011) identified twenty-three different density metrics that cities commonly use. Selecting the appropriate metric depends on the purpose and the scale at which it is applied.

Due to the preponderance of residential land use (approximately 80% of total urban land (Rudlin & Falk, 2014)) policy tends to focus on residential density. This has been the case in the UK at least since the establishment of byelaw terrace housing and the Tudor Walters Report (Local Government Boards for England and Wales and Scotland, 1918). Following Garden City Principles it established what it saw as a deliberately low target density of 8-12 dwellings per acre (20-30 dwellings per hectare) (Unwin, 1909; Whitehand & Carr, 1999).

It is tempting to assume that some optimum density level must exist yet research shows that high density can be as desirable as low density and that what is perceived as high-density varies internationally (Scanlon, White, & Blanc, 2018; Williams, 2009). This variation in the perception of density led Boyko & Cooper to recommend that density should be 're-conceptualised' adding 'softer' qualitative assessment to the 'harder' quantitative measures (2011). Barcelona is often held up as an ideal contemporary urban environment yet parts of Barcelona have the highest residential densities in Europe at 53,000 people per square kilometre (Rae, 2018).

The three most commonly used density measures; population density (people/area); dwelling density (dwellings/area) and building density (referred to in the UK as Floor Area Ratio or Site

Coverage – FSI and GSI respectively) establish a triangle linking people, homes and urban form (Batty, 2009; MIT, 2011).

To date London has put little emphasis on building density, focussing instead on population and dwelling density. Yet, these reveal little about the physical qualities of a place. High-rise towers in open parkland with large flats and low occupation rates could yield low densities across all measures while small low-rise houses with low separation distances and many occupants could yield both high population density and high dwelling density. For this reason measures of urban form which assess building height and bulk relative to open space have started to be linked with more qualitative assessments of liveability (Clifton, Ewing, Knaap, & Song, 2008).

As will be discussed throughout this paper, it is important to bear in mind that all density metrics are ratios: they are as affected by the reference area that they are measured against as they are by the quantity of the thing they measure.

## 4.2 Urban form, a theoretical framework

Vítor Oliveira states that "urban morphology means the study of urban forms, and of the agents and processes responsible for their transformation, and that urban form refers to the main physical elements that structure and shape the city – urban tissues, streets (and squares), urban plots, buildings to name the most important" (Oliveira, 2016, p. 2). This study is focused on urban form but sometimes the term 'morphology' may be used in relation to other texts, and the two terms should be read interchangeably. Quantifying urban form consists of establishing a reliable method for measuring the elements of the urban fabric to allow comparison.

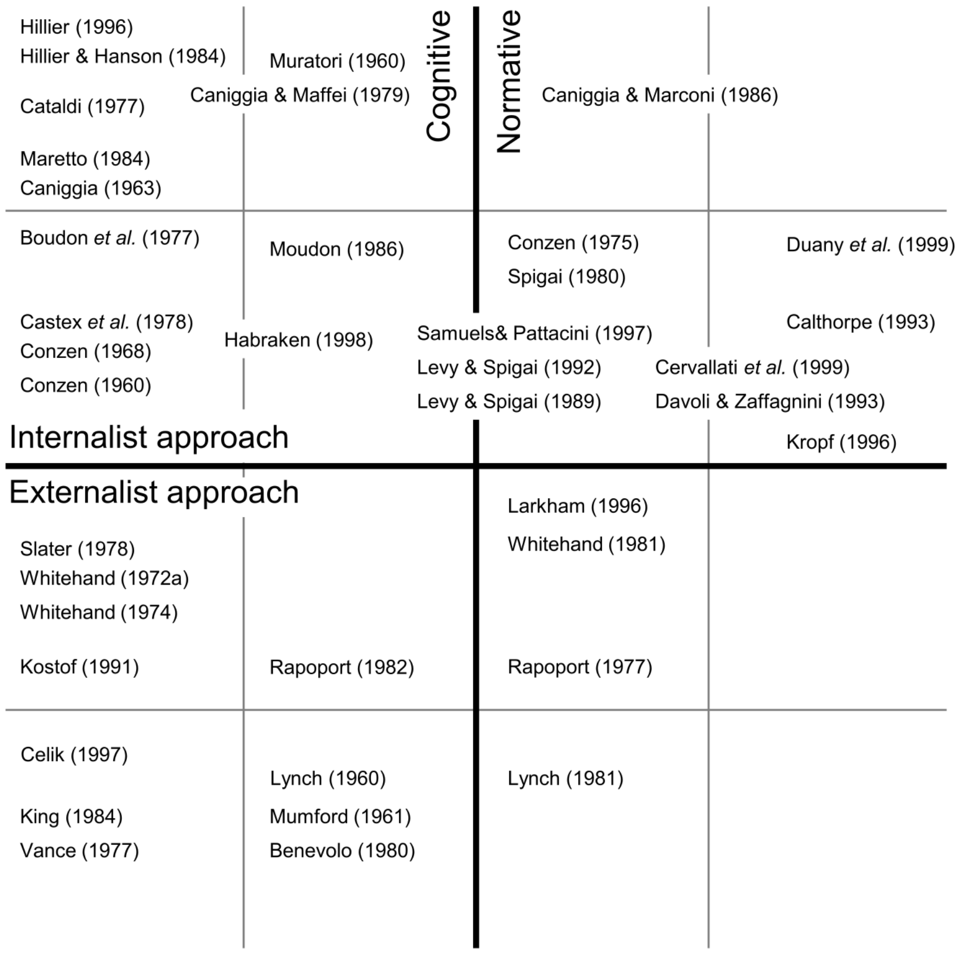



Figure 8: Categorization of urban morphology research (Berghauser Pont, 2018)

Berghauser Pont cites Gauthier and Gilliland when distinguishing generative, utopian, normative-prescriptive studies of urban morphology from analytic, descriptive studies. She sees the first group as idealised but lacking a factual basis and gives the example of Jane Jacob's work. The second group she describes as focused on "consistent and sound methodologies and techniques for measuring and comparing central variables of spatial urban form" (Berghauser Pont, 2018, p. 102; Gauthier & Gilliland, 2006).

She recognises the city as a cultural artefact which generates experiences, feelings and memories but she also emphasises that for designers to work confidently and precisely they need an accurate evidence base. She cites the work of Anne Vernez Moudon on 'space-morphology' which aims "to uncover the fundamental characteristics of urban geometries" (Moudon, 1992, p. 343).

She further identifies two branches within space-morphology both of which originated in the UK in the 1970s – Bill Hillier's work on Space Syntax at University College London (UCL) (Hillier, Leaman, Stansall, & Bedford, 1976) and Martin and March's work at the Centre for Land Use and Built Form studies at Cambridge University (Martin & March, 1972). She states that her work follows Martin and March's mathematical topographical approach rather than Hillier's configurational topological approach.

Berghauser Pont resists the inclusion of Michael Batty's work at the Centre for Advanced Spatial Analysis at UCL as a third branch within space-morphology. This study includes it because the data sources and tools that it uses to measure urban form fall squarely within the definition of urban analytics given by Michael Goodchild and cited by Michael Batty as a "new kind of urban research, one that exploits the vast new data resources that are becoming available from social media, crowd sourcing, and sensor networks..." (Batty, 2019, p. 403).

## 4.3 Urban form, a selected history

### *4.3.1 Conzen*

M. R. G. Conzen is credited with establishing geographical urban morphology in Britain. Known as the 'Conzenian tradition', it promotes a closer understanding between geography, architecture and planning (Larkham, 2006). The work is morphogenetic, i.e. focussed on the processes that generate particular forms and emphasises the relationship between the plot and the building block plan (J.W.R.Whitehand, 2001). His study 'Alnwick, Northumberland – A Study in Town-Plan Analysis' analyses "three distinct complexes of plan elements:

> i) streets and their arrangement in a street-system;
> ii) plots and their aggregation in street-blocks; and
> iii) buildings or, more precisely, their block-plans." (Conzen, 1960)

Importantly for this study, Conzen's work is explicitly cartographic. The Alnwick study is based on the "features of the built-up area shown on the 1/2500 Ordnance Survey Plans" (Conzen, 1960, p. 4).It should be noted that, while Conzen interpreted plots from Ordnance Survey (OS) maps, strictly speaking OS maps do not record land ownership boundaries. In the UK land ownership boundaries are separately recorded in title deeds held by the Land Registry using features such as walls, fences or hedgerows from OS maps as a reference. His study did not assess building height or floor area.

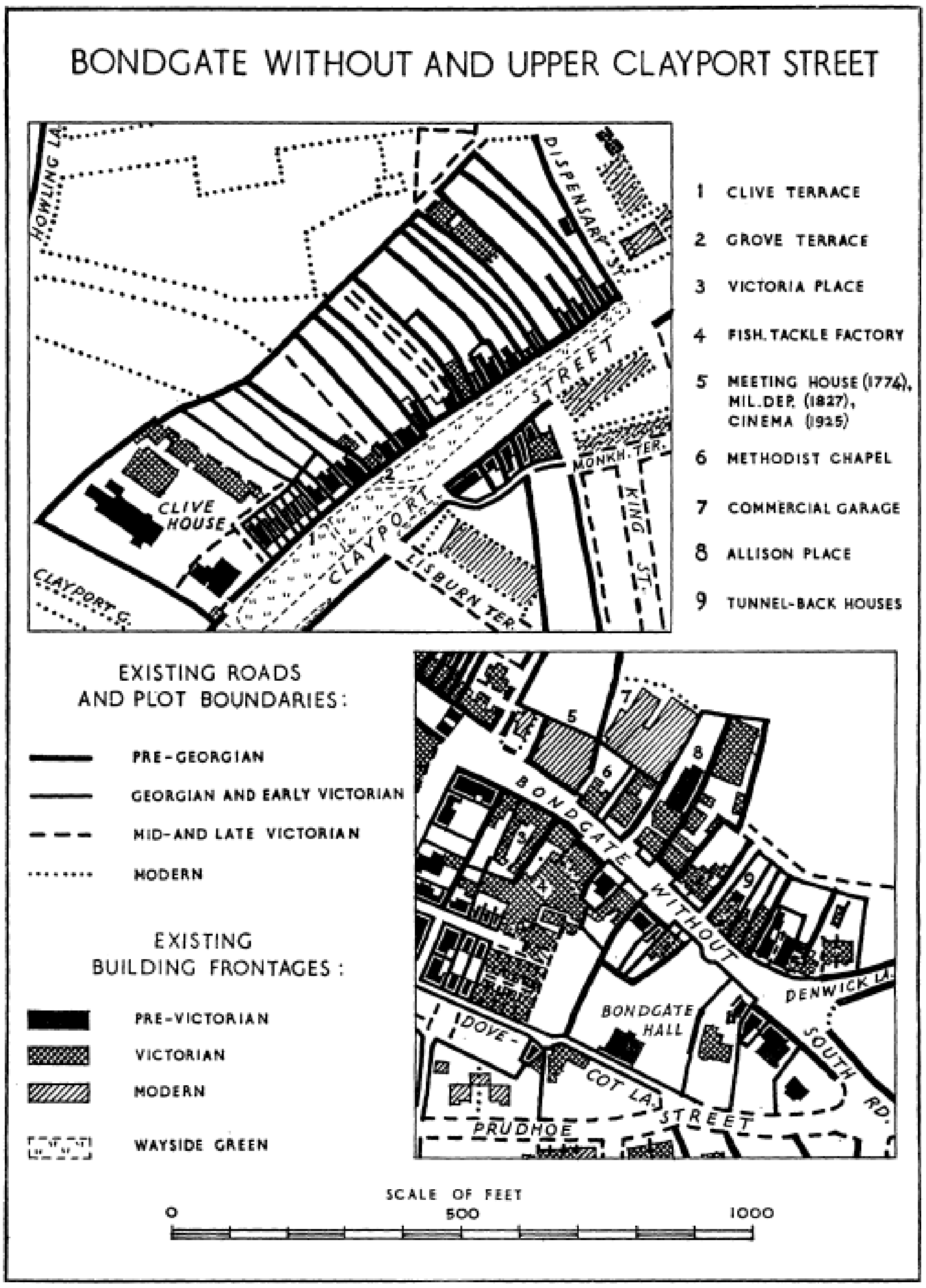



Figure 9: Streets, plots and buildings (Conzen, 1960, p. 45)

### 4.3.2 Unwin

Conzen may be credited with introducing the study of urban morphology to the UK but arguably Raymond Unwin had a much larger influence on the form of British towns and cities.

Unwin was a designer of Garden Cities and Ebeneezer Howard's direct successor (Martin & March, 1972). In 1912 he published *Nothing Gained by Overcrowding!*, a pamphlet which demonstrated that given a fixed through-house typology (i.e. no back-to-back or corner typologies) and an unlimited supply of development land, low-density development would provide home purchasers with significantly larger gardens for very little increased cost. The greater land take would also benefit landowners who would sell more land (Unwin, 1912). While Unwin's "limited point about low density" (Martin & March, 1972, p. 19) may seem of little interest to contemporary compact cities his work demonstrated the significance of a key metric that is often omitted from more recent studies of urban form – frontage. He showed that the proportion of public highway attributable to a property is defined by the length of its frontage and essentially unrelated to plot depth and therefore plot area.

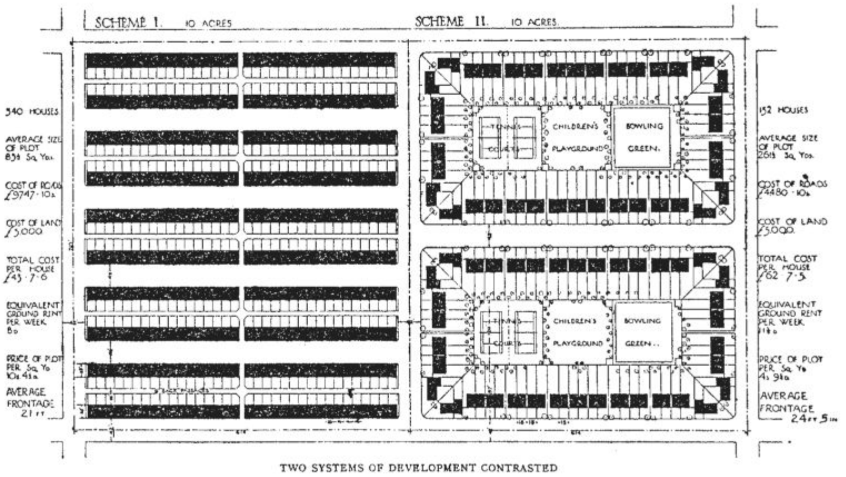
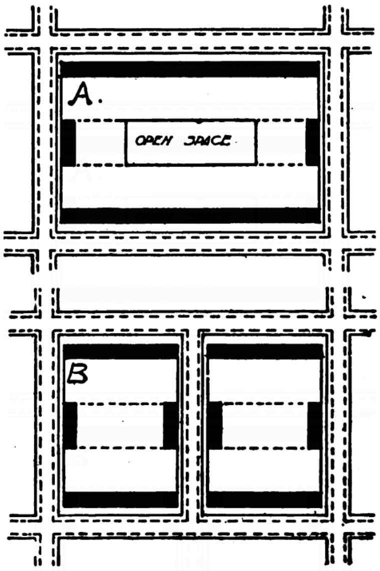



Figure 10: Unwin's preferred system of development (Scheme II) relative to standard by-law terrace housing (Scheme I), (Unwin, 1912)

Unwin's work has to be understood in the context of standard house plans enshrined in byelaws as a result of the Public Health Act (The United Kingdom Government, 1875). Due to an absolute commitment to ensuring every house had a front and a back façade to ensure adequate daylighting and ventilation, byelaw housing is characterised by "little or no provision for corner sites" (Unwin, 1909, p. 333). As Unwin's analysis shows this makes the additional frontage created at corners unusable (Local Government Boards for England and Wales and Scotland, 1918). (Figure 11)




*Illus. 232.—A shows area with cross road omitted. B shows extra cross road not justified by frontage gained.*

Figure 11: Diagram demonstrating unusable frontage generated when using byelaw house types (Unwin, 1909)

Unwin's meticulous cost based analysis of this unused frontage and unaccounted length of street network effectively enshrined into British residential site planning that street corners were unaffordable (Figure 12). Potentially this was beneficial to Unwin as it made Garden City proposals comparatively inexpensive, more commonly it led to the interminable runs of detached, semi-detached and terrace houses that typify British suburbs.

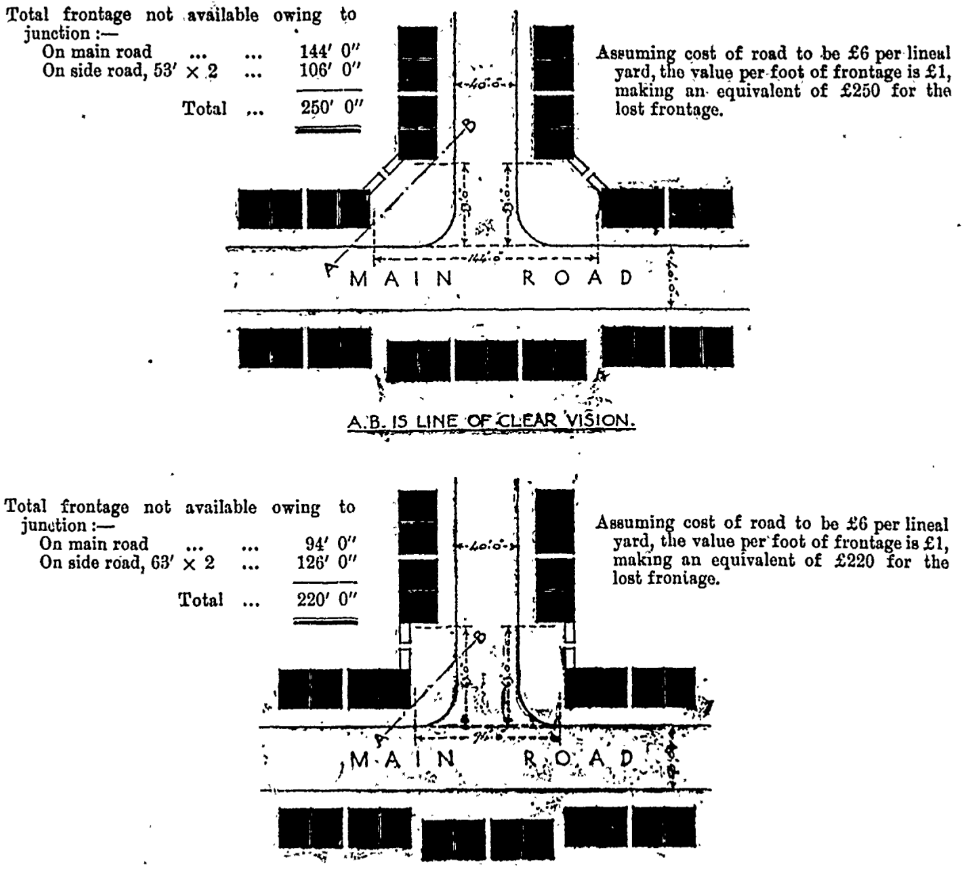



Figure 12: Cost based analysis of the expense of street corners without a corner house typology (Local Government Boards for England and Wales and Scotland, 1918, p. 13)

### *4.3.3 Martin and March*

Martin and March's work can perhaps best be seen as a counter point to Unwin's. Freed from post-war economy and the strictures of byelaw housing they could engage with corners. They also addressed building height, plan depth and the cut-off angle – the angle one must look up at from one side of the street to see sky above the facing building on the other side of the street.

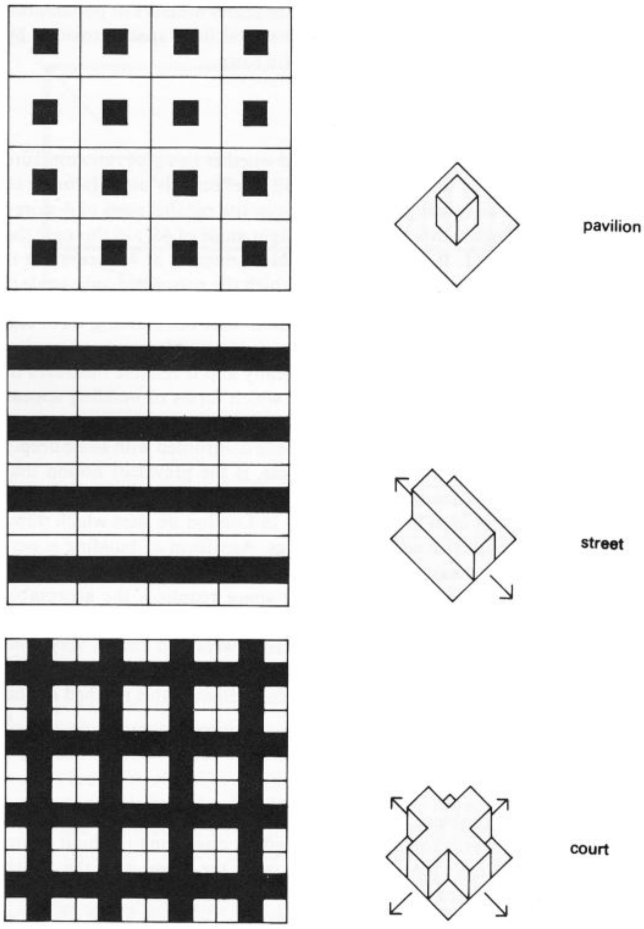



Figure 13: Arrays of pavilion, street and court forms (Martin and March, 1972)

Reacting against the results of modernism's preference for point blocks (Le Corbusier, 1924), *The grid as generator* (1972) and *Speculations* (1972) demonstrate the inefficiency of point blocks (towers) in comparison with courts (perimeter blocks) (Martin & March, 1972). They did this by using spatial modelling which kept many variables fixed – the cut-off angle, the building plan depth, the height of the buildings. The diagram that is often extracted compares abstract arrays of 'pavilion', 'street' and 'court forms' (Figure 13). As Martin noted "we find that the antiform [the courts] places the same amount of floor space into buildings which are exactly one third the total height of those in pavilion form" (Martin & March, 1972, p. 20).

It is a work that is often cited by those who support a return to traditional urban form and who suggest links to an improved quality of life. "There is now wide agreement that the high-density forms most appropriate for the compact-city adopt traditional urban land-use patterns such as streets and squares and medium-rise or low-rise high-density housing. Through these forms, it is possible to provide each dwelling with its own front door onto a public street, and to provide gardens for all family dwellings." (Burton, 2002, p. 222)

The studies are primarily abstract. As Steadman (2014, p. 353) notes "Martin and March's courts […] create a continuous grid (and it is unclear where any roads might run)". An illustration of its implications for Bloomsbury are shown but the image is a long way from the outcome that traditional urbanists would hope for – Bloomsbury's existing buildings are redistributed in a narrow band around open parkland (Figure 14).

For anyone looking to extract direct design guidance from the abstract studies Steadman, who worked with Martin and March, warns that the work of the Centre for Land Use and Built Form Studies was concerned with quantitatively assessing existing urban forms or a range of proposed urban forms in order to help the designer understand the implications of his/her decisions. The intention was not to create optimal solutions in an automated way (Steadman, 2016).

A variable in the study that has taken on perhaps unwarranted significance is the cut-off angle. As Martin and March noted, cut-off angle is a poor approximation for daylight, it is measured perpendicular to a facade and takes no account of extra light on external corners or reduced light on internal corners. Keeping it consistent was necessary to compare the plan forms of their studies. Yet a suggested cut-off angle of 45° will often appear in design guidance. Simple observation when walking down existing streets will reveal that this relationship is rarely encountered, and much steeper angles are generally found in the areas that are the most popular.

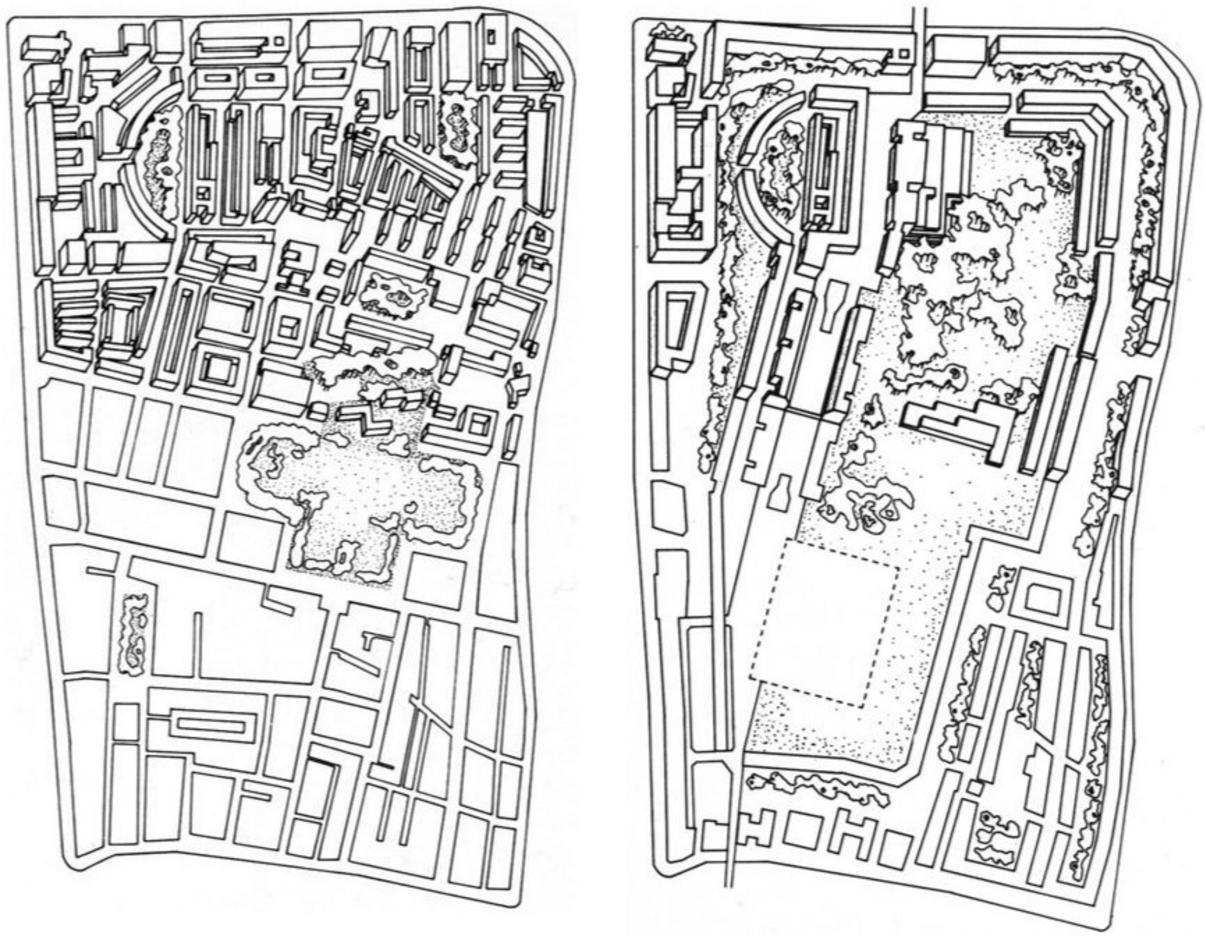


Figure 14: Theoretical redistribution of buildings in Bloomsbury (Martin and March, 1972)

### *4.3.4 Berghauser Pont and Haupt*

Typo-morphology, linking building typologies with urban form, is seen as missing from British work (Larkham, 2006). In the Netherlands, Berghauser Pont and Haupt's *Spacemate: the spatial logic of urban density* (2009) is specifically typo-morphological yet sees itself as part of the "mathematical-analytical approach, represented by Cerda, Unwin and Martin and March" (Berghauser Pont & Haupt, 2005, p. 57).

Their study establishes a standard method for measuring urban form which they apply at a variety of scales with the bulk of their work focussing on the island (the block) and the fabric (a wider area of similar character) (Berghauser Pont & Haupt, 2009). First they draw a boundary around what they call an area of aggregation. Second, within this boundary, they measure the total area of ground covered by building (the building footprint). Third, they multiply ground floor area by the height of the building in storeys to generate the total floor area of the building.

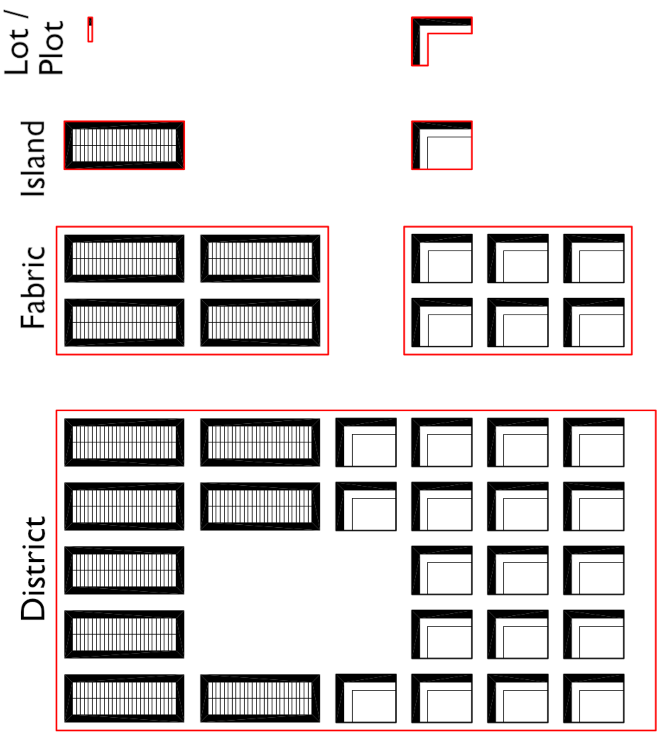



Figure 15: Range of scales of aggregation areas (Berghauser Pont & Haupt, 2005)

They divide the total area of building footprint by the area of aggregation to generate the GSI (the proportion of ground in a study-area covered by building):

$$GSI_x = B_x / A_x$$

$B_x$ = footprint of ($m^2$)
$A_x$ = area of aggregation x ($m^2$)
x = aggregation (lot (l), island (i), fabric (f), or district (d))

This index uses the unit square metres per square metres ($m^2/m^2$).

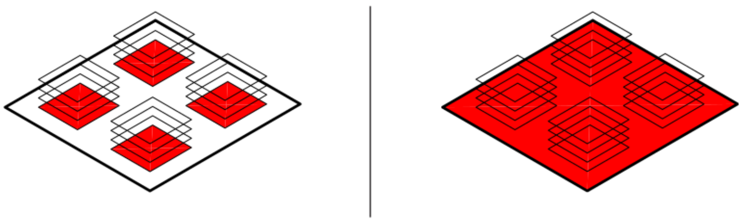


Figure 16: Ground Space Index (Berghauser Pont & Haupt, 2009, p. 122)

The Floor Space Index is the total building floor space measured at every level divided by the area of aggregation:

$$FSI_x = F_x / A_x$$

$F_x$ = gross floor area ($m^2$)
$A_x$ = area of aggregation x ($m^2$)
x = aggregation (lot (l), island (i), fabric (f), or district (d))

This index uses the unit square metres per square metres ($m^2/m^2$).

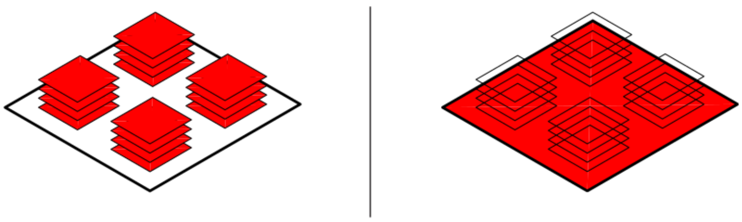


Figure 17: Floor Space Index (Berghauser Pont & Haupt, 2009, p. 122)

The third measurement that they make is the street network length within the area of aggregation. This has to be done at the scale of the fabric or district as the island and plot are net measurements that exclude public highway. The boundary of the fabric or district is drawn along the centreline of the street shared with the adjacent fabric or district area. To avoid double counting, the length of these edge streets is divided by two. The network density (N) is then the length of the network divided by the area of the fabric or district.

$$N_f = (\Sigma l_i + (\Sigma l_e)/2)/A_f$$

$l_i$ = length of interior network (m)
$l_e$ = length of edge network (m)
$A_f$ = area of fabric ($m^2$)

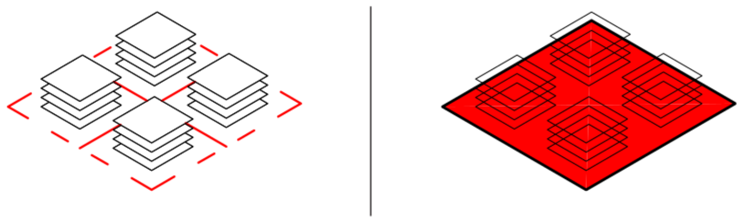


Figure 18: Network Length (Berghauser Pont & Haupt, 2009, p. 122)

Using ESDA techniques they found that, by plotting the FSI and GSI of areas of aggregation against one another, they could identify the prevailing building typology in that area according to how the values clustered on the graph. They called this the 'Spacemate'.

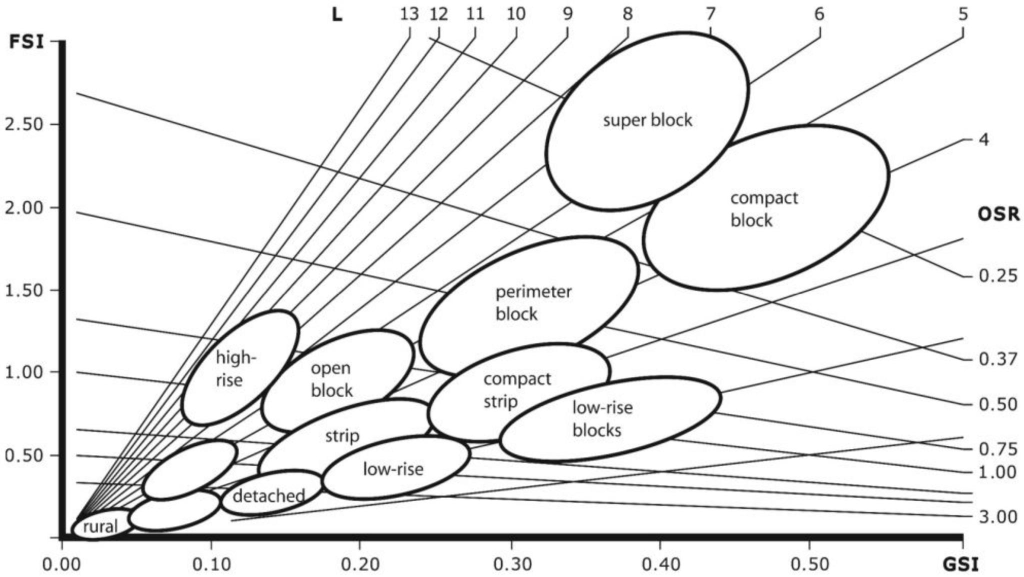



Figure 19: Typological clusters of urban fabrics in the Spacemate diagram (Berghauser Pont & Haupt, 2007, p. 4)

They subsequently found that by introducing N as a third axis to the graph the clustering was reinforced. They referred to this graph as the 'SpaceMatrix'. As a length to area ratio, N also introduced dimensions to what were otherwise dimensionless ratios. (Berghauser Pont, 2015; Berghauser Pont & Haupt, 2005, 2009).

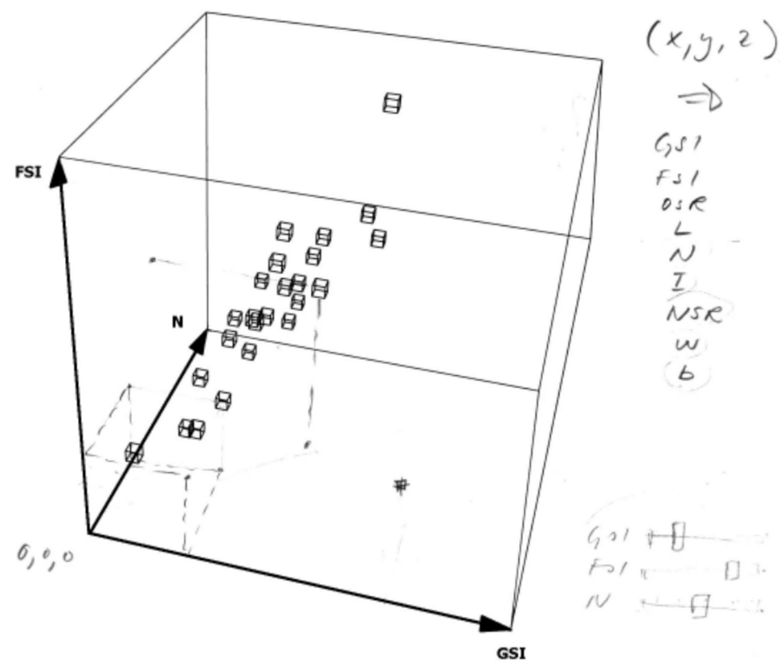



Figure 20: SpaceMatrix - FSI, GSI and N (network density) (Berghauser Pont and Haupt, 2009, p.98)

They state in their work that they believe they are the first to integrate N into measures of urban form and to assess it they model the impact of varying N and street width on the proportion of private buildable land to public highway land by area (Figure 21).

Their work is innovative because it demonstrates that plotting GSI and FSI against each other clusters areas together according to their dominant building typology. Their use of net urban blocks ('islands') as one of the reference areas for their measurements makes their method usable with purely physical mapping. While they do not ignore the relevance of plot divisions, nor is their work reliant on them. They identify that network density improved the correlation of building density measures with building types and speculated that it may be because of a relation between network length and the proportion of land available for residential development.

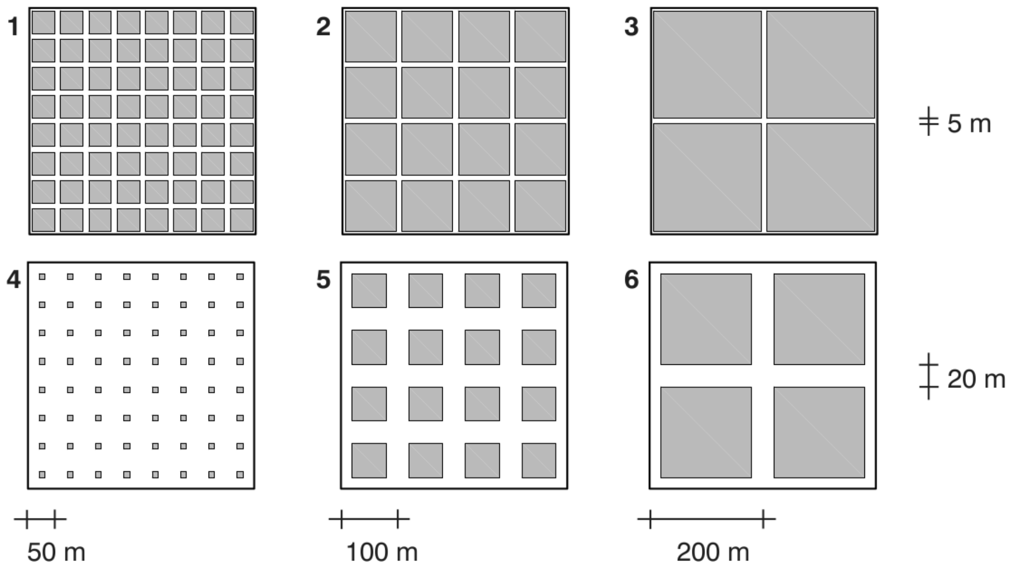



Figure 21: Proportion of public highway to private issue land by N and street width (Berghauser Pont & Haupt, 2009, p. 124)

### 4.3.5 *Louf and Barthelemy*

While Louf and Barthelemy initially set out to characterise cities by their street networks rather than their urban form, they are included here because they ultimately proposed a method based on quantifying the size and shape of gross urban blocks which they defined as "the cells of the planar graph formed by streets" (Barthelemy, 2017; Louf & Barthelemy, 2014, p. 2).

Similarly to Boeing they decided to use street network data from OSM to get global coverage generating the gross urban blocks by polygonising street centrelines. A side effect of this method which they note is that it removes cul-de-sacs (Figure 22).

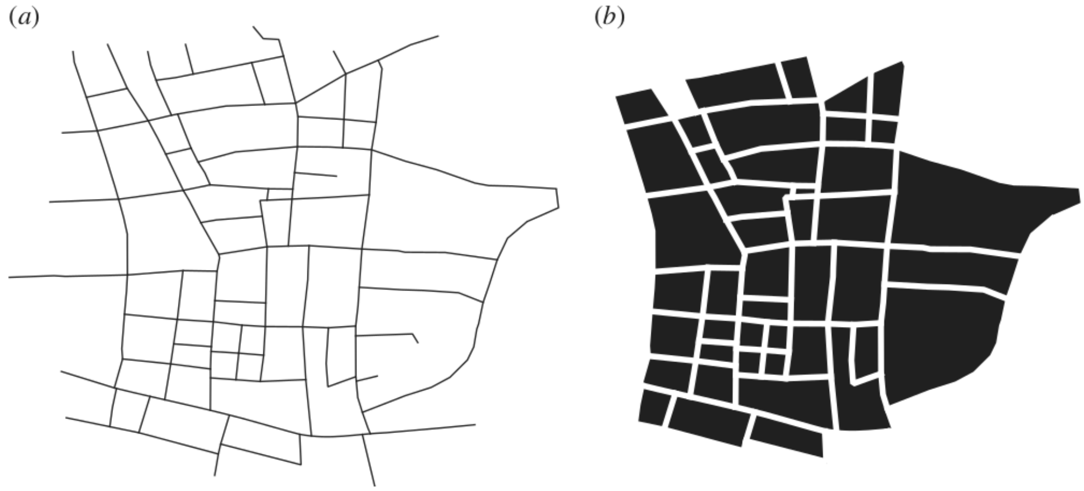



Figure 22: Polygonisation of the street network showing missing cul-de-sacs (Barthelemy & Louf, 2004)

To classify the urban blocks they measured their surface area and form factor (φ) – the ratio between the area of the block and its smallest enclosing circle. By plotting the distribution of the form factors they generated a 'fingerprint' for each city which they classified into one of four groups. Cities with:

1. medium-size, regular rectangular blocks
2. small blocks with a broad distribution of shapes
3. slight predominance of medium-size blocks with a diversity of shapes
4. small square blocks

While their method initially seems relevant for measuring urban form using OSM data it has a couple of significant short-comings. Firstly, omitting cul-de-sacs makes it impossible to assess building density against streets as it simply removes cul-de-sacs. Secondly, there are multiple ways of quantify the shape of a polygon (McGarigal, Cushman, & Ene, 2012). Their selection of 'form-factor' compares the area of the urban block with its smallest enclosing circle. Even if they had assessed net urban blocks including the cul-de-sacs this method of quantifying the polygons would continue to obscure their influence.

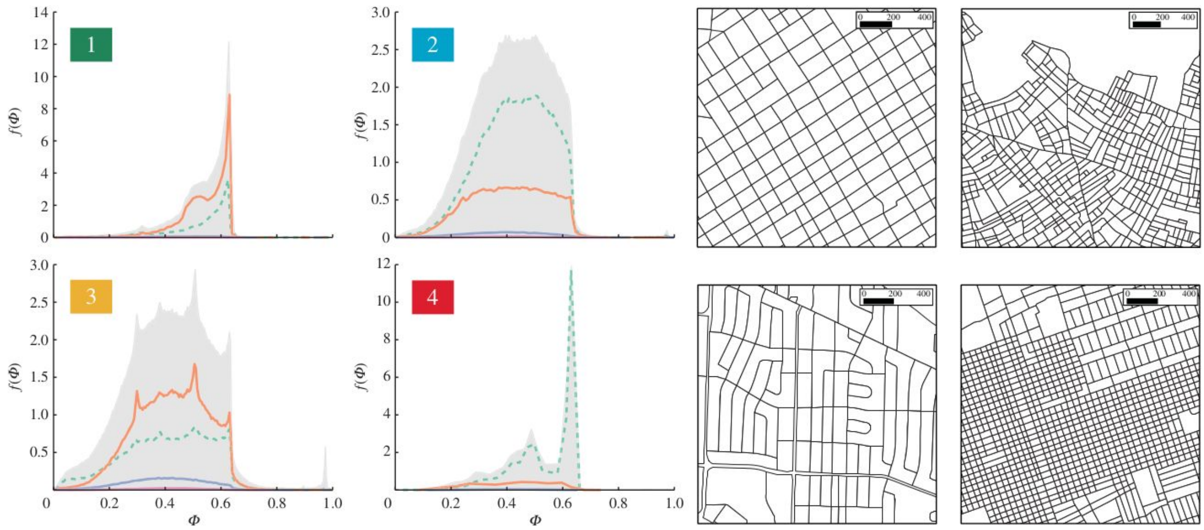



Figure 23: Distribution of gross urban block form factors for 1. Buenos Aires, 2. Athens, 3. New Orleans, 4. Mogadishu (Louf & Barthelemy, 2014, p4)

Urban blocks sit at a key scale in the urban fabric where architecture, land-use planning and transport planning meet (Panerai, Castex, Depaule, & Samuels, 2004). In the British context, despite Unwin demonstrating the importance of the relationship between the plot and the block (Unwin, 1909, 1912), urban blocks are still seen as lacking meaning (Boyko & Cooper, 2011; Panerai et al., 2004). As Barthelemy has noted "a complete characterization and exhaustive list of dominant mechanisms [controlling the the shape and the area of blocks] are however still lacking" (Barthelemy, 2017, p. 269).

# 5 Measuring density against plot or site area

This section challenges the London Plan's implicit assumption that generic area-wide density ratios measured against individual sites should reflect or generate consistent urban form.


Figure 24: Buenos Aires: Metropolitan Area and CABA (Bristow, 2019. Source: data.buenosaires.gob.ar)

## 5.1 Case study – The City of Buenos Aires

Coincidentally, at the same time that London was reviewing its approach to density metrics in the London Plan, the City of Buenos Aires (CABA) was also reviewing its approach to density metrics in its equivalent to the London Plan, the *Código Urbanístico*. As London concluded that it should introduce site-based building density measures, Buenos Aires concluded that it should scrap them.

Figure 25: Aerial view of CABA (Google Maps, 2019)

Buenos Aires, as many Latin American cities, follows a strict rectangular street grid (Figure 25). The resulting urban blocks, defined by the line where private plots meet the public highway, form part of the structure of the cadastre. Despite their absolute regularity, the plots within the blocks vary in size considerably (Figure 26).

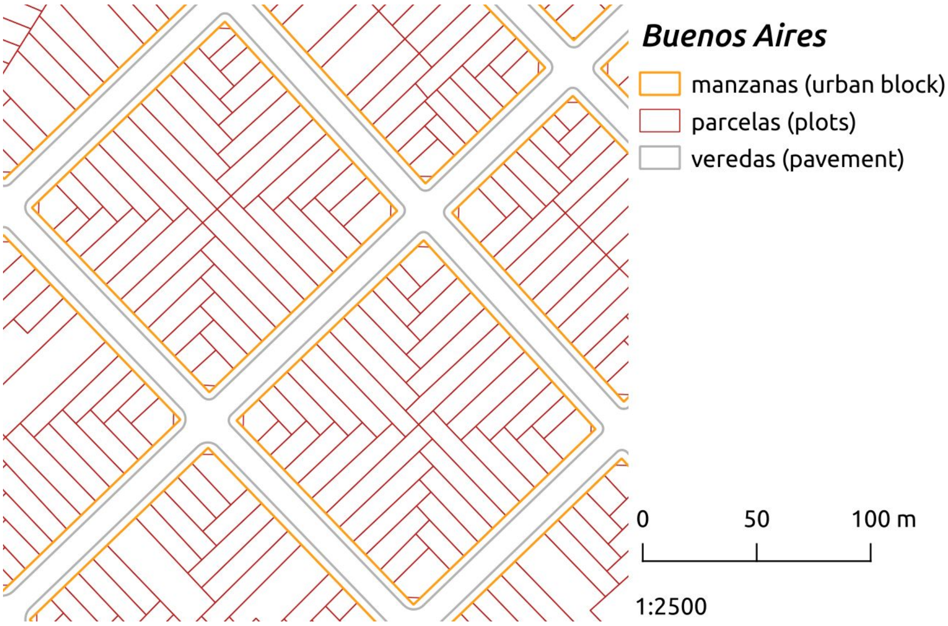


Figure 26: CABA, example subdivision of blocks into plots (Bristow, 2019. Source: data.buenosaires.gob.ar)

The previous plan defined how much could be built on an individual plot by applying a generic *Factor de Ocupación del Suelo* (GSI) and the *Factor de Ocupación Total* (FSI) to the plot area. This meant that owners of larger plots, typically in the middle of an urban block, could build more than those that owned small plots at the corners. The outcome was a stepped streetscape with corner plots often limited to their original 1 or 2 storeys and centre plots built up to 12 storeys (Figure 27).

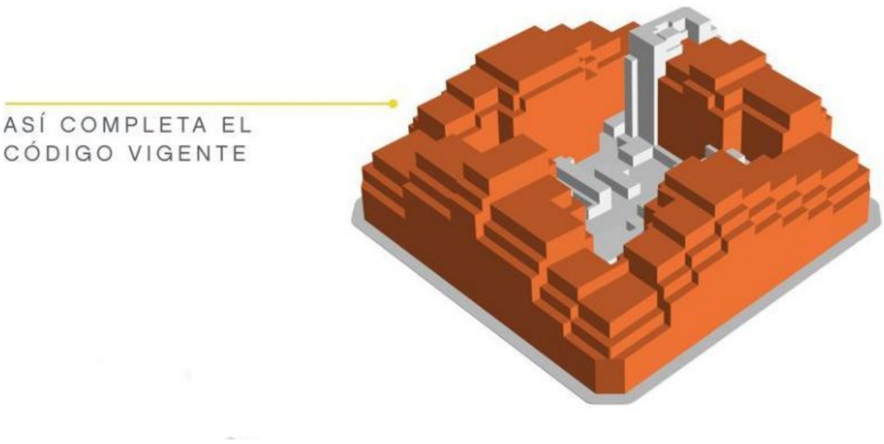


Figure 27: Previous *Codigo Urbanistico* linked FSI to Plot Area (Ministerio de Desarrollo Urbano y Transporte, 2018)

### 5.1.1 *New definition of buildable area*

To resolve this and create a more unified streetscape in December 2018 CABA approved a new *Código Urbanístico* (Buenos Aires Ciudad, 2019) which effectively moved the definition of the city's urban form up from the scale of the individual plot to the combined urban block. The new buildable footprint is defined as the area between the block's frontage line and an inwards offset of that line to 1/4 the block depth (Figure 28).

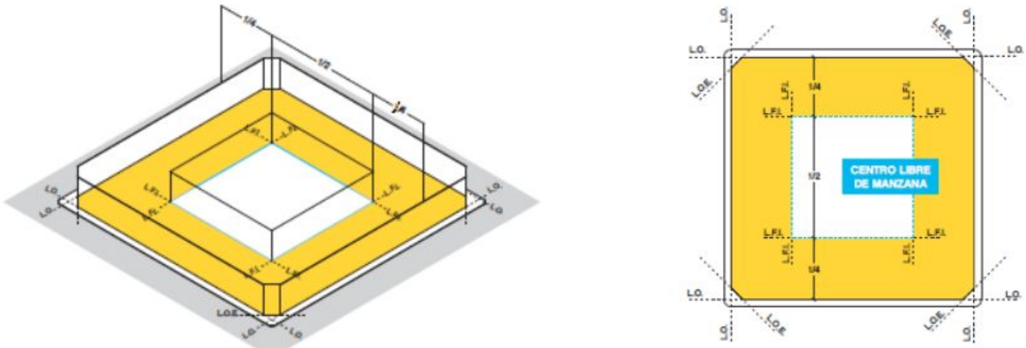



Figure 28: New definition of buildable area (yellow) defined as an offset of the frontage line inwards to 25% of the block's total depth (Buenos Aires Ciudad, 2019)

Each plot owner is entitled to build-out whatever portion of this area falls within their plot up to a height which is also common to the whole urban block. This is intended to create a more uniform streetscape (Figure 29).

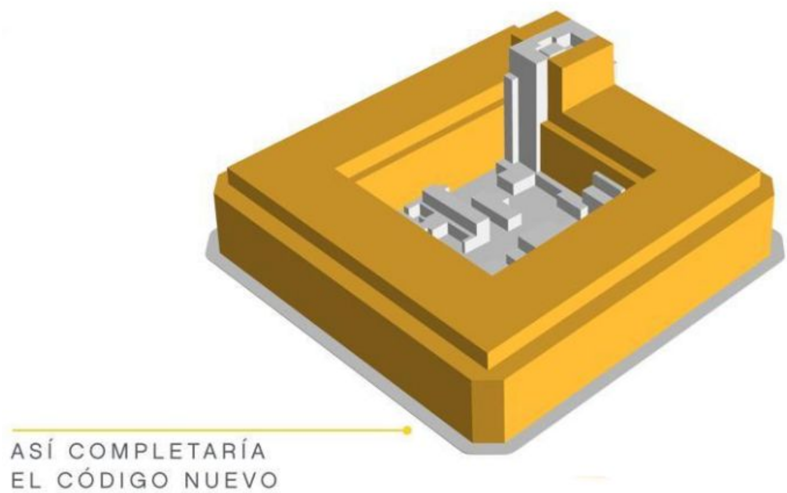



Figure 29: Intended outcome of changes (note grey building pre-existing) (Ministerio de Desarrollo Urbano y Transporte, 2018)

A consequence is that the volume of building that is allocated to each plot individually has changed significantly. Primarily this results in a windfall for small corner plot owners who can now build-out their entire corner plot to the common height. The windfall is dealt with by creation of a new tax (*plusvalía*) that is intended to balance out the changes in land value.

### *5.1.2 Building typology*

Figure 30: Side view of typical building typology showing the light-well (Bristow, 2019)

The ¼ block offset may seem arbitrary but a standard block in Buenos Aires is about 100 x 100m making the offset around 25m. This coincides with the plan depth of the contemporary common building type - four flats back to back around a light-well and stair core (Figures 30 & 31).

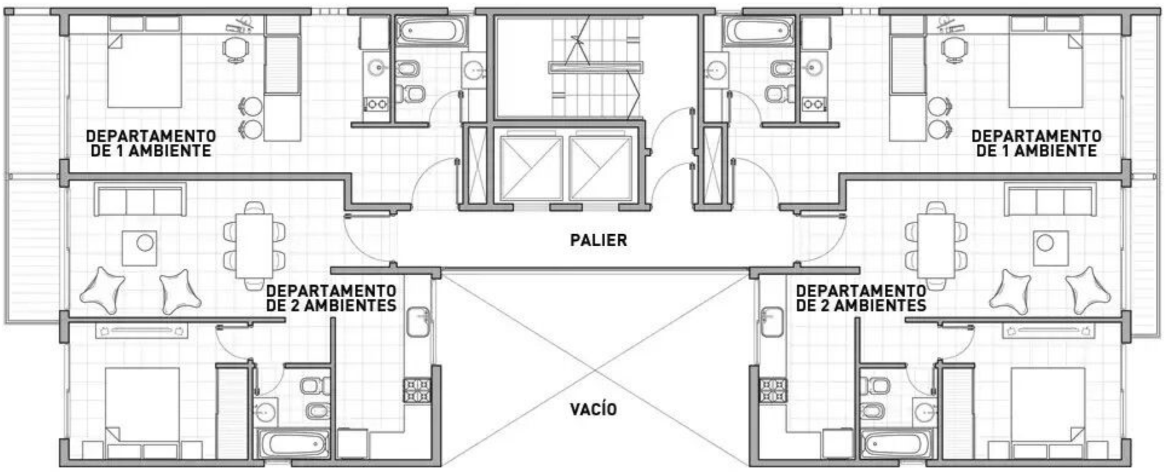



Figure 31: Common building type approximately 25m deep from front to rear façade - note bathroom and kitchen windows in party walls will eventually be covered by neighbouring buildings.

### *5.1.3 Building heights*

In order to manage the final capacity of each urban block according to where it is in the city (e.g. central and well-connected, peripheral and primarily residential etc.), having fixed the frontage line and the building depth, the key variable becomes the building height. To control this the city produces maps that give the maximum height permissible on each block (Buenos Aires Ciudad, 2018). The only variation is that where one side of a block fronts a wider/more significant road the properties on that side are allowed to go higher. (Figure 32)

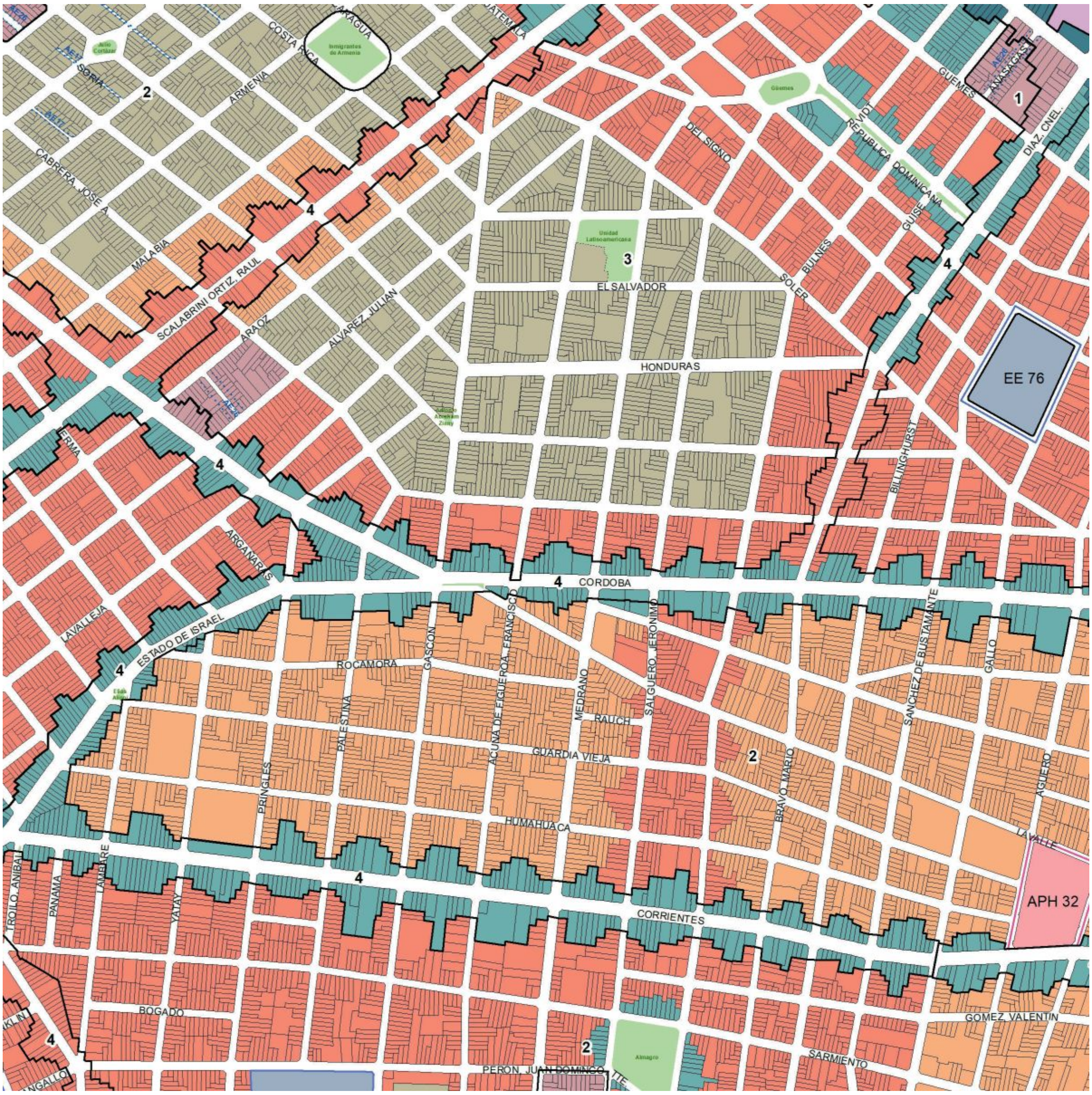



Figure 32: Plan of permitted building height on an urban block basis in CABA – note extra height along main roads (Buenos Aires Ciudad, 2018)

### *5.1.4 Summary*

Under the old definition, area-wide density ratios applied at the scale of the plot almost inevitably generated an undesirable outcome for the urban form. Under the new definition a consistent streetscape and total built capacity for the CABA can be generated just from the combination of the outline of urban blocks, the plan-depth of the typical building typology and a plan showing where height should go.

Compliance checking becomes easy as it is no longer necessary to know the area of a plot to be able to verify the permissible height/size of building. It demonstrates that, in terms of urban form, the division between neighbouring buildings and plots is essentially irrelevant. The aggregate capacity is what matters.

Density calculations against a physically observable boundary between the public highway and private building lots are freed from invisible land title boundaries and data sets that are often not publicly available. This makes it possible to measure urban form at a global scale from purely physical mapping such as OSM.

Aggregating beyond the urban block comes with its own problems. Neighbourhood boundaries are subjective – should they be religious, political, statistical, areas of consistent urban character? How much of a local park or square should be included?

The method that CABA is implementing is particularly based on the observation that, when aggregated to the level of the urban block, residential buildings can be treated as linear rather than area based forms. This comes from the realisation that acceptable limits on internal daylight and fresh air levels define a plan-depth that is constant. At the scale of the urban block, the GEA of residential buildings can be more significantly increased by making them longer or taller, rather than deeper.

## 5.2 The effect of plot size and shape on density

In order to test whether the problems identified with plot-based density ratios in Buenos Aires are also present in London, three empirical studies of plot size and shape were carried out. In all cases the plot divisions within the blocks are real examples. (See inset pages 'The effect of plot size and shape on density')

***Buenos Aires***

In the first study, a generic single dwelling is applied onto each plot within a typical Buenos Aires block. Plot width/frontage is consistent but plot depths reduce as they approach the corner. This reduces the plot area and so drives-up the measured plot density.

***London suburban***

In the second study, a generic single dwelling is applied onto each plot within a typical suburban London block subdivided in accordance with byelaw housing requirements. The plots are essentially identical and so a consistent plot-based density ratio is maintained but this is at the expense of being able to complete the corner of the block with buildings.

***London central***

The third study, 'London - central' is a real extract of OS MasterMap building footprints overlaid on land ownership divisions extracted from the Infrastructure for Spatial Infrastructure in Europe (INSPIRE) polygon index (HM Land Registry, 2017). The area selected is a conservation area that many people would consider a good example of traditional urban design. Despite the even streetscape, the unevenness of the land ownership boundaries generates plot-based density measurements that vary wildly from 38-215 dwellings per hectare.

***Discussion***

If the desire in modern compact cities is to generate even streetscapes using closed perimeter urban blocks then all three studies demonstrate that it is simply wrong to expect this to be the outcome of applying a single generic density ratio to every plot in block.

**Legend**

Usable Frontage
Urban Block Perimeter
Street Centreline
Pavement
Houses

**Plot Density (D/Ha)**

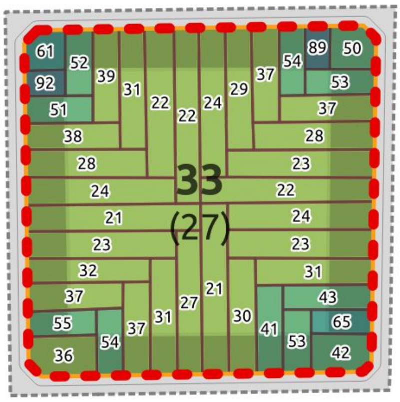
0 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 120
120 - 140
140 - 225

**33** Net block density (D/Ha)

(27) Gross block density measured to centre of street (D/Ha)

Imagery ©2019 Google, CNES / Airbus, Maxar Technologies

0 25 50 75 100 m




# The effect of plot size and shape on density

The first two studies apply a generic single dwelling onto each plot (as they would have been developed originally) and measure the density of each plot and the overall block.

The third study 'London - Central' is a real extract of Ordnance Survey MasterMap building footprints overlaid on INSPIRE plot boundaries.Some plots contain multiple buildings but the assessment is still on the basis that each building is a single dwelling.

All three examples show that ***closed perimeter urban blocks, formed of buildings with consistent height and plan depth, are incompatible with density values measured against the plot area.***

- The Buenos Aires example maintains the plot's width/frontage but reduces plot's length as it approaches a corner - reducing its area and so increasing its density.
- The London - Suburban example maintians a consistent plot-based density measurement but only because the buildings don't complete the corners.
- The London-Central example is of good quality terraced housing in a conservation area that many people would consider a good example of urban design. Yet the fragmentation of the land ownership generates plot-based density measurements that vary wildly from 38-215 dwellings per hectare.

## Buenos Aires

### Building typologies

- Terraced houses
- Corner house

### Plots

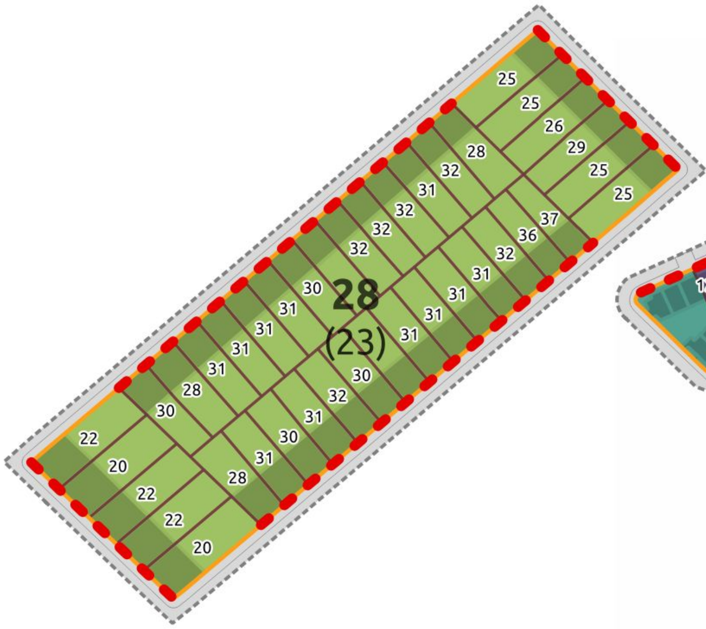
- vary in size
- smaller towards the corners
- plot density varies

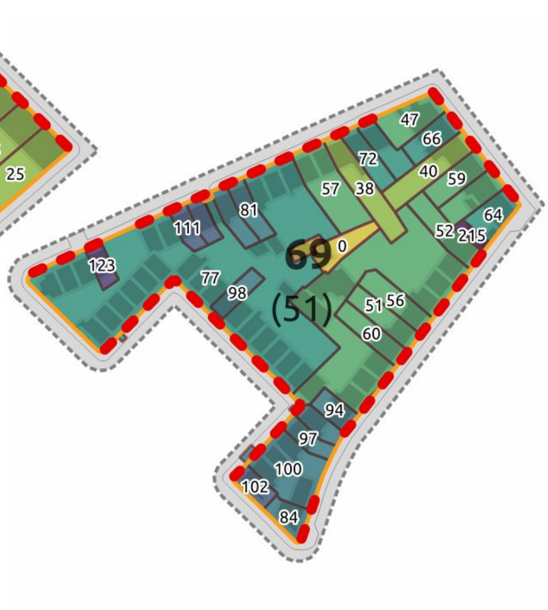
### Urban Block

- Complete perimeter block

Imagery ©2019 Google, Bluesky, Getmapping plc, Infoterra Ltd & Bluesky, Maxar Technologies, The GeoInformation Group

Imagery ©2019 Google, Bluesky, Getmapping plc, Infoterra Ltd & Bluesky, Maxar Technologies, The GeoInformation Group




## London - Suburbs

### Building typologies

- Semi-detached houses

### Plots

- consistent size
- density also consistent

### Urban Block

- Incomplete perimeter block
- Lack of a corner building typology and standard plot sizes prevent full use of the perimeter of the block

## London - Central

### Building typologies

- Terraced houses

### Plots

- varying sizes due to fragmented land ownership
- density ranges from 38-215 dwellings/ha.

### Urban Block

- Incomplete perimeter block
- Lack of a corner building typology prevents full use of the perimeter

## 5.3 The linear form of residential buildings

Having demonstrated that a consistent urban form is incompatible with single generic plot-based density ratios, the next conceptual shift that the Buenos Aires case study offers is that, at the scale of an urban block, residential buildings can be treated as linear forms rather than area based shapes.

Due to the need to give all habitable rooms direct access to daylight and fresh air residential buildings have plan-depth restrictions that commercial and industrial buildings do not. In CABA, the common apartment building typology designed to work with the standard plot width has a plan-depth of around 25m. In London, the equivalent might be 13m for a building with deck access flats or 20m for corridor access flats. (Figure 33)

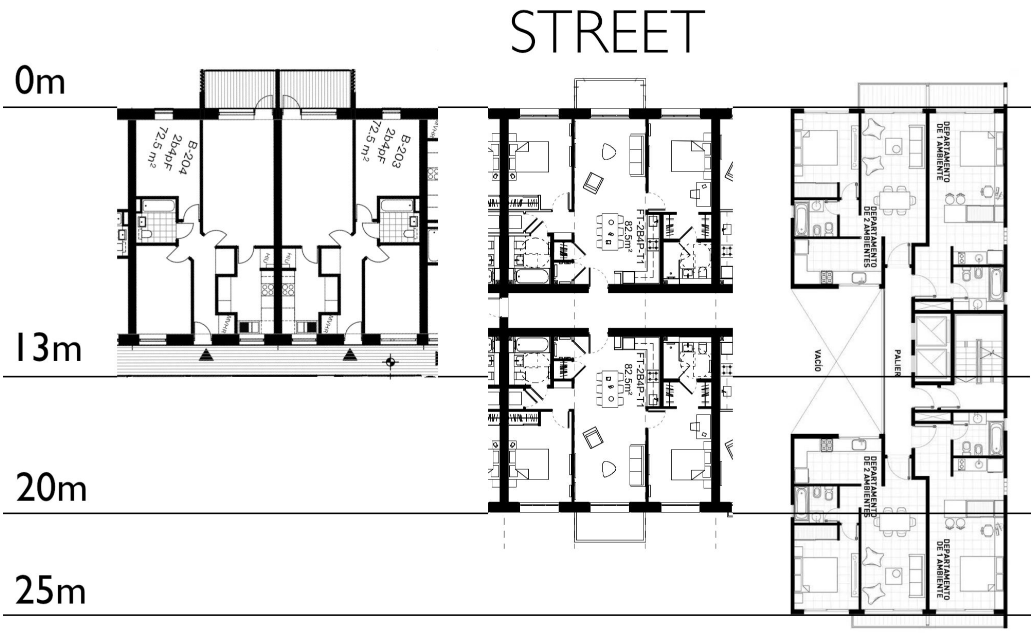



Figure 33: Building Typology and Plan Depth. Dual-aspect deck-access flats (London); single-aspect corridor-access flats (London); flats with light-well and lift-access (Buenos Aires)

Even when working with detached or semi-detached houses, it is a matter of simple observation to show that at the scale of the block, they can be generalised as a dotted or dashed line occupying a narrow strip of land inset from the edge of the block. Its thickness, defined by the plan-depth, which varies very little from house to house (Figure 34).

Figure 34: Semi-detached housing, Shirley, London (Imagery © 2019 Google, Bluesky, Getmapping plc, Infoterra Ltd & Bluesky, Landsat/Copernicus, Maxar Technologies, The Geoinformation Group)

Intriguingly in relation to Martin and March's work, it is even possible to conceptualise a residential tower as a linear building form when one considers that it consists of a ring of habitable rooms arranged around a service core. Expanding the footprint of the tower does not result in greater habitable area in the centre, only around the increased length of its perimeter.

What this suggests is that to understand in detail the drivers behind particular urban forms it is necessary to understand the relationship between building typologies, plot divisions and streets but that, at a more generalised level, residential capacity potentially could be assessed by measuring the area of residential buildings against the length of the perimeter of the urban block.

## 5.4 The importance of corners

***London suburban terraces – open corners***

As already discussed in the literature review, suburban London is characterised by rows of byelaw housing laid-out according to the recommendations of the Tudor Walter's Report (1918). No corner buildings were used and every house has a generous, equal size garden. All plots have an approximately equal net plot density. As Unwin (1909) demonstrated, this comes at a cost. Corners are 'expensive' - they create lengths of street that are not usable building frontage. Consequentially, corner plot gross density (measured to street centreline) is lower than the other plots and so to maximise the area-wide gross density urban blocks must be made as long as possible and the number of corners kept to a minimum(Figure 12 & 35).

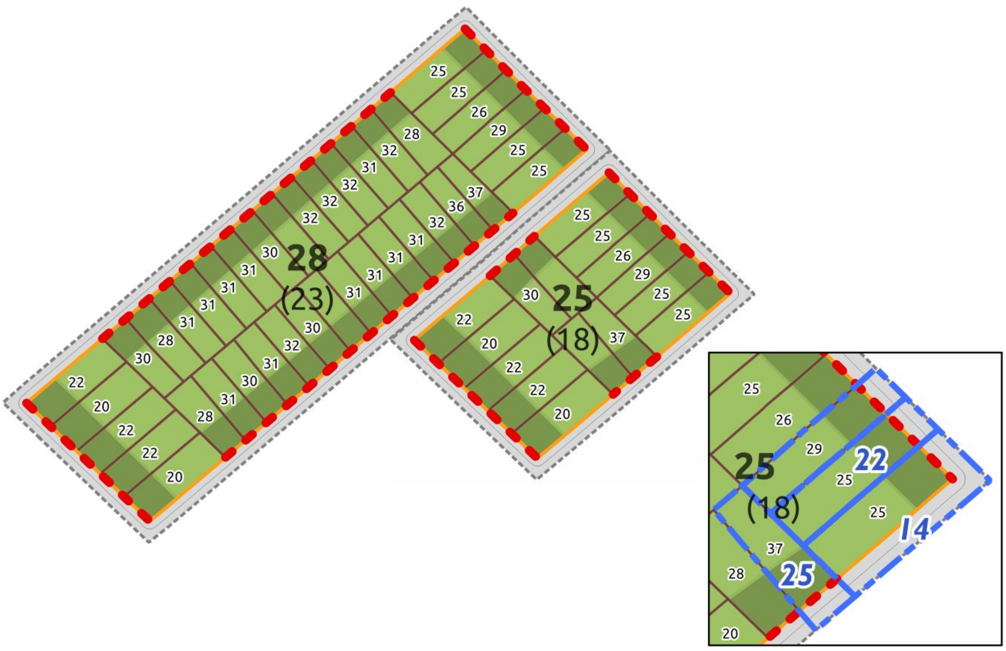



Figure 35: Typical London suburban block, no corner building typology used. Note the gross density of the corner plot is lower than its neighbours (Bristow, 2019)

***Complete perimeter blocks***

Reconfiguring the corner plots and introducing a corner building typology completely inverts the relationship. The corner plots become the plots with the highest gross plot density and so, to maximise the wider-area's gross density, blocks must be as small as possible (to the limits of acceptable separation distances) and the number of corners maximised. There are consequences chiefly that net plot density cannot be kept consistent. In this simplified example, the net and gross densities of the corner plots treble. Perhaps counter-intuitively, assuming corner buildings can be used, introducing new streets and dedicating more land to public highway increases gross residential density because of the extra frontage it creates (Figure 36).

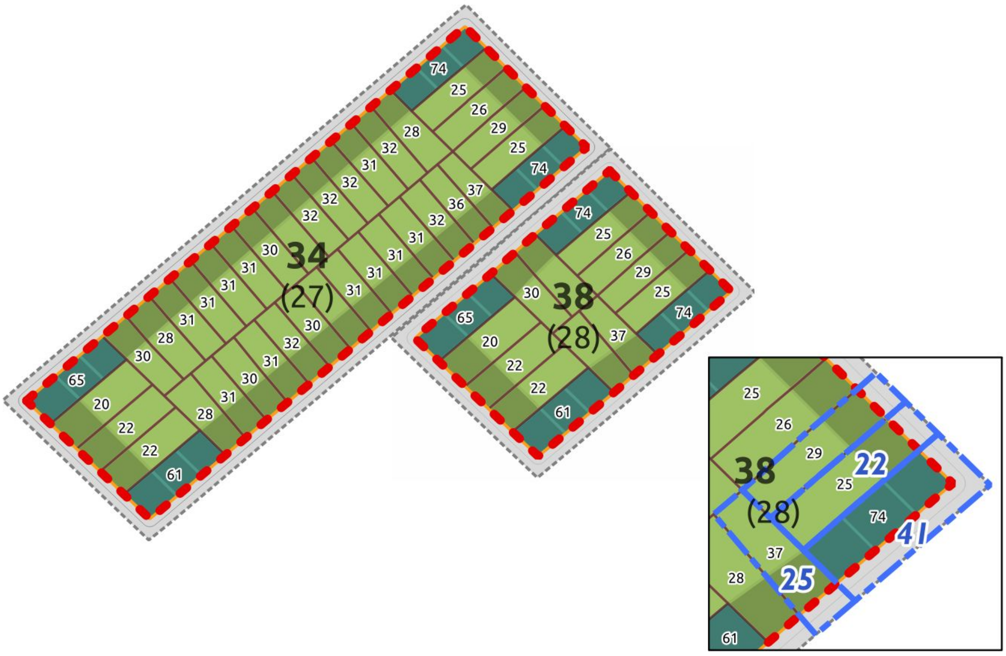



Figure 36: Typical London suburban block, introduction of a corner building typology. Note the gross density of the corner plot is now higher than its neighbours' (Bristow, 2019)

### *Discussion*

As this section has demonstrated there are multiple reasons why the residential density of a wider area cannot be generically applied to individual plots. From the city's point of view, the relative densities of individual plots should be of little consequence. It needs to make best use of the total area of land available to it including public highway and other open spaces. Assuming corner-building typologies can be used this is best achieved by maximising the frontage available in an area by minimising block size. The simple model of the closed perimeter block (Figure 36) assumes this can be achieved with buildings of a similar type to the existing houses. In reality, this is perhaps unlikely but a similar effect could be achieved by combining two or three of the end plots and introducing a small block of flats of the same height and plan-depth as the neighbouring houses that wraps around the corner. An existing London typology that could achieve this would be the corner mansion block.

## 5.5 The modifiable areal unit problem

While it is beyond the scope of this paper to investigate this in depth, what is being demonstrated in the studies above is the impact of the Modifiable Areal Unit Problem (MAUP). This has been recognised in relation to census data since 1934 and was notably explored by Openshaw (1984). It recognises that, for geographic phenomena that are not uniformly distributed, where a boundary is drawn has a significant impact on the ratio being measured. This is found at both changes between scale of reference area and with variation within the same scale of reference area

***Changes between scale of reference area***

Typically, the density of the built environment is measured at a range of scales:

- the individual plot
- the urban block
- the neighbourhood
- the wider area

As the scale of the reference area increases from the plot to the wider area, the area measured includes a greater proportion of land dedicated to uses other than residential, e.g. transport infrastructure, open/green space, etc. Simply by expanding the boundary of the area being measured, the residential density will fall.

***Change within the same scale of reference area***

It might seem that the problem can be avoided by consistently measuring densities at one particular scale of reference area and in practice, this is what is done. Common examples are:

- Population densities are measured against census tracts and reported as people per square kilometre (pop/km2).
- Proposed residential developments are measured against the site/plot and quoted as dwellings per hectare (d/ha.)

However as the three empirical studies above (CABA, London suburban and London central) demonstrate this does not resolve the problem either. The geometric limitations on how to divide a block into plots make it unavoidable that corner plots behave differently from other plots. Even in the case where this appears not to be the case, London suburban, a shift from net to gross measurements reveals the same problem but at a different scale.

The plan-depth of residential buildings does not increase in proportion to greater plot depth and residential buildings tend to remain stubbornly stuck to the plot-edge adjacent to the public highway. There are practical reasons for this. First, buildings need to be accessed from the public highway. Second, the further they are set back from the highway the greater the length and cost of connections to public infrastructure networks whether the highway itself or the water supply, drainage, electricity, telecoms, gas, etc. and the further that postal workers, refuse collectors, etc. have to travel. Aggregated across multiple properties these additional distances and costs can be very significant indeed.

## 5.6 Final method for measuring urban form

Despite urban blocks being seen as lacking meaning in Britain (Boyko & Cooper, 2011; Panerai et al., 2004) all of the key texts in the literature review either explicitly or implicitly operate at the scale of the urban block: Conzen's street blocks, Unwin's frontage line (which corresponds to the perimeter of the urban block), Martin and March's 'general plots', Berghauser Pont and Haupt's 'islands'.

The ambiguity of neighbourhood boundaries, the demonstrated problems with measuring against plots, the observation that residential capacity is strongly related to the block's frontage line all combine to support measuring residential density against the urban block. Therefore, following Berghauser Pont and Haupt (2009) the following initial metrics will be generated for each urban block:

- Street length
- Gross urban block area
- Net urban block area
- Total building ground floor area
- Building heights (storeys)
- Total building gross floor area (all storeys)
- Frontage length

It should be noted that by focussing uniquely at the scale of the urban block this study does not address Berghauser Pont and Haupt's (2009) concept of tare space, the additional space in a wider area that is not used for buildings but which is not public highway either e.g. parks, squares etc. This study does account for the public highway network by using gross urban blocks. As suggested by Steadman (2014), further detail could be added to the assessments by incorporating the additional metrics below. Due to time limits these have not been implemented in this initial study but could be implemented in future work:

- Street width
- Building set-back
- Building plan-depth (which seems to correlate with a local building type)
- Rear garden separation

# 6 Reviewing and editing OpenStreetMap

This section steps through each stage of analysing urban form from OSM data. It describes adding data to OSM, downloading data from OSM, and using a new Python library OSMuf to download, process and visualise it. Sample commands are given in the text and a complete example notebook is included in the Appendices section of this document. A statistical analysis of the results is beyond the scope of this paper but the visualisations suggest conclusions that are in-line with the earlier case-studies.

## 6.1 Viewing the map

OSM can be viewed and edited via its homepage ([https://www.openstreetmap.org/](https://www.openstreetmap.org/)). This displays a map similar to other web maps. What is shown is a grid of rendered images of OSM's underlying data. In the image below the street network is shown in white, residential land use areas in grey, and building footprints in light brown.

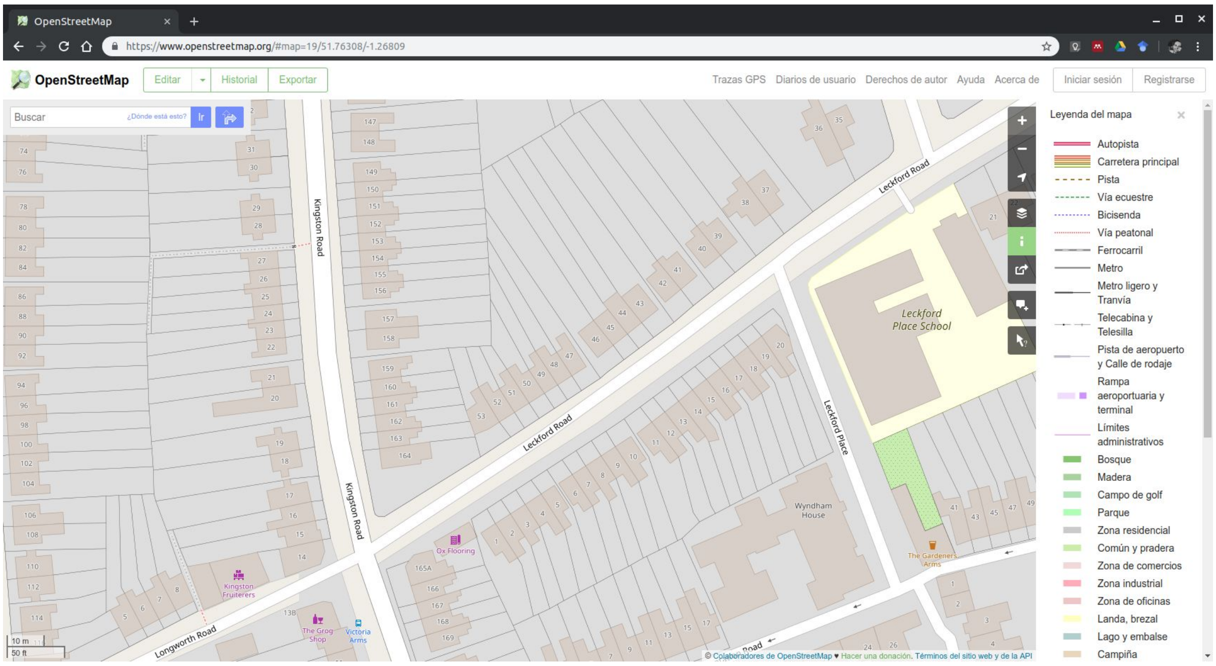



Figure 37: OSM home page [[https://www.openstreetmap.org](https://www.openstreetmap.org)](OSM contributors, 2019)

To measure urban form from OSM three sets of geometry are needed:

- Highway network centrelines
- Land use or urban block polygons

- Building footprints with building height information in storeys

Where this information is missing, it needs to be added. The workflow for checking and adding information is as follows:

1. Review the study area in OSM, checking streets, land use areas and buildings.
2. Add, update or amend them directly on OSM following community guidelines.
   - i Land use areas should not extend over public highways
   - ii Buildings must be tagged with their height in storeys (e.g. `building:levels = 2`)

## 6.2 Editing the map

After creating an account and logging in, an 'edit' button give access to a new interface. This shows OSM's data overlaid on aerial imagery licensed for use as a reference. Existing geometry and attributes can be amended, new geometry can be manually digitised by tracing over the aerial imagery provided and attributes added into a standard form. In the image below, a single building footprint has been selected for editing and its height in storeys (levels) is displayed.

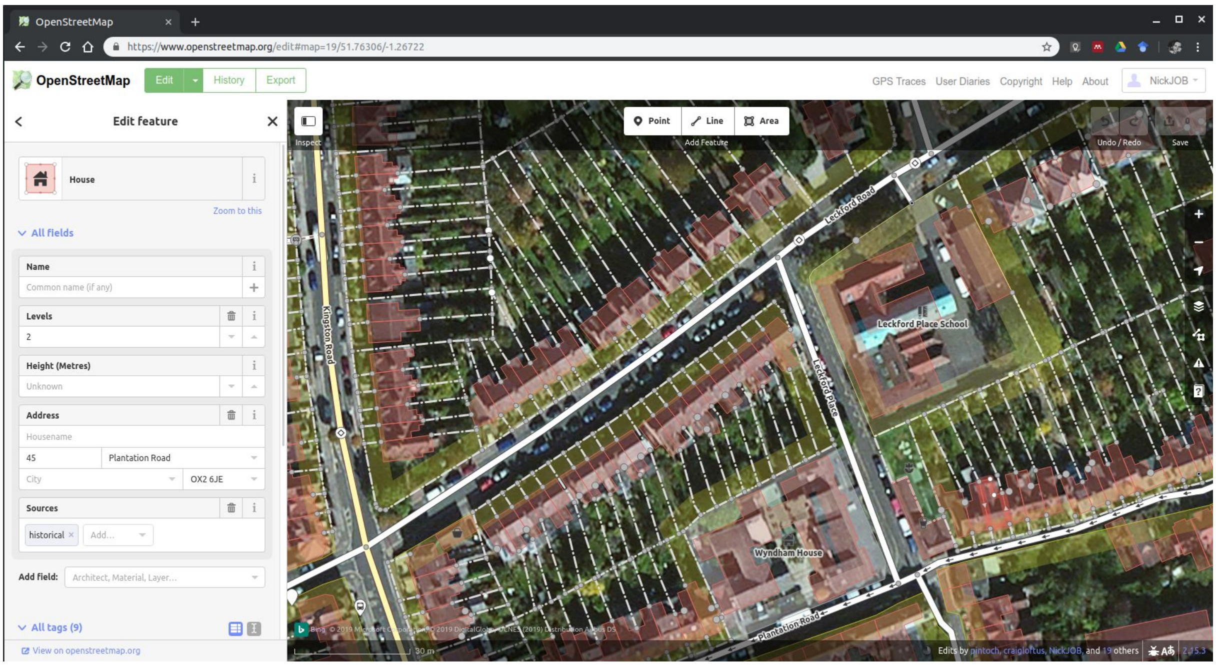


Figure 38: OSM home page, edit mode (OSM contributors, 2019)

The aerial imagery that is available for use with OSM generally shows enough detail to be able to map the lines of streets and the outlines of individual buildings and urban blocks. The resolution of aerial imagery used by OSM varies but can be as high as 7cm per pixel. The image below (Figure 39) is from the Open Cities Africa project (World Bank, 2018)which has resulted in OSM's adoption by the government in Zanzibar as its official source of topographic mapping (World Bank, 2019).

Figure 39: OpenAerialMap of Zanzibar 7cm resolution [http://www.zmi-geonode.org] (ZMI and the Revolutionary Government of Zanzibar – Commission for Lands, 2018)

***Building heights***

Adding building heights is the most opaque part of the process. To assess which buildings have building height information it is generally faster to download the data, visualise the heights, return to OSM, add the information where missing, download again, visualise, repeat.

Finding the building height information to add is also trickier than simply tracing the plan areas. Building heights can be assessed from street view imagery licensed for use with OSM (e.g. Mapillary or Microsoft Streetside) or by physically surveying an area and adding them under the 'building:levels' tag.

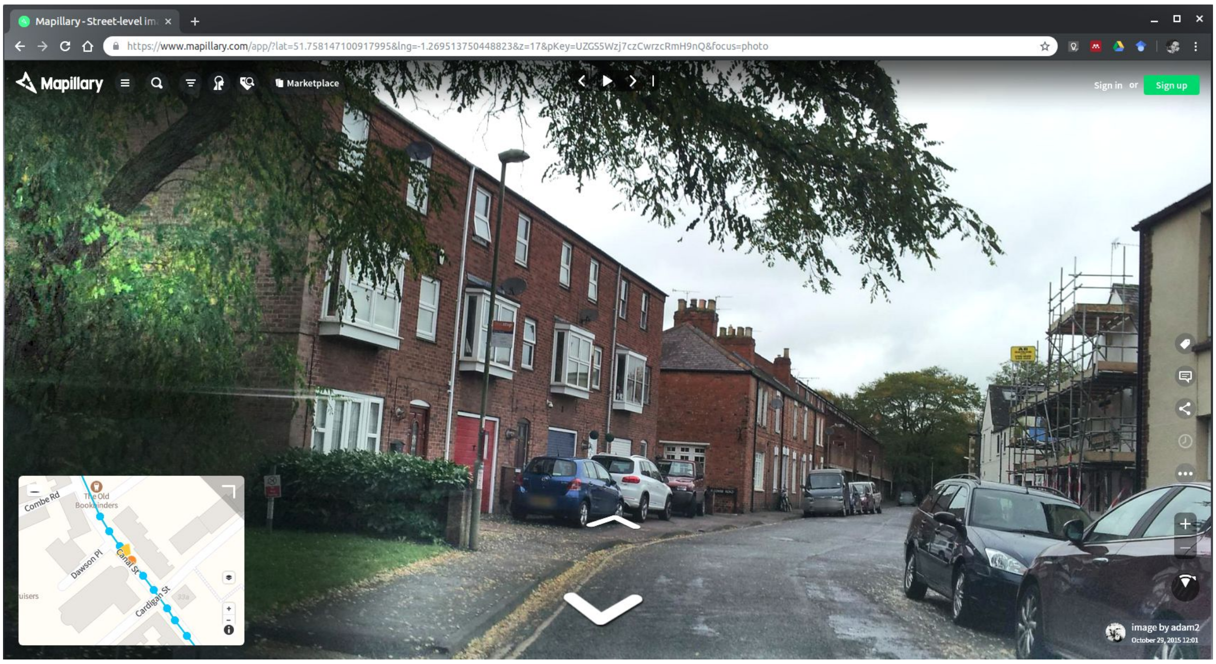


Figure 40: Mapillary street view imagery (Bristow, 2019)

Separate editors are available and provide greater control and more powerful tools. The most popular solution is called JOSM (https://josm.openstreetmap.de/) which has an interface similar to GIS or CAD software. Once edits have been made and saved to OSM the tile images have to be re-rendered by OSM's server before the changes appear on the OSM homepage, this process may take some minutes.

As with any community project the most active members can be extremely influential – engagement with the local mapping community is recommended. While safeguards do exist, any OSM member is free to add, modify or delete any OSM data. A clear example of this was encountered when updating the Buenos Aires study area. OSM allows urban blocks to be mapped directly as shapes tagged with `place = city_block`. The local OSM community in Buenos Aires was divided over the use of this tag and some local members deleted the new shapes as they were created as they felt they did not comply with OSM guidelines. After engaging with the local community through their Telegram chat group it was agreed that direct mapping of city blocks was valid and could continue.

## 6.3 Accessing the data

Once up-to-date, OSM data can be exported directly from the homepage in OSM's own storage format. It can also be downloaded from third parties such as Geofabrik (https://download.geofabrik.de/) who may also process it into common file formats such as shapefiles for use with GIS software.

A third option is to access the data via the Overpass API. This is in effect a direct link to the OSM database, allowing queries to be made and returning the latest version of the requested elements. This avoids the need to manage large numbers of files and ensures you are always working with the latest OSM data.

# 7 Measuring urban form with OSMuf

This section describes how OSMuf creates the metrics and ratios it needs to carry out ESDA.

OSMuf is a Python library that packages together a set of pre-determined methods that download OSM data, process it into measures of urban form, analyse it, and presents the results in some standardised visualisations. This makes it possible to quantitatively and visually compare urban form from OSM's global mapping database. It is built on top of OSMnx and other core libraries in the Python geospatial data stack. This means that in future work it will be possible to compare the results from different packages that perform different analysis. For example, building density might be assessed against street network centrality.

## 7.1 Setting-up the workspace

A detailed description of installing Python and the additional libraries is beyond the scope of this paper. Further information on the environment and required libraries is included in the Appendix. Essentially, Conda ([https://www.anaconda.com/distribution/](https://www.anaconda.com/distribution/)) is used to set-up a virtual environment into which OSMnx is installed from conda-forge. OSMuf can then be downloaded from [https://github.com/AtelierLibre/osmuf](https://github.com/AtelierLibre/osmuf) and installed into the same environment. The goal is to have an isolated virtual environment with OSMuf, OSMnx, GeoPandas etc. all available within the Jupyter notebook interface.

Jupyter's interface runs inside a web browser and allows short lines of code to be written and executed step-by-step in a series of cells and the results displayed immediately. This allows code to be written, tested and edited more or less line-by-line with the results building up in a sequential order. The first couple of steps are illustrated within the Jupyter interface (Figures 41 & 42), the subsequent steps are illustrated with just a sample line of code and its visual output.

### *7.1.1 Importing libraries*

The first step in an analysis is to import the libraries necessary for the study (Figure 41). It is only necessary to import libraries whose commands you need to access directly:

Once the libraries are imported the various functions within them are accessed with the 'dot notation' e.g. `osmuf.study_area_from_point()`.

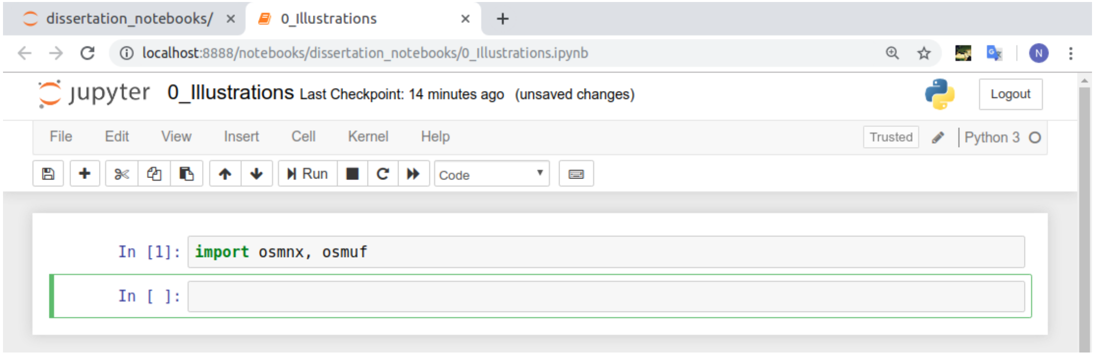



Figure 41: Jupyter imports (Bristow, 2019)

## 7.2 Downloading data

### 7.2.1 *Defining a study area*

OSMuf works uniquely with individual urban blocks that fall within "windowed subsets of the map" (Haining & Wise, 1997). Each study-area's bounding box is defined by a distance north, south, east and west of a geographic centre point:

| **Place** | **Latitude, Longitude** |
|---|---|
| Colegiales, Buenos Aires, Argentina | -34.5798,-58.4422 |
| Clerkenwell, London, UK | 51.5266,-0.1109 |
| Welwyn Garden City, Hertfordshire, UK | 51.7938,-0.189 |
| Bromley, London, UK | 51.395,-0.006 |

Using a 1x1km fixed-size bounding box allows presentation of the study areas at a consistent scale relative to one another and defines the geographic extent of the initial download from OSM.

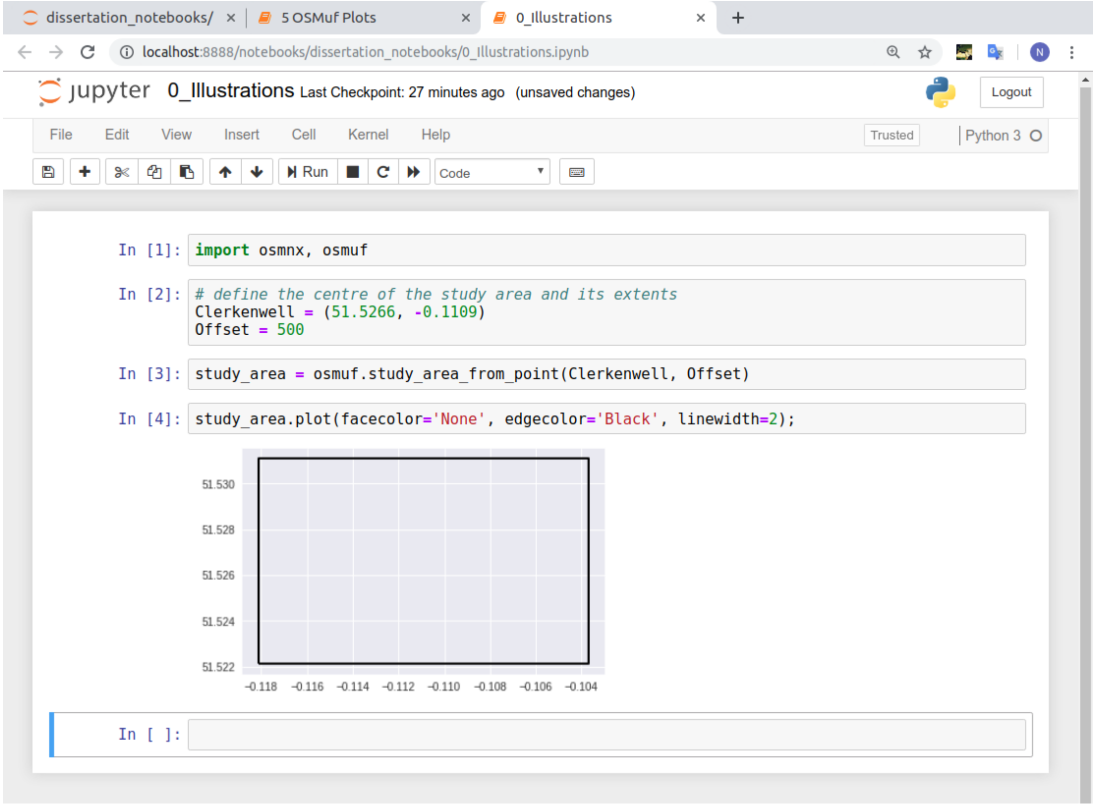



Figure 42: Jupyter - Study area. Note that the 1km square appears squashed as it is in unprojected geographic coordinates (Bristow, 2019).

### 7.2.2 *Urban blocks and land use*

This study was carried out by adding urban block outlines tagged as `place = city_block` directly to the OSM database. While this is within OSM's guidelines [https://wiki.openstreetmap.org/wiki/Tag:place%3Dcity_block], given that urban blocks can also be created from contiguous islands of land within the highway network, it could be seen as an unnecessary duplication for this purpose. Forming urban blocks by dissolving together contiguous land use polygons (tagged as `landuse=*`, `amenity=*`, `leisure=*` etc.) would be a better approach as they could add further detail to the analysis. For example, if a significant area of an urban block is dedicated to a park it would be useful to discount that from residential density calculations.

The same parameters that were used to define the extent of the bounding box are used to define the OSM query for urban blocks.

```
urban_blocks = osmuf.places_from_point((-34.58,-58.44), 500)
```

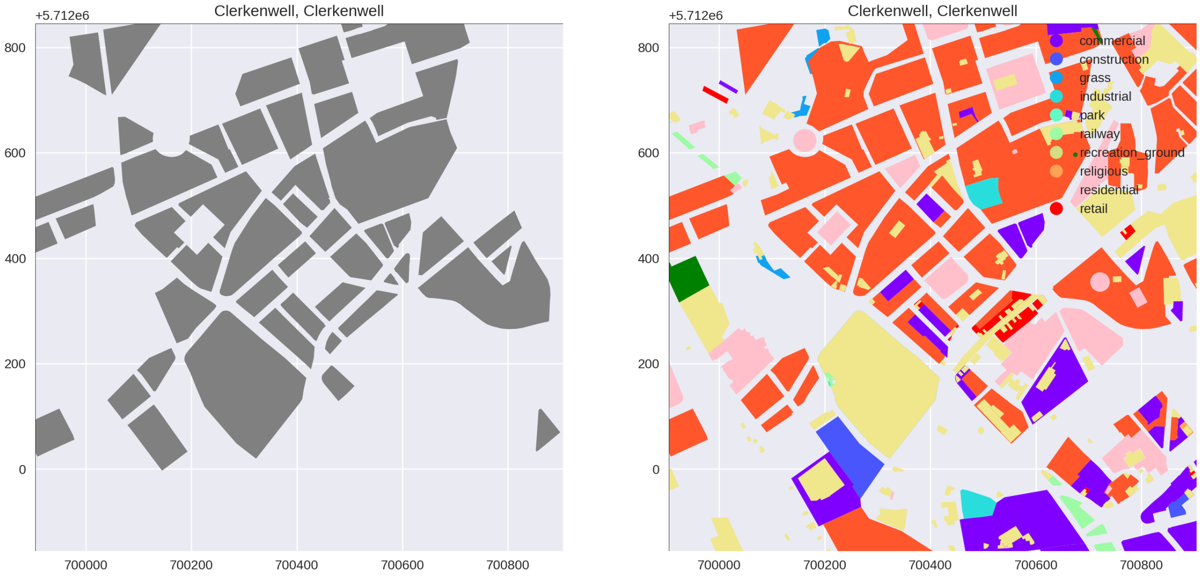



Figure 43: Urban blocks and land use shapes in Clerkenwell, London. The different colours represent different OSM land use tags e.g. residential is red, squares are pink (Bristow, 2019; Map data © OpenStreetMap contributors)

### *7.2.3 Highway network*

Highway network centrelines are used to generate gross urban blocks and to calculate network metrics. In OSM all footpaths, roads and cycleways, public or private, are represented by a line tagged with `highway=*` where the `*` is replace by the type of highway e.g. `highway=residential`.

The bounding box is not used to define the extent of the download as the highway network must entirely surround all of the urban blocks including where they extend beyond the bounding box. Instead the extent of the download is defined by a shape that completely encloses the urban blocks which is offset to a distance approximately one block further away.

The highway network is initially stored as a NetworkX graph suitable for primal graph analysis by OSMnx but it is then converted to a GeoPandas GeoDataFrame for analysis by OSMuf.

```
street_graph = osmuf.street_graph_from_gdf(urban_blocks)
street_gdf = osmuf.streets_from_street_graph(street_graph)
```

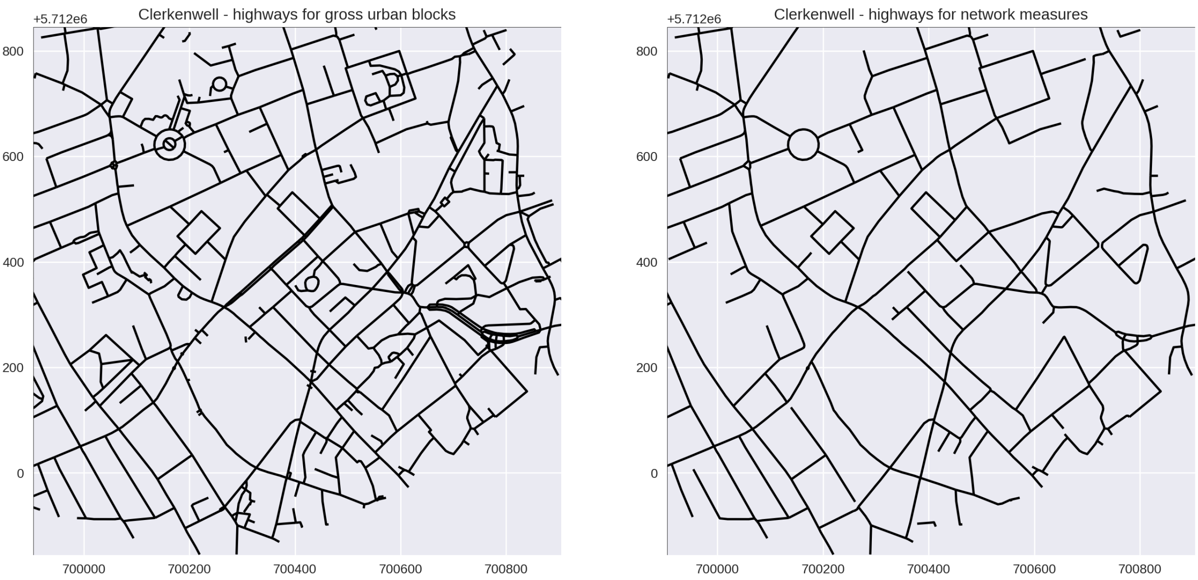



Figure 44: OSM highway network lines, Clerkenwell, London. Left, all highway lines including footpaths, cyclepaths etc.. Right, only drivable highway lines (Bristow, 2019; Map data © OpenStreetMap contributors)

### *7.2.4 Building footprints*

Buildings in OSM are represented as closed shapes (polygons) tagged with `building=*` where `*` could be a simple `yes` or may refer to the building type e.g. `building=office`. Similarly to the highway network building footprints must be downloaded to cover the full extent of every urban block even when they extend beyond the bounding box.

```
buildings = osmuf.buildings_from_gdf(urban_blocks)
```

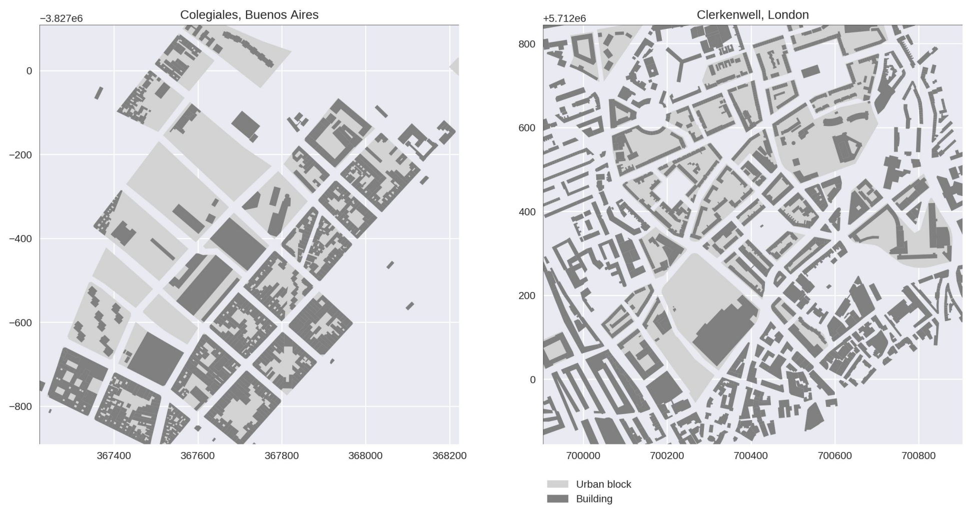



Figure 45: Building footprints displayed over urban blocks. Left, Colegiales, Buenos Aires. Right, Clerkenwell, London (Bristow, 2019; Map data © OpenStreetMap contributors)

The data that is downloaded with the buildings is entirely dependent on what OSM contributors have added. A sample is shown below:

| | nodes | addr:city | addr:housenumber | addr:postcode | addr:street | amenity | architect | building | building:cladding | name | ... | clinic | note_2 | official_name | building:levels_1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **70298958** | [839173568, 839173561, 839173566, 839173554, 5... | London | 156 | EC1R 5DU | Clerkenwell Road | pub | NaN | yes | NaN | The Clerk & Well | ... | NaN | NaN | NaN | NaN |
| **98525949** | [1139831956, 1139831194, 1139830003, 113983005... | London | 28 | WC1X 0AS | Mount Pleasant | NaN | NaN | yes | NaN | WCS Digital Prints | ... | NaN | NaN | NaN | NaN |
| **98525959** | [1139830490, 4282890512, 4282890513, 113983177... | London | 42-44 | NaN | Rosebery Avenue | NaN | NaN | yes | NaN | NaN | ... | NaN | NaN | NaN | NaN |
| **98525966** | [1139831445, 1139831934, 1139831166, 113983030... | London | 12 | EC1R 5HL | Coldbath Square | NaN | NaN | commercial | NaN | Institute of Biomedical Science | ... | NaN | NaN | NaN | NaN |
| **98532011** | [1733573853, 1139898137, 1139898951, 113989670... | London | 136 | EC1R 5EN | Clerkenwell Road | place_of_worship | NaN | yes | NaN | St Peter's Italian Catholic Church | ... | NaN | NaN | NaN | NaN |
| **99813663** | [580990288, 1153948493, 1153948483, 1153948513... | London | 62 | EC1R 4QE | Exmouth Market | restaurant | NaN | yes | NaN | Hummus Bros | ... | NaN | NaN | NaN | NaN |

Figure 46: Sample building data from OSM (Bristow, 2019. Data © OpenStreetMap contributors)

In order to calculate the FSI, the only tag that OSMuf requires for each building footprint is `building:levels` with the height in storeys.

### *7.2.5 Projecting the data*

OSM stores geometry in the WGS84 Web Mercator (EPSG:3857) geographic coordinate (Latitude and Longitude) reference system. To be able to calculate metric areas and lengths OSMnx is used to project all geometry to a local Universal Transverse Mercator (UTM) c artesian grid which has its units in metres.

```
buildings_prj = osmnx.project_gdf(buildings)
```

## 7.3 Generating secondary geometry

The three sets of geometry downloaded from OSM are then processed to generate secondary supporting geometry.

### *7.3.1 Gross urban blocks*

Where net urban blocks can be formed by dissolving together contiguous land use areas, gross urban blocks extend to the centreline of the surrounding public highways.

```
gross_urban_blocks = osmuf.gen_gross_city_blocks(street_graph, urban_blocks)
gross_urban_blocks_prj = osmnx.project_gdf(gross_urban_blocks)
```

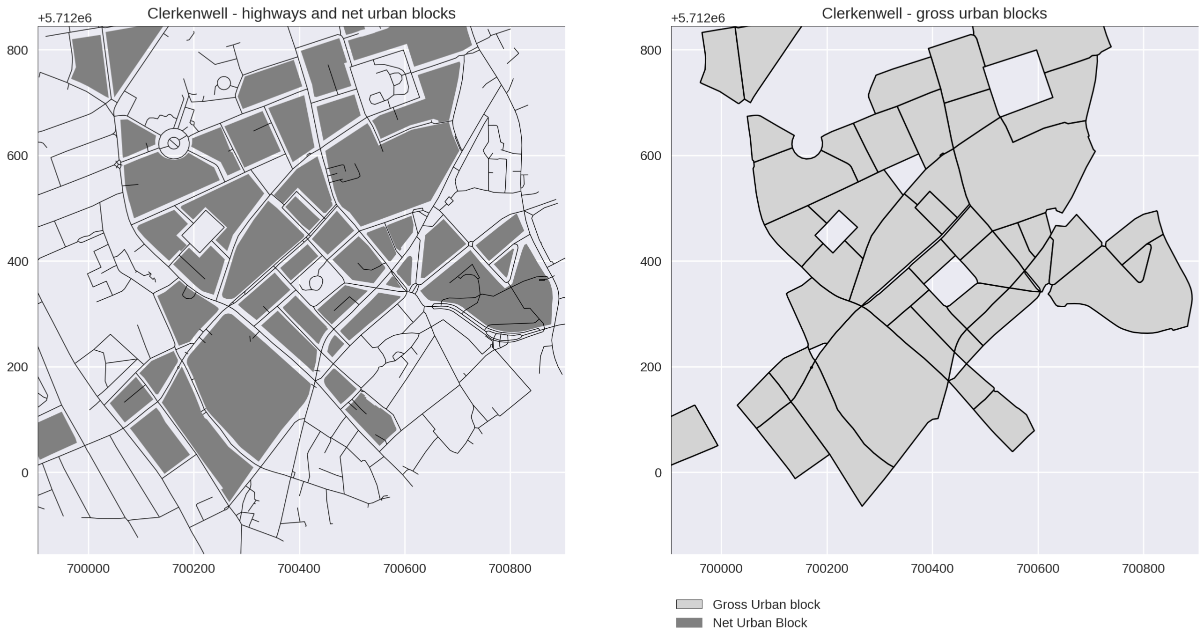



Figure 47: Highways and net urban blocks combine to generate gross urban blocks (Bristow, 2019. Map data © OpenStreetMap contributors)

Generating gross urban blocks from the highway network is a two-step process. First, the long highway centrelines are sub-divided at every junction, and the resulting fragments are 'polygonized' using Shapely's polygonise method `shapely.ops.polygonize`. This creates polygons wherever touching linear fragments form a closed shape.

Best results were achieved by using all highway geometry including footpaths, cycleways and private ways (Figure 44 & 47). If they were not used, pedestrianised or cycle only streets left gaps in the network and generated overly large urban blocks. Using all OSM highway geometry does result in over fragmentation of gross urban blocks (e.g. split by footpaths that cross them) but a second step dissolves these fragments together according to whether they intersect with a common net urban block. The gross urban blocks are then also projected to UTM coordinates.

### 7.3.2 *Complete required geometry*

At this point all of the geometry necessary for the study is available to OSMuf:

1. (Net) Urban Block polygons
2. Highway network lines
3. Gross Urban Block polygons
4. Building Footprint polygons

## 7.4 Measuring urban form against the urban block

### *7.4.1 Extracting basic areas and lengths*

Aside from the `building:levels` and `highway` attributes, the only information required from each of the downloaded elements is their OSM id number and their geometry. The areas and lengths of the geometries are not included in the data attributes so these are measured directly from the projected geometry. For example `buildings_prj['footprint_m2'] = buildings_prj.area` measures the area of every building polygon and writes it into a new column in the building data called `footprint_m2` (Figure 48). In a similar way we can generate:

- The area of each building footprint ($m^2$)
- The total Gross External Area of each building (footprint_m2 x building:levels)($m^2$)
- The area of each net and gross urban block ($m^2$)
- The perimeter length of each net urban block (m)

| | building_id | building:levels | geometry | footprint_m2 | total_GEA_m2 |
|---|---|---|---|---|---|
| **9255635** | 9255635 | 6 | POLYGON ((367341.0853806165 -3827818.694235605... | 5770.9 | 34625.5 |
| **9337825** | 9337825 | 3 | POLYGON ((367542.848264683 -3827002.921289418,... | 273.6 | 820.9 |
| **9340682** | 9340682 | 3 | POLYGON ((367577.8722019927 -3826949.276700229... | 153.0 | 459.1 |
| **101885095** | 101885095 | 4 | POLYGON ((367538.4479627716 -3827335.977596004... | 2014.8 | 8059.3 |

Figure 48: Building metrics generated by OSMuf (Bristow, 2019. Initial data © OpenStreetMap contributors)

### *7.4.2 Associating building metrics with an urban block*

In order to assess the built density in relation to each urban block the data for all of the buildings on each urban block has to be aggregated. A spatial join adds the id number of the urban block to each building:

| | building_id | building:levels | geometry | footprint_m2 | total_GEA_m2 | city_block_id |
|---|---|---|---|---|---|---|
| **9255635** | 9255635 | 6 | POLYGON ((367341.0853806165 -3827818.694235605... | 5770.9 | 34625.5 | 668445117 |
| **9337825** | 9337825 | 3 | POLYGON ((367542.848264683 -3827002.921289418,... | 273.6 | 820.9 | 671358872 |
| **9340682** | 9340682 | 3 | POLYGON ((367577.8722019927 -3826949.276700229... | 153.0 | 459.1 | 671358872 |
| **101885095** | 101885095 | 4 | POLYGON ((367538.4479627716 -3827335.977596004... | 2014.8 | 8059.3 | 670341036 |

Figure 49: Building data with block id added (Bristow, 2019. Initial data © OpenStreetMap contributors)

Plotting the building footprints coloured by urban block id shows whether this was successful (Figure 50):

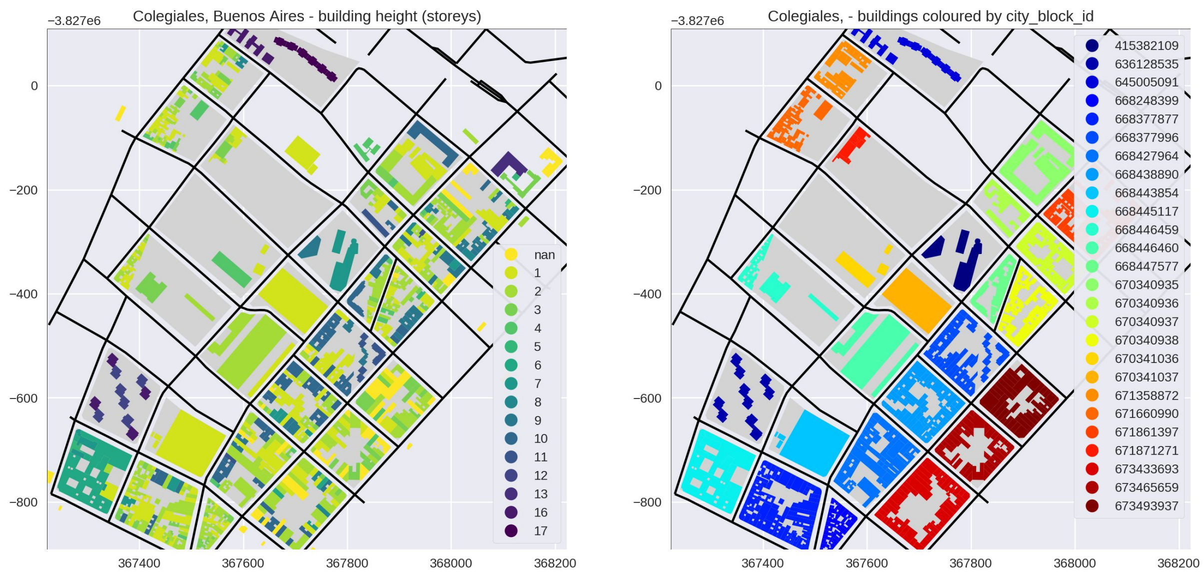



Figure 50: Buildings coloured by storeys above ground and by block id (Bristow, 2019. Map data © OpenStreetMap contributors)

The building footprint areas and GEAs are then aggregated together based on the block id numbers creating a temporary DataFrame with the total sum of building footprint and GEA per urban block. The urban block ID is then used to join this aggregated building data to the urban block GeoDataFrame (Figure 51):

| | city_block_id | net_area_m2 | frontage_m | gross_area_m2 | geometry | footprint_m2 | total_GEA_m2 |
|---|---|---|---|---|---|---|---|
| 0 | 415382109 | 12802.91 | 453.35 | 17609.92 | POLYGON ((367782.5331005618 -3827401.893272361... | 4178.8 | 31285.0 |
| 1 | 636128535 | 16441.42 | 505.66 | 21248.35 | POLYGON ((367340.3616997305 -3827505.100204745... | 3592.8 | 48933.7 |
| 2 | 645005091 | 18845.25 | 648.33 | 78576.77 | POLYGON ((367594.319630042 -3826860.513222478,... | 3435.1 | 56851.1 |
| 3 | 668248399 | 4227.72 | 311.05 | 8135.91 | POLYGON ((367532.3839805268 -3827790.541791959... | 3478.9 | 6925.6 |

Figure 51: Urban block data with aggregated building data (Bristow, 2019. Initial data © OpenStreetMap contributors)

### *7.4.3 Network length per urban block*

Network length per urban block is the length of the public highway network that shares an edge with each urban block. Because it is a measure of the public highway it is by definition a gross measure. Following Berghauser Pont and Haupt's (2009) example, to avoid double counting, the length of the street separating one block from another is divided by two – one half allocated to each block. Cul-de-sacs which are completely internal to a single block have their full length allocated to that block.

As Louf and Barthelemy showed in their study (2014), generating gross urban blocks by polygonizing the highway network has the effect of removing cul-de-sacs (Figure 22). Cul-de-sacs are a fundamental part of the urban fabric (this is evident in Welwyn Garden City, UK) just omitting them prevents any meaningful investigation of the link between street layouts and building density.

Calculating the length of street network attributable to each gross urban block is again a two-step process. First the perimeter of the gross urban block is measured:

```
gross_urban_block_prj['outer_streets_m'] = gross_urban_block_prj.length
```

Next a spatial join adds the full length of any drivable public highway fragment that is completely contained within the perimeter of the gross urban block (i.e. the cul-de-sacs, Figure 52) to a column called `gross_urban_block_prj['inner_streets_m']`.

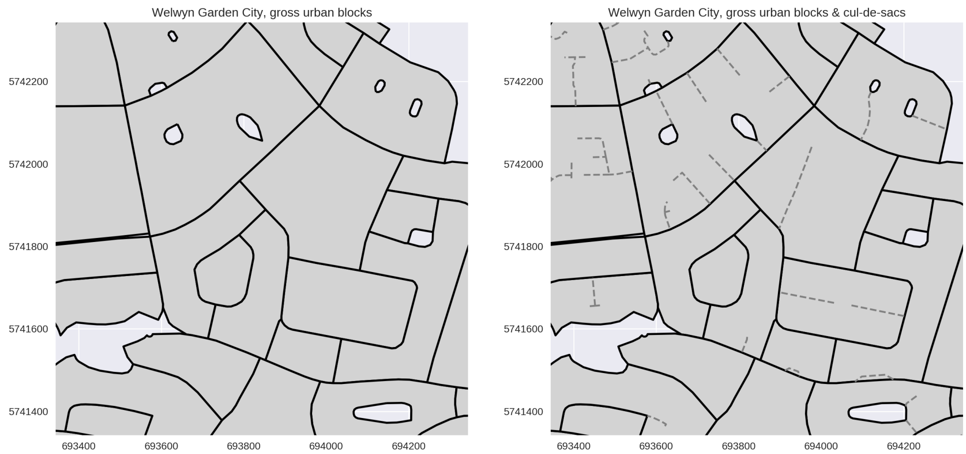



Figure 52: Gross urban blocks formed by polygonising the highway network. Left, showing the removal of cul-de-sacs. Right, adding the cul-de-sacs back (Bristow, 2019. Map data © OpenStreetMap contributors)

The final network length is calculated as half the length of the outer streets plus the full length of inner streets. (Figure 53)

| | city_block_id | gross_area_m2 | inner_streets_m | outer_streets_m | network_length_m | geometry |
|---|---|---|---|---|---|---|
| 0 | 415382109 | 17609.92 | 0.0 | 531.05 | 265.52 | POLYGON ((367782.5331005618 -3827401.893272361... |
| 1 | 636128535 | 21248.35 | 0.0 | 589.65 | 294.82 | POLYGON ((367340.3616997305 -3827505.100204745... |
| 2 | 645005091 | 78576.77 | 574.8 | 1531.17 | 1340.38 | POLYGON ((367594.319630042 -3826860.513222478,... |
| 3 | 668248399 | 8135.91 | 0.0 | 407.34 | 203.67 | POLYGON ((367532.3839805268 -3827790.541791959... |

Figure 53: Gross urban block network length data (Bristow, 2019. Data © OpenStreetMap contributors)

## 7.5 Generating ratios

In the context of London needing to 'optimise' (i.e. increase) its density, the starting point for the study was to investigate the relationship between building density and the street network. Following the Buenos Aires case study questions were raised about the relationship between building density and the area of a plot. With the basic metrics now in place the ratios exploring the relationship between them can be calculated. Both net and gross ratios are used:

| Reference Geometry | Ratio | Measures |
|---|---|---|
| Urban Blocks | Net to Gross Area Ratio | The proportion of private developable land relative to land dedicated to public highway. |
| Net Urban Block | FSI | The aggregated building floor area (all storeys) relative to the area of the net urban block |
| | GSI | The aggregated building footprint area relative to the area of the net urban block |
| | Frontage Density (or Perimeter Area Ratio) | The total perimeter of the net urban block relative to its area |
| Gross Urban Block | FSI | The aggregated building floor area (all storeys) relative to the area of the gross urban block |
| | GSI | The aggregated building floor area (all storeys) relative to the area of the gross urban block |
| | N | The length of street network relative to the area of the gross urban block |

In order to specifically assess how frontage and network length mediated between building capacity and the area of a piece of land, two further ratios are generated:

| Reference Geometry | Ratio | Purpose |
|---|---|---|
| Net Urban Block perimeter length | FSI / Frontage Density | Explores whether the density of building is related to the density of frontage for each Net Urban Block |
| Gross Urban Block street network length | FSI / N | Explores whether the density of building is related to the density of the street network for each Gross Urban Block |

# 8 Exploratory Spatial Data Analysis of sample areas using OSMuf

Once all of the metrics and ratios have been generated, OSMuf provides various standard visualisations to facilitate comparison of the selected study areas. Due to the patchy nature of OSM building and land-use coverage OSMuf cannot currently benefit from the kind of large-scale automated data analysis of the kind carried out by Geoff Boeing when he analysed the street networks of 27,000 towns and cities. Where it does make use of the code based approach is in the consistent and reproducible application of its data analysis method in order to generate directly comparable visualisations and metrics of cities as geographically diverse as Welwyn Garden City, London and Buenos Aires.

The six visualisations created for each study area are as follows:

1. Urban block size
2. Urban block shape
3. GSI per urban block
4. Building heights
5. FSI per urban block
6. Network Density

The full sets of visualisations for the four sample areas (Colegiales, Buenos Aires; Bromley and Clerkenwell, London; Welwyn Garden City) are included in the Appendix. This section selects one example of each visualisation that illustrates its significance.

## 8.1 Block size

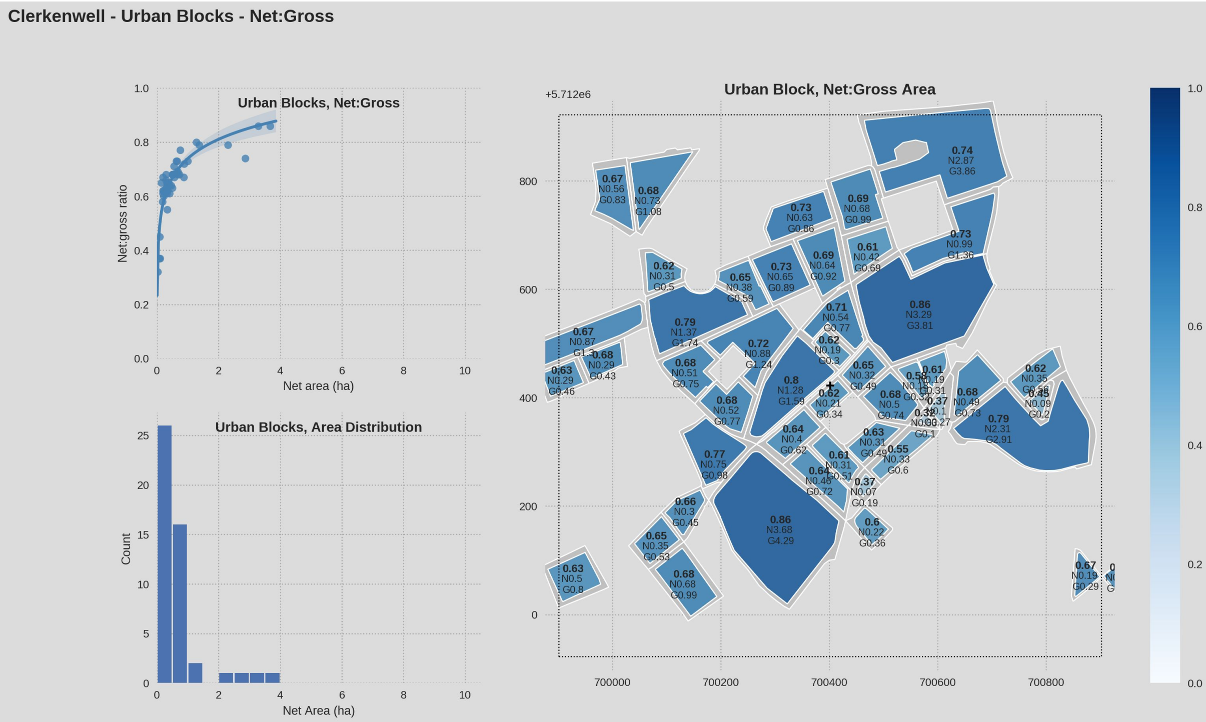


Figure 54: Urban Block Size (Bristow, 2019; Map data © OpenStreetMap contributors)

Presenting the urban blocks at a consistent scale reveals that their sizes vary widely across the case-studies – in Clerkenwell, London the smallest is 0.07ha, in Buenos Aires they are based on a standard 1.5ha and both Welwyn Garden City and Bromley have net urban blocks of over 10ha.

### *Clerkenwell, London*

Clerkenwell's high proportion of small blocks (<1.5ha) is interesting because the scatter graph shows their net-to-gross area ratios increasing rapidly as the net area increases from 0-1ha before levelling off at between 80 and 90% above 1.5ha (which is consistent with the other case-studies).

### *Discussion*

If residential building capacity were proportional to site area (as implied by London's SRQ density matrix) then the net-to-gross graph would suggest that making net urban blocks at least 1.5ha would maximise building capacity by ensuring that no more than 20% of a gross urban block’s area would be ‘lost’ to public highway. i.e. bigger blocks would increase total gross building capacity. But, as was found in the case-study, when considering residential buildings, this assumption doesn’t necessarily hold true.

## 8.2 Block shape

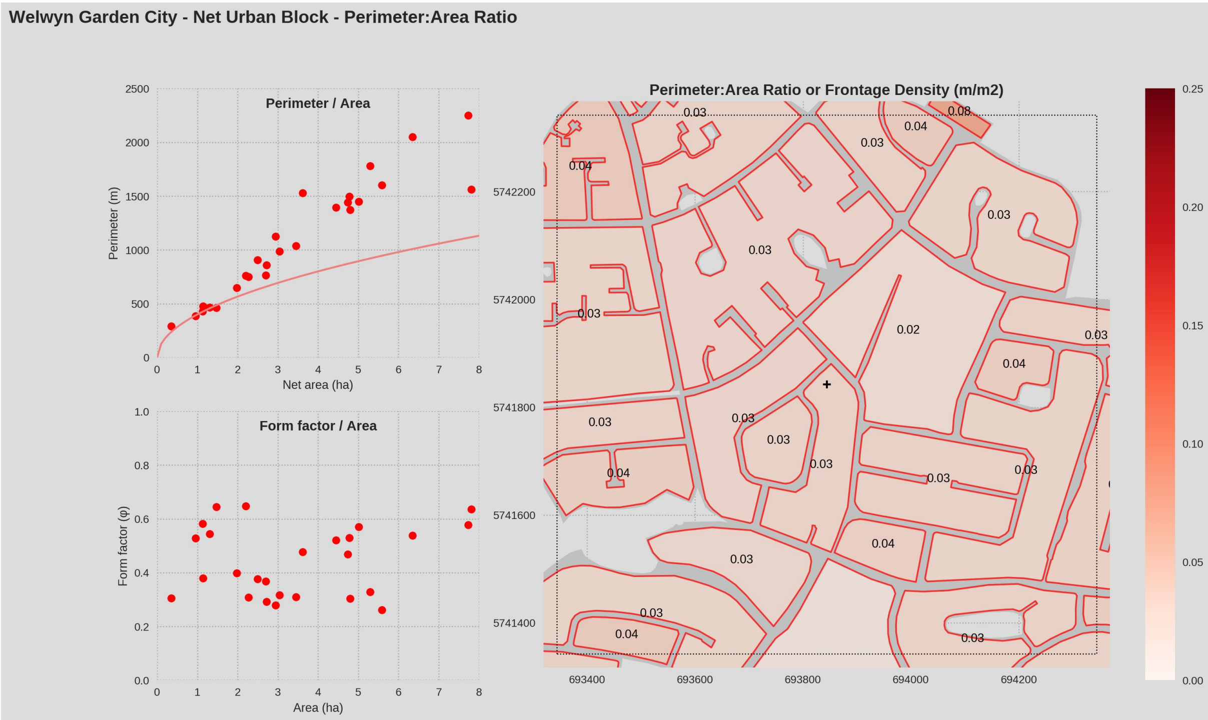



Figure 55: Urban Block Shape (Bristow, 2019; Map data © OpenStreetMap contributors)

Louf and Barthelemy (2014) used Form Factor (φ) – the ratio between the area of a polygon and its Smallest Enclosing Circle (SEC) – to quantify the shape of gross urban blocks. The bottom graph shows form factors against net block area.

***Welwyn Garden City***

Welwyn Garden City, designed by Louis de Soissons, follows Garden City principles. It is characterised by a high proportion of cul-de-sacs. These makes the perimeters of its blocks very irregular but they have little impact on the net area and so they do not significantly affect form factor measurements.

***Discussion***

During the course of this study it became evident that cul-de-sacs can significantly impact urban capacity by creating frontage and so an alternative way to quantify block shape was required. PAR measures the length of the edge of a block relative to its area. It is shown in the top graph. The red line indicates the PAR of a square urban block – as its area grows its PAR initially rises rapidly but quickly tails off. We can see however that the values measured in Welwyn Garden

City do not follow this line. Instead the cul-de-sacs deliberately manipulate the urban block perimeters ensuring that frontage length continues to grow proportionally with the block area despite the very large block sizes.

As a regular polygon grows the ratio between its perimeter and area decreases. In urban terms less frontage is created for the land take. In Welwyn Garden City this is countered by the introduction of cul-de-sacs. In urban environments with more regular block shapes, simply by sub-dividing the blocks into smaller ones helps to keep the PAR high for the gross land take.


Figure 56: Buildings follow frontage (Bristow, 2019. Map data © OpenStreetMap contributors)

## 8.3 GSI per block


Figure 57: GSI per net urban block (Bristow, 2019. Map data © OpenStreetMap contributors)

Net GSI (the proportion of the net urban block covered by building footprint) is the first building density ratio assessed. If the building capacity of a piece of land is directly proportional to its area (as generic area-wide density measures suggest) then the GSI should remain constant regardless of the size of each urban block. This is what we see for both Welwyn and Bromley (see Appendices) but not for Clerkenwell (Figure 57) or Colegiales.

### *Clerkenwell, London*

Clerkenwell is interesting because it has a fairly consistent building typology (4-6 storey terraces or apartment buildings) and so an even streetscape. The GSI by block area graph clearly shows GSI falling rapidly as the area of the net urban blocks increases. If the lessons from the Buenos Aires case study apply here as well, we might instead expect to find that the quantity of building is linked to the frontage length. In the lower graph, plotting GSI against Frontage Density (which has the useful effect in this case of controlling for building height) shows that this is indeed the case. The more frontage per area, the more building per area.

***Discussion***

This visualisation supports the findings of the earlier Buenos Aires case-study and calls into question area based density ratios. It shows that, in this sample at least, building density is positively correlated with frontage density and negatively correlated with net block area. i.e. smaller blocks have a higher building capacity.

This visualisation is perhaps the clearest demonstration of the core finding of this study. It confirms that, despite the apparently inefficient net-to-gross area ratio of small blocks, the higher frontage density created by more closely spaced streets actually generates a higher gross building density.

## 8.4 Building heights

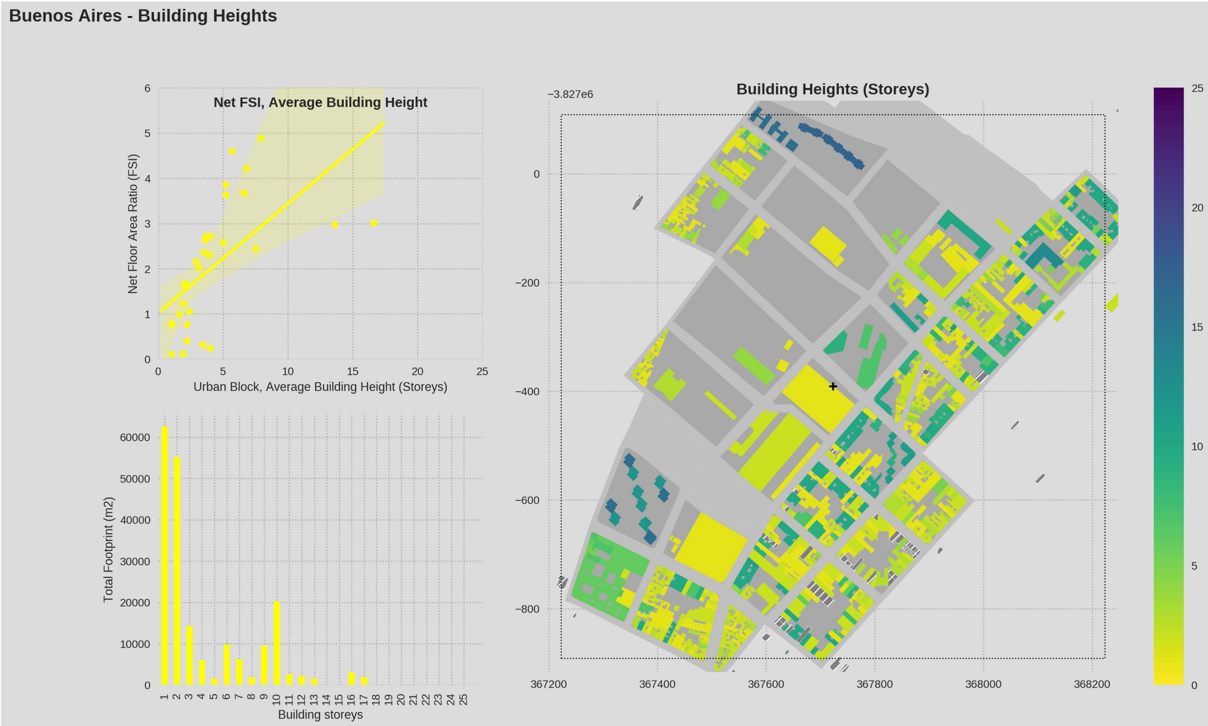



Figure 58: Buenos Aires, building heights (Bristow, 2019. Map data © OpenStreetMap contributors)

Adding storeys to existing buildings clearly increases an areas overall building capacity. However for towers specifically, their low GSI (due to the large space required between them) is rarely offset by their increased height when compared to courtyard type buildings.

### *Buenos Aires*

An example of this is shown in the south-western corner of the Buenos Aires sample area (Figure 58). One urban block has 10 towers of 12-16 storeys roughly arranged in an 'X', its FSI is 3.0. Immediately to the south a block with courtyards rises to only 6 storeys but its FSI is 4.5. The second block rises to less than half the height of the towers but has 50% more floor space.

### *Discussion*

The map of building heights in Buenos Aires shows the characteristic stepped streetscape created by permitting narrow 10 storey apartment buildings immediately next door to old 1-2 storey terrace houses. The map also shows the footprints of 1-2 storey buildings nearly completely covering some of the deep plots. This is characteristic of Buenos Aires' *casas chorizo* and of its vertical mixing of uses. The ground floor of a building is often occupied by deep-plan commercial/retail use. This is possible as light and air can be brought in to one storey, perhaps two, through its roof. The much taller elements, the residential apartment buildings would cause unacceptable shading to neighbours and so they are limited to a strip of land around the perimeter of the block.

This building arrangement of many residential storeys above ground floor retail is very common in Buenos Aires and is reflected in the GSI measurements which are high. To reveal a similar alignment of the residential elements with the frontage line (as seen so clearly in Clerkenwell's GSI graphs) we can filter the building footprints by number of storeys. Progressively removing one-storey then two-storey buildings makes the alignment of the tall residential elements with the frontage line clearer (Figure 59).

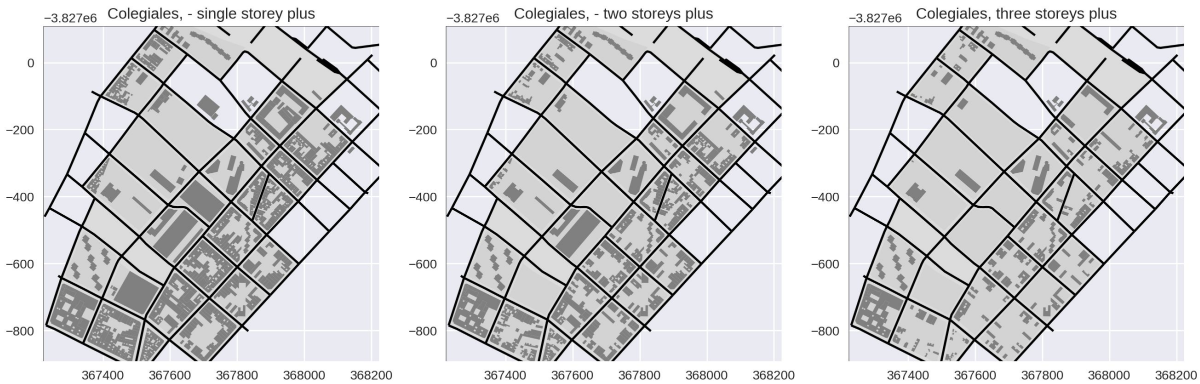



Figure 59: Buenos Aires, as height increases built form is increasing limited to a band around the edge of the urban block (Bristow, 2019. Map data © OpenStreetMap contributors)

## 8.5 FSI per block

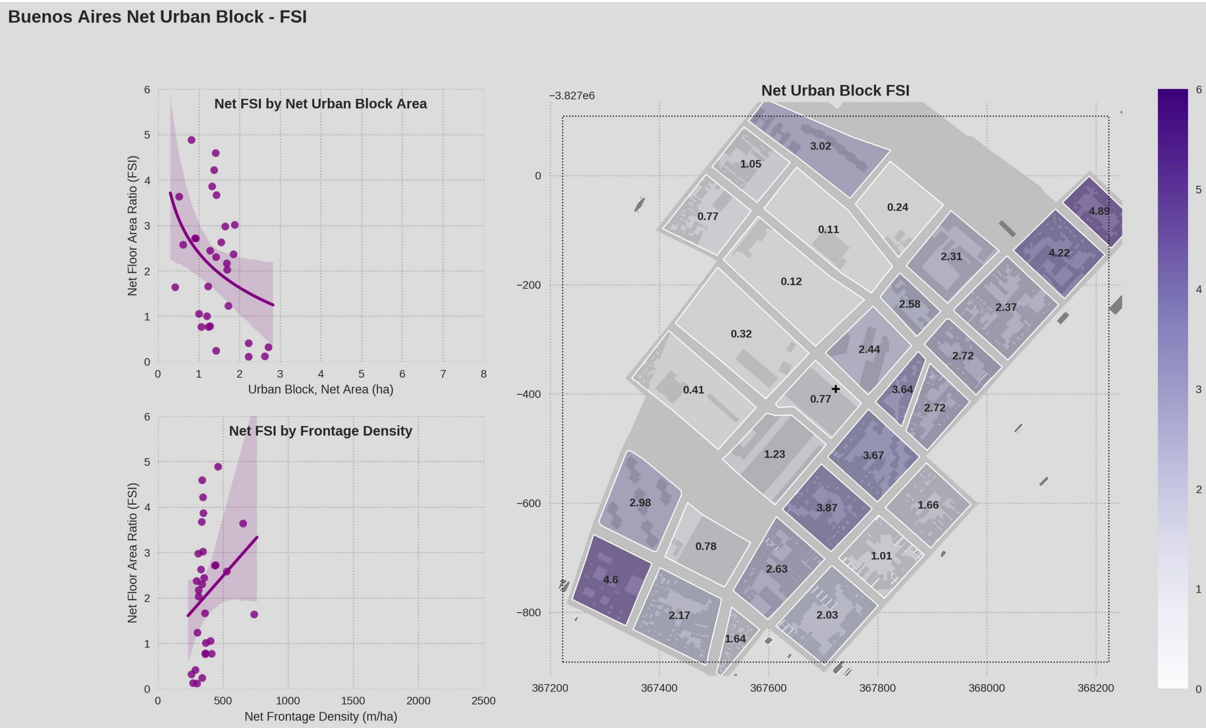



Figure 60: FSI per net urban block. Colegiales, Buenos Aires (Bristow, 2019. Map data © OpenStreetMap contributors)

The FSI is the final measure of building density and shows the total building floorspace (GEA) on an urban block relative to its area (net in this case). In Bromley, Welwyn Garden City and Clerkenwell where all building are similar heights the FSI broadly follows the GSI – lower for larger blocks with a lower PAR, higher for smaller blocks with a higher PAR.

***Buenos Aires***

Buenos Aires has an extremely regular urban grid which produces very little variation in either block size or shape and hence frontage density. This is shown by the clustering of all of the FSI measurements in a nearly vertical line on the left hand side of the scatter graphs. Yet, as the graphs here also show, there is still a large variation in FSI between the blocks. This large vertical spread can be accounted for by Buenos Aires' large variation in neighbouring building heights and, if we look at Buenos Aires 'FSI per average Building Height' graph (Figure 58) it shows a stronger relationship between FSI and average building height per urban block than the other sample areas.

***Discussion***

While the Clerkenwell sample areas more obviously supports the hypothesis of this work – that building density is related to frontage density – the Buenos Aires case above demonstrates that OSMuf does reliably reveal when this relationship is not found in the sample. In Buenos Aires' case because the fixed grid ensures almost no variety in frontage density between blocks.

# 8.6 Network density and frontage density


Figure 61: Network Density - Welwyn Garden City (Bristow, 2019; Map data © OpenStreetMap contributors)

This paper argues that a block's gross building capacity is positively correlated with its frontage length and yet, it is hard to see the impact of network density and frontage density on building density in the graphs for Buenos Aires, Bromley and Welwyn Garden City. Within the Buenos Aires sample, as already discussed, the blocks are largely fixed in terms of size and shape. This means that it is simply not possible to reveal any correlation between building capacity and frontage length from this sample alone.

Similarly, the Welwyn Garden City and Bromley samples reflect street layouts which were specifically designed to create a single area-wide density by locking building density and frontage density together. As we saw in the case study, all net plots and blocks were specifically designed to have the same low residential density and this was achieved with a very clear understanding of the relationship between residential buildings and streets. Accordingly the measured values all cluster very tightly around a narrow set of values in the lower-left corner of the scatter graphs.

### *Clerkenwell*

Only the Clerkenwell sample area shows any real spread in its network and frontage densities as a result of its more varied, and perhaps less designed, street layout. Indeed, a gentle positive correlation is shown between building density and frontage or network density.

### *Discussion*

It might seem disappointing that the selected sample areas do not to immediately reveal a strong correlation between building density and frontage density but this is largely to be expected. It is unreasonable to expect to be able to identify the effect of network density on building density when the street layouts in the sample areas were specifically designed to control for this.

In the Clerkenwell case while, some correlation was found, it doesn't appear particularly strong, potentially being muddied by the cumulative effects of the other metrics such as building height. In order to explore this relationship further it is necessary to turn to spatial modelling.

## 8.7 Modelling the relationship between building capacity and frontage length

In order to test the relationship between building density and frontage density while controlling for the effects of the multiple other variables, a simple abstract spatial model was created. It is very similar to the model which Berghauser Pont & Haupt (2009) used to investigate the correlation that they had noticed between building typology and network density (Figure 62). In *Space, Density and Urban Form* the concept of 'transition density' is discussed. It is described as "the level of concentration of borders of different entities in a certain area" (Berghauser Pont & Haupt, 2009, p. 88). They focus on network density as the measure of transition density, i.e. the length of the border between one urban block and the next, and assess it in area terms.

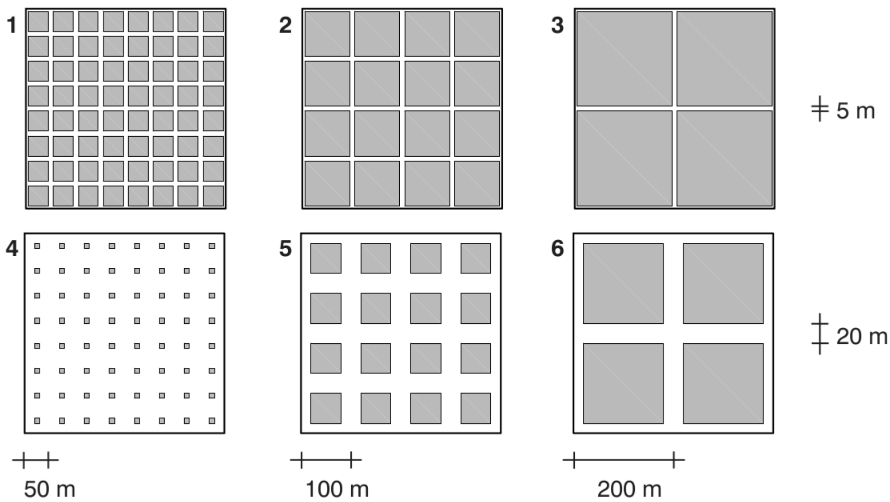



Figure 62: Proportion of public highway to private land by area (Berghauser Pont and Haupt, 2009, p. 124)

This study has suggested that the transition density that they identified, street network density, is not the critical ratio and that really the transition density that should be studied is that of the border between the blocks and the highway land that surrounds them (the frontage line). Whether to measure against network density or frontage density is potentially a moot point. By graphing network length against frontage length for all of the blocks in all of the samples it is possible to show that the two are essentially directly proportional. Street width varies very little in these samples and so, as we might expect, each urban block's frontage length is approximately equal to double its street network length (Figure 63).

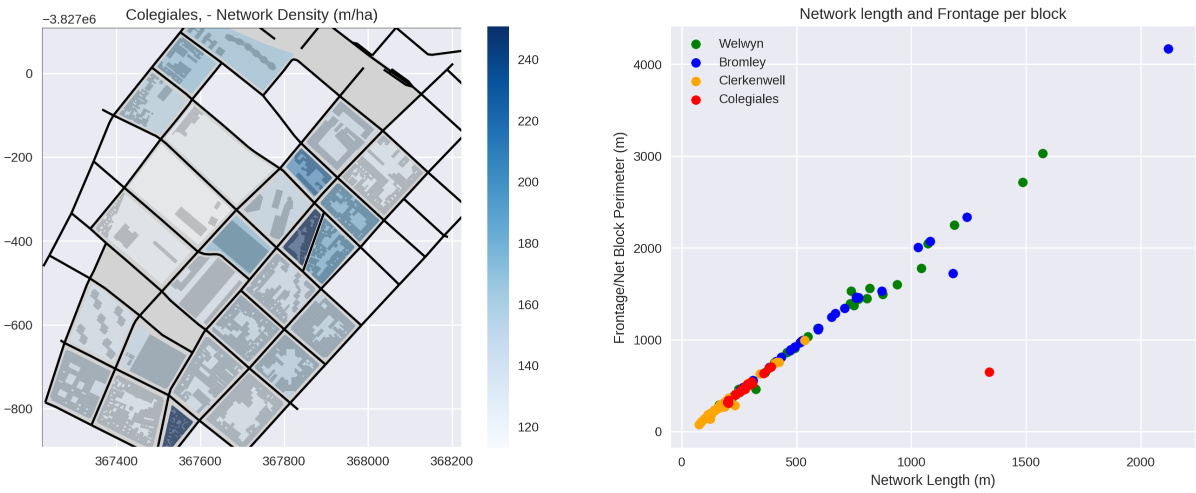



Figure 63: Frontage length plotted against street length (Bristow, 2019. Map data © OpenStreetMap contributors)

In their version of the model (Figure 62), six sample street grids show three variations of street grid spacing and two variations of street width. The discussion focuses on the relative area of the public network space (white) and Private Issue Land (PIL) (grey) and works on the assumption that 60% of PIL is required (ibid. p.125). Despite network density being a linear measure (m/ha.) it is immediately combined with road width to create an area based measure of the proportion of land dedicated to public highway. This is largely similar to OSMuf's assessment of the net to gross area for each block. While this is an important consideration when considering the relative values and development costs of areas of public and private land it is less clear how it relates to built form – and this is in fact omitted from their model.

Repeating the abstract study but this time including a band of building the depth of a standard building typology around the perimeter of the block addresses this and reveals the negative correlation between street grid spacing and building density (Figure 64). Interestingly the relationship gets stronger as the buildings get higher. The model shows that increasing the number of streets does indeed lead to an increase in land dedicated to public highway but, more significantly, that the resulting smaller blocks have a higher frontage density and, in turn, a higher gross building density.

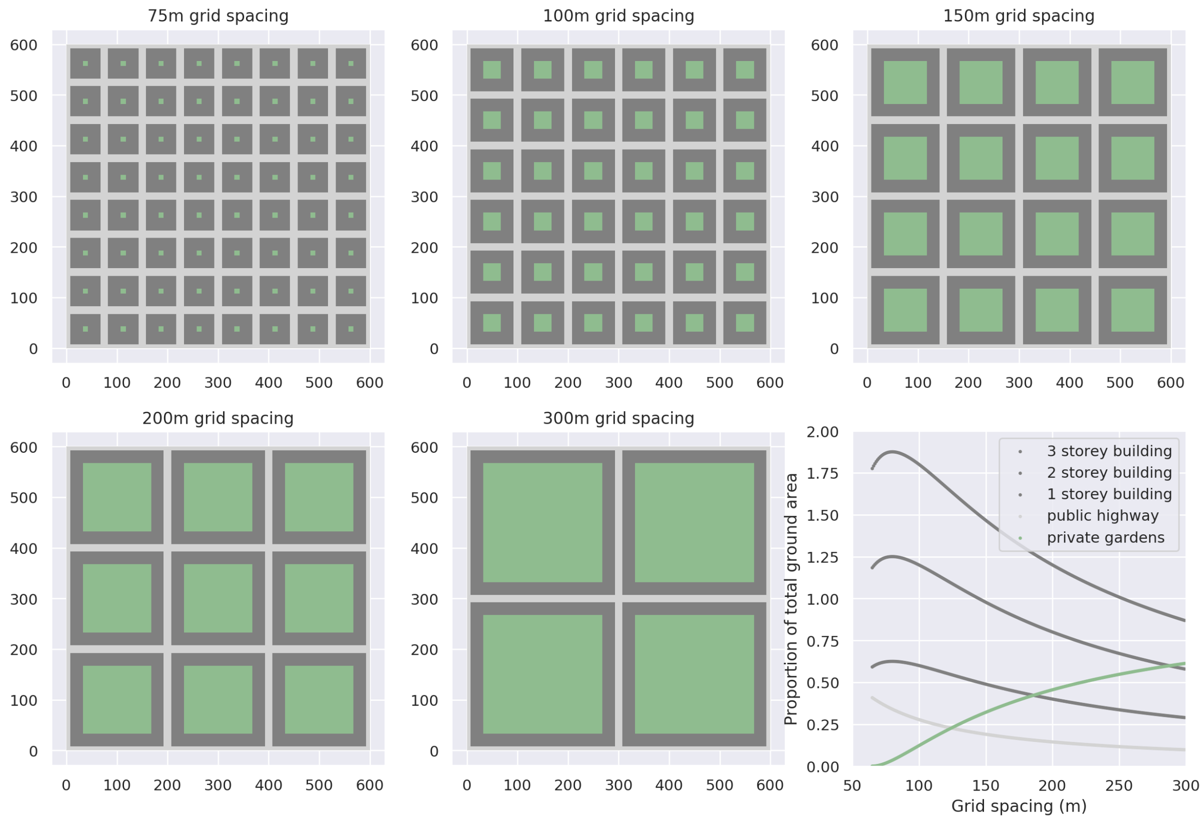



Figure 64: Street network grid spacing and building density (Nick Bristow, 2019)

Having demonstrated that street network length and frontage length are directly proportional (Figure 62) we can shift the focus of transition density away from road centrelines and on to the frontage line(the outline of the net urban block). Including an abstract building in the model allows us to make a much stronger connection between building density and grid spacing and hence frontage density.

# 9 Conclusions and recommendations

This study was prompted by London's decision to drop its site-based residential density thresholds and to introduce urban design guidance to assess the residential building capacity of individual sites. This raised questions about how street layout and urban block size impact building capacity. To address these questions a case study of Buenos Aires' approach to defining urban form helped to develop an improved method method for quantifying urban form which was subsequently implemented in software and tested against sample areas.

Increasing residential density is seen as the solution to sustainable urban development and London's housing crisis. It is a matter of considerable irony therefore that, in the UK, Garden City principles are the only development principles mention by name in the NPPF when their clearly stated aim was to promote low-density development (Unwin, 1912).

## 9.1 Key Findings

### *9.1.1 The incompatibility of site-based residential density ratios with compact urban form*

Plot size, shape and location all affect plot density ratios. By applying generic dwellings onto real-world plot divisions the effect was found to be up to a factor of 5 even in areas of apparently consistent traditional urban form. This is due to a variety of factors:

- geometric restrictions on plot divisions particularly at corners
- residential buildings being generally linear in form
- residential buildings above 1 story are rarely distributed uniformly across a site
- residential buildings tend to be aligned along the frontage line

In the case where consistent net plot densities were found, suburban London, this is by design – a result of applying standard byelaw house types (with no corner type) onto standard plot divisions. Assessing corner plots in this scenario on a gross basis (i.e. to the centreline of adjacent streets) reveals their inefficient use of land and explains the extended linear urban blocks that this fixed typology generates.

Modelling the effect of introducing a corner building typology into this scenario had the effect of flipping the gross density of corner plots from the lowest on a block to the highest. This finding has significant implications for urban design as it has the effect of inverting the relationship between street network density and building capacity. In the open corner scenario gross building capacity is maximised by minimising street corners and maximising urban block length, in the closed corner scenario gross building capacity is maximised by maximising the number of street corners and minimising urban block size in order to drive up their perimeter to area ratio. Counter-intuitively from the point of view of net site/plot-based density ratios this means that, assuming there are no restriction on the use of corner buildings, an area's gross residential building capacity can potentially be increased by taking away residential land and giving it over to the street network.

The Modifiable Areal Unit Problem was found to have a very significant impact on density ratios measured at the scale of the plot. While not tested directly, London's measuring of density against the even more ambiguously defined site boundary only exacerbates this problem.

Ultimately, if a consistent urban form with closed corners is the desired outcome, assuming that the residential capacity of a site should be directly proportional to its area (as implied by London's SRQ density matrix) is misguided.

Assessing urban form at the scale of the urban block (an aggregation of contiguous plots) is found to generate improved results, smoothing out the effects of plot divisions and better reflecting the strongly observed relationship between the generalised linear form of residential buildings and a block's frontage line.

***Potential implications for London***

London tends to focus most of its development on a few large sites. As sites increase in size their measured density tends to fall. As shown, this is because capacity is not proportional to site area, it is more closely related to frontage density. The typical immediate response to the dropping area-based density is to try to increase it by increasing building height (as we have seen residential plan-depth is largely limited by the local building typology).

This paper argues that, perhaps counter-intuitively, another option would be to split the site with new streets reducing the area of developable residential land but increasing the length of frontage facilitating increasing the length of the residential buildings. Increasing building capacity but potentially bringing building height back under control. Gross density could be increased even further by ensuring narrow streets and separation distances are used which might even make it possible to reintroduce house typologies as part of a dense urban environment and not to have to rely uniquely on tall apartment buildings.

### *9.1.2 Improved method for measuring urban form*

To investigate these relationships a key set of metrics and ratios was developed:

***Metrics***

- Street network length
- Street width
- Frontage length
- Building plan-depth
- Building height
- Building Set-back
- Minimum separation distance (across back-gardens)

***Ratios***

- Gross Block FSI
- Gross Block GSI
- Network Density
- Net Block FSI
- Net Block GSI
- Frontage Density

From a city's point of view, with responsibility for managing the totality of the land available, Gross FSI is the ultimate measure of the building capacity of a piece of land. By working at the scale of the urban block it becomes clear that Gross FSI is the result of the interaction between all of the metrics listed. This is useful information for designers as it encourages them to consider the totality of the urban environment and enables them to make informed decisions trading off one metric against another e.g. trading off street grid spacing and street width against building height.

Increased residential building capacity can be achieved by manipulating the building form:

- Plan-depth can be increased (but only to the limits of the local residential building types).
- Building height can be increased by adding extra storeys.
- Building length can be increased by closing corners, removing gaps between detached and semi-detached houses etc.

What is masked by area based density ratios measured at the scale of the plot/site is the relationship between the street layout and residential building capacity. This is best understood by assessing residential building capacity against gross frontage density.

In Berghauser Pont & Haupt's work they mention the concept of a transition density. They identified this as the gross network density which they conceptually aligned with the boundaries between neighbouring gross urban blocks. This study has found that the transition density is improved by using frontage density instead which assesses the boundary between developable land and the street network. How closely street network density and building density aligns with frontage density is a function of street width and building set-back and plan depth.

Gross frontage density can be increased by:

- Increasing street network length
- Reducing street width
- Manipulating perimeter in relation to area by introducing cul-de-sacs (e.g. Welwyn Garden City)

### *9.1.3 OSMuf: measuring urban form from OpenStreetMap*

A benefit of assessing urban form in relation to the urban block perimeter is that the boundary is typically observable and unambiguous (Yoshida, 2005). It means that all of the measures of urban form listed above can be extracted purely from physical mapping without reference to land ownership boundaries. This means that it is viable to generate internationally comparable measures of urban form using open-source software and open data.

In order to test the findings above, this study successfully made use of Exploratory Spatial Data Analysis to quantify urban form from OpenStreetMap data. Following Geoff Boeing's work on OSMnx, it implemented the improved method for measuring urban form in a python library called OSMuf. This quantifies urban form from OpenStreetMap data and has been shared under an open source software licence. The study found OSM building and land-use mapping is significantly less complete than its highway network information, currently preventing large-scale automated analysis of urban form. It is however possible to add the missing data at a neighbourhood scale with sufficient accuracy to assess urban form against the urban block. This makes assessment of building density possible where more traditional sources of detailed physical mapping and land title information are either restricted or non-existent. It also makes this method of measuring urban form as accessible to community mapping groups as it is to professional development teams.

## 9.2 Supporting studies

The key findings are not without precedent. Unwin's work (1909, 1912) was entirely premised on the relationship between residential buildings and streets though its advice seems to have largely been forgotten. Other more recent studies have however observed the correlation:

"The most important finding, perhaps, was that the street network density exerted the greatest influence on building density and building frontage ratio in most iterations of the models." (Vialard & Carpenter, 2015, p. 15)

"The density of streets increases in proportion to the density of properties, which is to the degree of land subdivision [...] If properties are to be independently accessible from the public system, then it is to be expected that greater subdivision requires more street length because there is a limit to the practically useful depth/frontage ratio of the average property" (Peponis, Allen, French, Scoppa, & Brown, 2007). It should be noted that Peponis et al. found no similar tendency was evident for non-residential buildings.

## 9.3 Limitations

This study does not account for areas of public space (other than highway) such as parks and squares which are captured in Berghauser Pont & Haupt's neighbourhood scale analysis as 'tare space'. It has also focussed only on common building typologies found in Buenos Aires and London. Further work would be necessary to determine its compatibility with other residential building typologies in other places.

## 9.4 Future work

Basing OSMuf, a software library for quantifying the urban form of buildings, on OSMnx, a software library for quantifying the urban form of street networks, opens up an intriguing opportunity for adding further depth to the study of the relationship between street networks and buildings. For example, are building height and network centrality related?

In many countries, though notably not in the UK, census data is reported aggregated to the scale of the urban block. This also opens up the possibility of a more integrated approach to investigating the three-way relationship between population density, dwelling density and building density.

The implications of the findings of this study for the way that infrastructure costs are allocated in development models could be significant. For example, allocating infrastructure costs based on net-to-gross land area ratios would suggest benefits in making blocks large, while assessing them against frontage density might suggest benefits in making blocks small.

From a purely geometric point of view, generalising residential buildings to linear forms suggests that there might be some value in investigating their relationship to land at the city-scale by investigating them as space-filling curves.

## 9.5 Recommendations

Measuring residential density against plot area (or site area as in London) is simply misleading and should be scrapped. It obscures the relationship between residential buildings and streets and varies wildly purely as a result of the geometric division of blocks into plots.

Introducing frontage density as a transition density between residential building capacity and land area would clarify the relationship between residential buildings and streets. This was confirmed by Exploratory Spatial Data Analysis of the sample areas by OSMuf which found building density to be negatively correlated to the area of a block and the positive correlation with frontage density was shown in spatial modelling.

The concept of the urban block is often seen as missing from the UK's understanding of urban form. As this paper has demonstrated the unavoidable interaction between local building typology, plot division and street layout can only be appreciated at the scale of the urban block.

Increasing residential building capacity by focussing on urban design as London is proposing to do will need to address this failing.

Managing residential building capacity at the city scale with measures of urban form requires integrated transport and land use planning. Increased gross residential density is entirely compatible with houses rather than apartments if, for example, closely spaced narrow streets are combined with reduced separation distances and the occupation of corner plots by small apartment buildings or mansion blocks. Introducing small corner apartment buildings in suburban areas could increase the mix of dwelling sizes and provide homes for those whose life style does not require family houses and large gardens.

On this basis a significant increase in London's total residential building capacity could be achieved by subdividing the extend runs of suburban byelaw housing, introducing new streets improving permeability and creating opportunities for denser corner plots. Distributing new housing in this way would reduce the pressure on the limited number of large sites that London's current approach to accommodating housing growth requires.

Quoting residential densities in the abstract without reference to the size and shape of the area being measured and whether the measurement is net or gross, is essentially entirely meaningless.

## 9.6 Contributions to knowledge

This work builds on the work of Berghauser Pont and Haupt, Oliveira, Boeing etc. and contributes a renewed understanding of the importance of frontage density. It also contributes OSMuf as an open source Python software library for quantifying urban form from OpenStreetMap data.

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# 11 Appendices

## 11.1 The Python Geodata Stack

***Python***

The mapping and data analysis for this paper were carried out using the Python Geodata stack. Python is a computer language that is easy to learn, popular and capable. Built on top of the core language, the Python community shares solutions to common tasks in the form of libraries. Libraries are collections of small blocks of Python code that perform common tasks such as downloading data, processing it, displaying a result etc. Libraries make it possible to benefit from work that other people have already done. A high-level library will depend on a hierarchy of lower-level libraries. Each one of these libraries will have its own version number and commonly one library will rely on a specific version of another library.

***Conda***

To avoid clashes between projects which require different versions of specific libraries, it is typical to create a virtual environment for a project. A virtual environment creates an isolated copy of Python and additional libraries. Conda effectively allows you to create a clean workspace on your computer with a fresh installation of Python isolated from other copies that may exist on your system this helps to avoid conflicts. Conda also manages the installation of libraries. At the start of this study the top level library was OSMnx.

***Software Stack***

1. Implement the methodology in a Python library – this will be a proof of concept, developed to a level suitable for demonstrating the viability of the proposed methodology
2. Apply the methodology to a selection of case studies.
3. Make some initial observations based on the metrics generated in order to demonstrate that the proposed methodology is viable.

***OSMnx***

OSMnx is in built on top of NetworkX, a library for analysing the topology of network graphs, and GeoPandas a library which makes "working with geospatial data in python easier".

GeoPandas in turn is built on Pandas, one of Python's key data analysis libraries, and Shapely, a library that enables the manipulation and analysis of planar geometric objects.

It downloads OSM points, lines and polygons and their associated data and analyses the primal graph of highway networks using NetworkX, downloads polygon data into a GeoPandas GeoDataFrame.

***Pandas & GeoPandas***

Pandas is a data analysis library that works with tabulated data (similar to a database or spreadsheet) where each row represents a single record and each column represents an attribute of that record. GeoPandas is an extension of Pandas that allows Shapely geometry to be included as part of each record.

***Shapely***

Converts lists of coordinates into geometry (points, lines or shapes) such that they can be manipulated in way that is similar to methods available in a GIS package.

***Matplotlib***

Creates graphs and shows them on the screen, allowing data to be visualised.

***Jupyter Notebooks***

When carrying out exploratory data analysis in Python it is common to work in a Jupyter Notebook (Kluyver et al., 2016). A notebook is essentially an interactive web page on your computer in which you can write documentation, execute small chunks of code and immediately see the results. This makes developing code much more transparent as you can see what each piece of code does before moving on to the next one.

***OSM urban form (OSMuf)***

As the code in a notebook develops it either becomes too unwieldy for the notebook format or pieces of code need to be repeated or reused in another notebook. At this point it becomes more practical to collect these pieces of code into a separate library which can, in turn, be imported for use in the notebook.

OSMuf, the proof of concept Python library that will be developed as part of this research, will make use of OSMnx's tools for accessing OSM data and network analysis, it will then directly use GeoPandas and Shapely to generate the measures of urban morphology and Matplotlib to display them (Hunter, 2007).

#### *GitHub*

In order to keep track of the code as it develops, to be able to collaborate on it, or simply to share it, it can be published on a platform such as GitHub.

## 11.2 Method for measuring urban form

***Workflow***

1. Define a study area
    a) centre point coordinates (latitude, longitude)
    b) offset distance north, south, east and west (meters)
2. Use OSMnx to download OSM data within the study area:
    a) urban blocks (where available)
    b) highway centre lines
    c) land use areas
    d) building footprints
3. Create net and gross urban block geometry
    a) Either use the urban blocks downloaded directly from OSM
    b) Or create net urban blocks by merging contiguous land use polygons
    c) Create gross urban blocks by polygonising the highway network, merging any fragments that overlap the same net urban block
4. Generate building data:
    a) measure building footprint area
    b) calculate gross building floor area (building footprint area x building height in storeys)
    c) add the id number of the net urban block that that the building is within
    d) add the id number of the nearest highway to the building
5. Calculate urban block data:
    a) measure net urban block area

b) measure gross urban block area

c) net:gross ratio (net urban block area/gross urban block area)

d) length of frontage (perimeter length of the net urban block)

e) perimeter:area ratio (length frontage/net urban block area)

f) Calculate the length of highway attributable to each urban block as half the length of the perimeter of the gross urban block plus the full length of any cul-de-sacs contained within the gross urban block. Divide the results by the area of the gross urban block to generate the network density.

g) network density (length of highway/unit area)

h) aggregate the sums of the footprint areas and total floor areas for all of the buildings within each urban block. Divide the results by the area of urban block to generate the GSI and FSI for each urban block – this is done for both the net and gross urban blocks.

i) Floor Area Ratio (Floor Space Index) per urban block

6. Experimental measures

    a) Calculate median building plan depths

    b) street width:height ratios

7. Use Matplotlib to visualise the data both as maps and graphs

## 11.3 Example Jupyter notebook

# 5 OSMuf Plots

August 29, 2019

```
In [1]: %load_ext autoreload
        %autoreload 2
```

```
In [2]: # dictionary of places of interest for convenience,
        # Clerkenwell was 51.5266
        places = {'Buenos Aires':(-34.5798,-58.4422),
                  'Clerkenwell':(51.5273,-0.1109),
                  'Welwyn Garden City':(51.7938,-0.189),
                  'Bromley':(51.395,-0.006)
                 }
```

## 1 OSMuf

OSMuf is a collection of functions which generate measures of urban form from OSM data. It builds on OSMnx and GeoPandas.

```
In [3]: import pandas as pd
```

```
In [4]: import osmuf as ouf
        import osmnx as ox
```

### 1.1 Define a study area, download and project primary OSM data

- Define a study area from point and distance
- Download OSM polygons tagged as 'place' from the same point and distance. Keep only those tagged as "place=city_block"
- Download OSM buildings and filter the attributes to the minimum
- Download OSM streets that overlap the city blocks - this is to ensure all of the buildings on a city block are downloaded and not clipped to the study area

Define a place name for the study, a centre point and a distance from the centre point to define the study area.

```
In [5]: # choose one of the study areas
        place_name = 'Bromley'
        point = places[place_name]
        distance = 500
```

```
In [6]: # define study area
        study_area = ouf.study_area_from_point(point, distance)

        # include projected version temporarily to deal with rotation
        study_area_prj = ouf.projected_study_area_from_point(point, distance)

        # download urban blocks
        city_blocks = ouf.places_from_point(point, distance)
        # download buildings on the urban blocks
        buildings = ouf.buildings_from_gdf(city_blocks)

        # download streets around the urban blocks to polygonize
        street_graph_for_blocks = ouf.street_graph_from_gdf(city_blocks)
        streets_for_blocks = ouf.streets_from_street_graph(street_graph_for_blocks)

        # download driveable streets to calculate network density
        street_graph_for_networkd = ouf.street_graph_from_gdf(city_blocks,
                                                              network_type='drive')
        streets_for_networkd = ouf.streets_from_street_graph(street_graph_for_networkd)
```

Project the dataframes to change from geographic coordinates (lat, long) to projected UTM (meters)

```
In [7]: # project the dataframes to local UTM coordinates
        # study_area_prj = ox.project_gdf(study_area)
        city_blocks_prj = ox.project_gdf(city_blocks)
        streets_for_blocks_prj = ox.project_gdf(streets_for_blocks)
        streets_for_networkd_prj = ox.project_gdf(streets_for_networkd)
        buildings_prj = ox.project_gdf(buildings)
```

Check alignment by plotting them:

```
In [8]: # display the dataframes to check their alignment
        ax = city_blocks_prj.plot(figsize=(10,10), color='gainsboro')
        buildings_prj.plot(ax=ax, color='grey')
        streets_for_blocks_prj.plot(ax=ax, color='red', linewidth=0.75, linestyle=':')
        streets_for_networkd_prj.plot(ax=ax, color='grey')
        study_area_prj.plot(ax=ax, edgecolor='white',facecolor='None', linewidth=2)

Out[8]: <matplotlib.axes._subplots.AxesSubplot at 0x7fcfbce017b8>
```


## 1.2 Generate secondary data

```
In [9]: # generate gross city blocks from the street graph and net city blocks
        gross_city_blocks = ouf.gen_gross_city_blocks(street_graph_for_blocks,
                                                      city_blocks)
```

```
# project the new gross city blocks
gross_city_blocks_prj = ox.project_gdf(gross_city_blocks)

# calculate network density for each gross urban block
gross_city_blocks_prj = ouf.measure_network_density(streets_for_networkd_prj,
                                                    gross_city_blocks_prj)

# generate the footprint area and total GEA for each building
buildings_prj = ouf.measure_buildings(buildings_prj)

# join the id of the city block onto each building
buildings_prj = ouf.join_buildings_place_id(buildings_prj,
                                            city_blocks_prj)

# calculate the net_to_gross for the net_city_blocks
city_blocks_prj = ouf.measure_city_blocks(city_blocks_prj,
                                          gross_city_blocks_prj)

# calculate measures of the regularity of the net_city_blocks
city_blocks_form_factor = ouf.gen_regularity(city_blocks_prj)

# join the id of the city block onto each building
# buildings_prj = ouf.join_buildings_place_id(buildings_prj, city_blocks_prj)

# aggregate building measures and merge onto city blocks
city_blocks_prj = ouf.join_places_building_data(city_blocks_prj,
                                                buildings_prj)
```

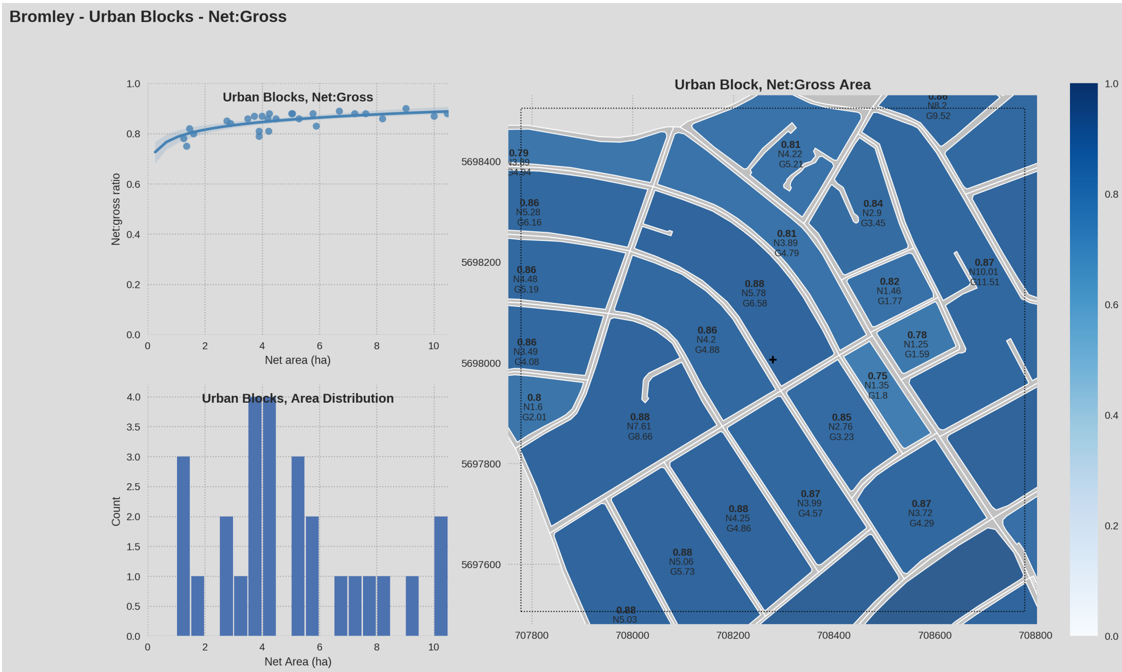
# 2 OSMuf Plots

## 2.1 1. Block Size

In [10]:
```
fig, ax = ouf.layout_3_plots()
fig.suptitle(place_name + ' - Urban Blocks - Net:Gross',
             fontsize=16, fontweight='bold', ha='left', x=0.02)

ouf.ax_block_ntg_to_size(ax[0], city_blocks_prj)

ouf.ax_block_area_distribution(ax[1], city_blocks_prj)

ouf.ax_map_block_size(ax[2], study_area_prj,
                      gross_city_blocks_prj, city_blocks_prj)

fig.savefig('../local_images/00_blocks_size_{}.png'.format(place_name),
            transparent=False, dpi=200, bbox_inches="tight",
            facecolor='gainsboro')
```

```
/home/nick/anaconda3/envs/osmnx_osmuf-dev/lib/python3.7/site-packages/seaborn/regression.py:27
```

```
grid = np.c_[np.ones(len(grid)), np.log(grid)]
```

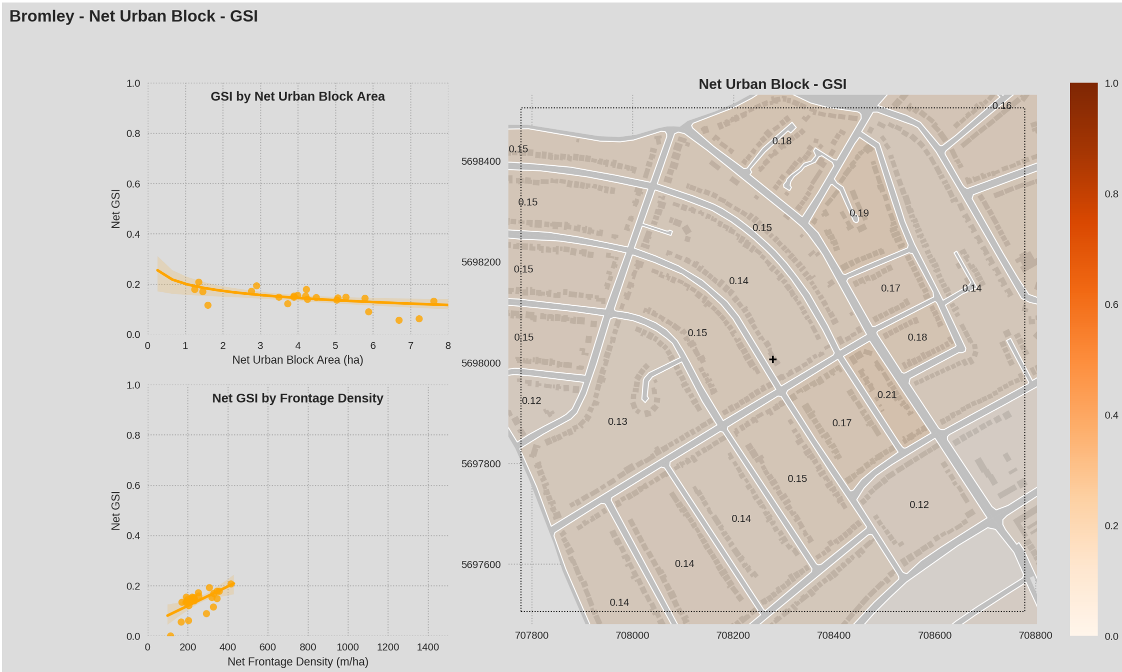



## 2.2 2. Form Factor

```
In [11]: fig, ax = ouf.layout_3_plots()
         fig.suptitle(place_name + ' - Net Urban Block - Perimeter:Area Ratio',
                      fontsize=16, fontweight='bold', ha='left', x=0.02)

         ouf.ax_block_perimeter_to_area(ax[0], city_blocks_prj)
         ouf.ax_form_factor_to_area(ax[1], city_blocks_form_factor)
         ouf.ax_map_form_factor(ax[2], study_area_prj, gross_city_blocks_prj,
                                city_blocks_prj, city_blocks_form_factor)

         fig.savefig('../local_images/01_blocks_form_factor_{}.png'.format(place_name),
                     transparent=False, dpi=200, bbox_inches="tight",
                     facecolor='gainsboro')
```

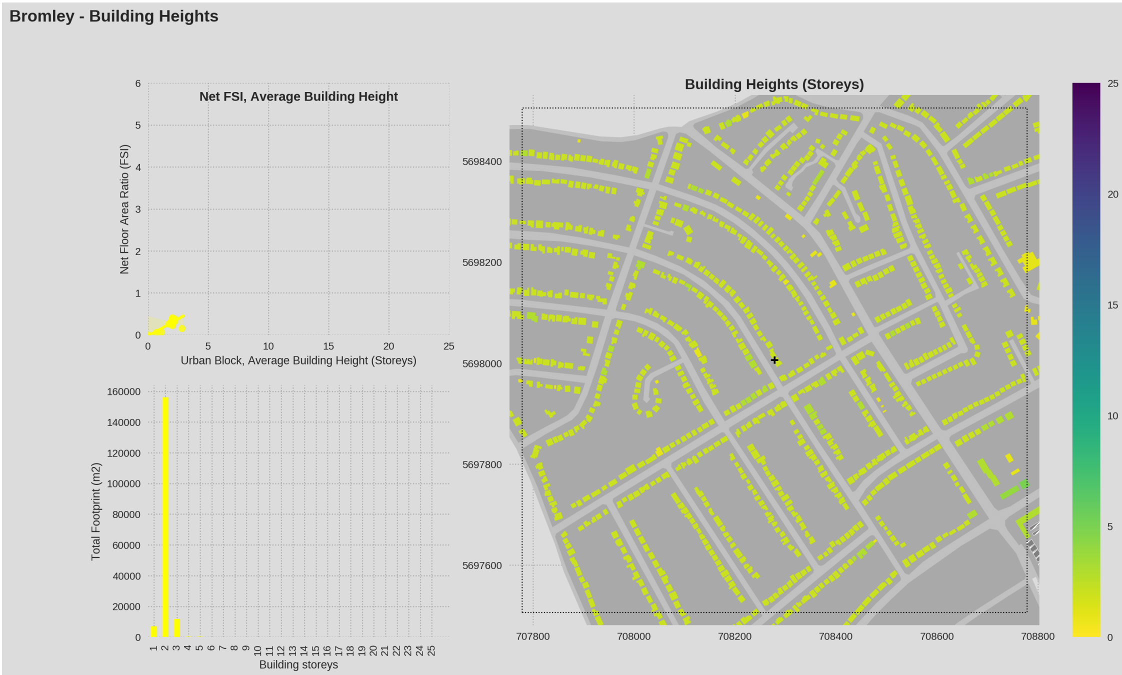

# 3 3. Net Urban Block - GSI

```
In [12]: fig, ax = ouf.layout_3_plots()
         fig.suptitle(place_name + ' - Net Urban Block - GSI', fontsize=16,
                      fontweight='bold', ha='left', x=0.02)

         ouf.ax_net_GSI_to_net_area(ax[0], city_blocks_prj)
         #ouf.ax_building_footprint_to_net_area(ax[0], city_blocks_prj)
         ouf.ax_net_GSI_to_frontage_density(ax[1], city_blocks_prj)
         #ouf.ax_GSI_distribution(ax[1], city_blocks_prj)
         ouf.ax_map_GSI(ax[2], study_area_prj, gross_city_blocks_prj,
                        city_blocks_prj, buildings_prj)

         fig.savefig('../local_images/02_blocks_by_GSI_{}.png'.format(place_name),
                     transparent=False, dpi=200, bbox_inches="tight",
                     facecolor='gainsboro')
```



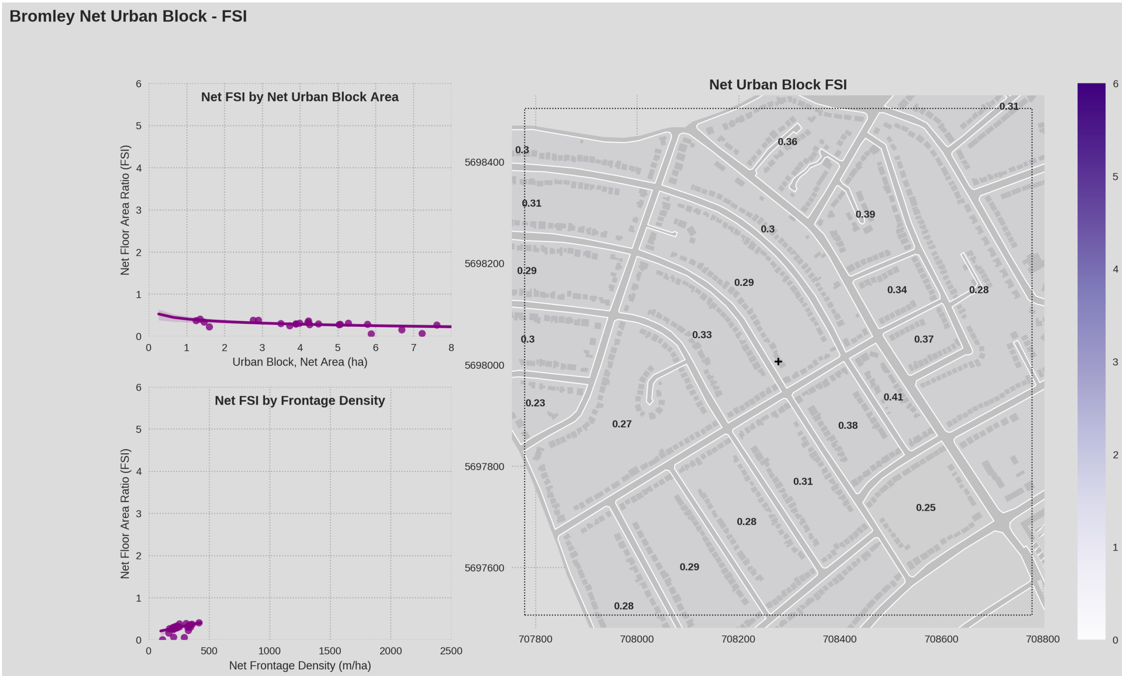

# 4 4. Building Heights

In [13]:
```
fig, ax = ouf.layout_3_plots()
fig.suptitle(place_name + ' - Building Heights', fontsize=16,
             fontweight='bold', ha='left', x=0.02)

ouf.ax_net_FSI_to_avg_building_height(ax[0], city_blocks_prj)
ouf.ax_building_height_distribution_by_area(ax[1], buildings_prj)
ouf.ax_map_building_heights(ax[2], study_area_prj, gross_city_blocks_prj,
                            city_blocks_prj, buildings_prj)

fig.savefig('../local_images/04_building_heights_{}.png'.format(place_name),
            transparent=False, dpi=200, bbox_inches="tight",
            facecolor='gainsboro')
```



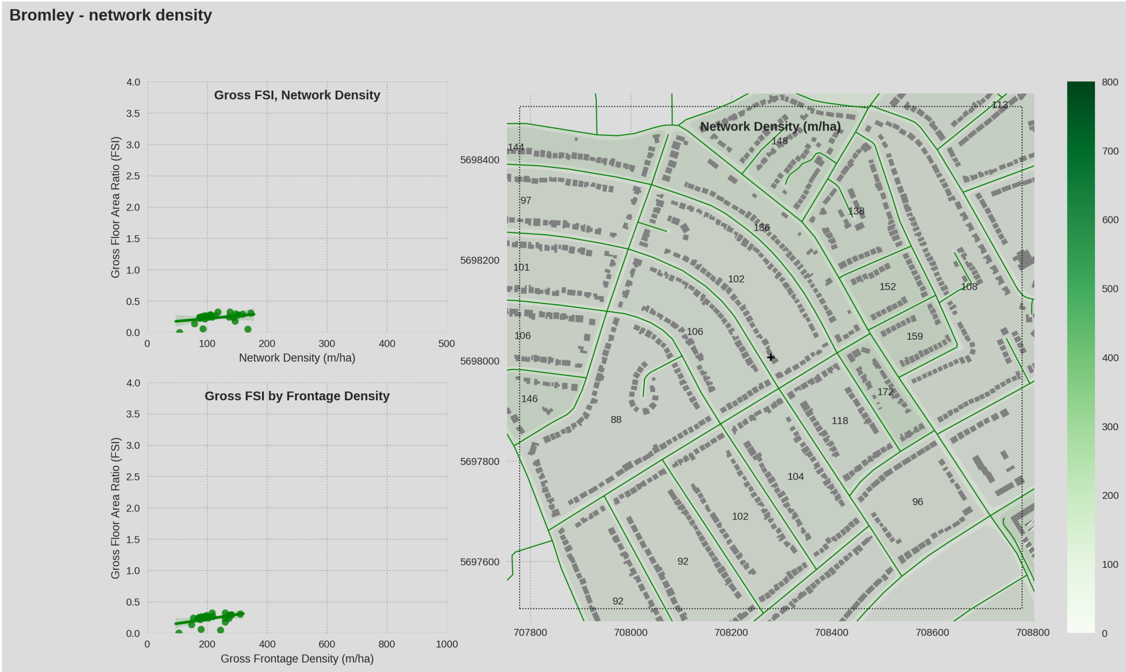

# 5 5. FSI

In [14]:
```
fig, ax = ouf.layout_3_plots()
fig.suptitle(place_name + ' Net Urban Block - FSI', fontsize=16,
             fontweight='bold', ha='left', x=0.02)

# ouf.ax_gross_FSI_to_gross_area(ax[0], city_blocks_prj)
#ouf.ax_building_GEA_to_net_area(ax[0], city_blocks_prj)
ouf.ax_net_FSI_to_net_area(ax[0], city_blocks_prj)
###ouf.ax_gross_FSI_to_gross_frontage_density(ax[0], city_blocks_prj)
ouf.ax_net_FSI_to_frontage_density(ax[1], city_blocks_prj)
#ouf.ax_building_GEA_to_frontage(ax[1], city_blocks_prj)
ouf.ax_map_FSI(ax[2], study_area_prj, gross_city_blocks_prj,
               city_blocks_prj, buildings_prj)

fig.savefig('../local_images/04_blocks_by_FSI_{}.png'.format(place_name),
            transparent=False, dpi=200, bbox_inches="tight",
            facecolor='gainsboro')
```




# 6 6. Network Density

```
In [15]: fig, ax = ouf.layout_3_plots()
         fig.suptitle(place_name + ' - network density', fontsize=16,
                      fontweight='bold', ha='left', x=0.02)

         # ouf.ax_gross_FSI_to_gross_area(ax[0], city_blocks_prj)
         ouf.ax_gross_FSI_to_network_density(ax[0], city_blocks_prj)
         ### ouf.ax_network_density_to_gross_area(ax[1], gross_city_blocks_prj)
         ouf.ax_gross_FSI_to_gross_frontage_density(ax[1], city_blocks_prj)
         ouf.ax_map_network_density(ax[2], study_area_prj, gross_city_blocks_prj,
                                    city_blocks_prj, buildings_prj,
                                    streets_for_networkd_prj)

         fig.savefig('../local_images/06_network_density_{}.png'.format(place_name),
                     transparent=False, dpi=200, bbox_inches="tight",
                     facecolor='gainsboro')
```


Bromley - network density
Gross FSI, Network Density
Gross Floor Area Ratio (FSI)
Network Density (m/ha)
Gross FSI by Frontage Density
Gross Frontage Density (m/ha)
Network Density (m/ha)

## 11.4 ESDA of sample areas

*See separate A3 document*

# Measuring residential building density at the scale of the urban block

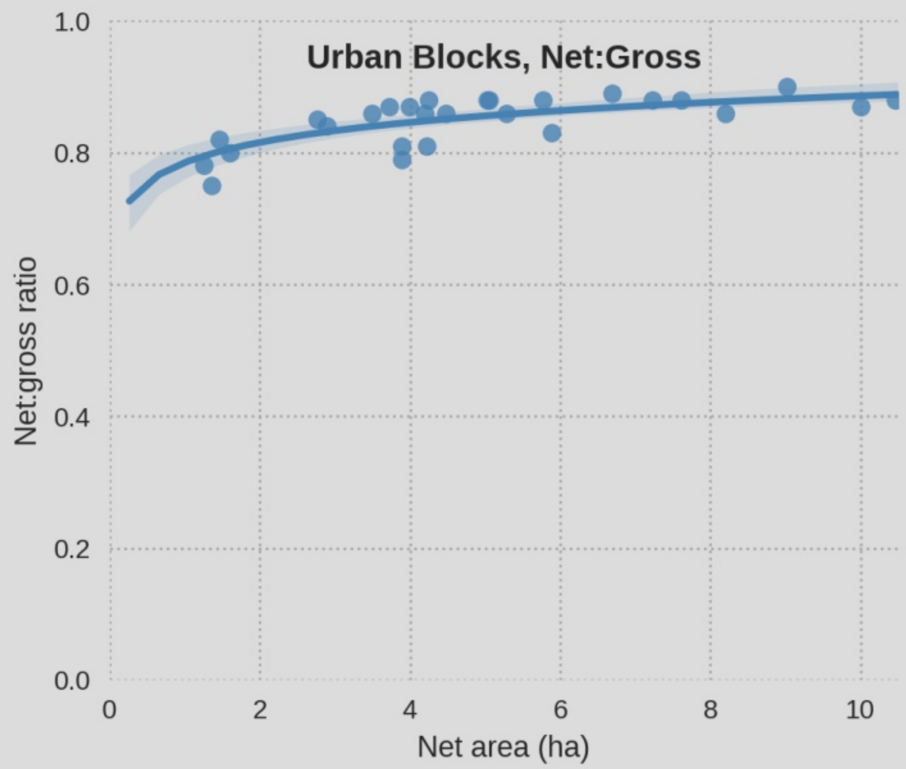
OSMuf: a Python library for quantifying urban form from OpenStreetMap

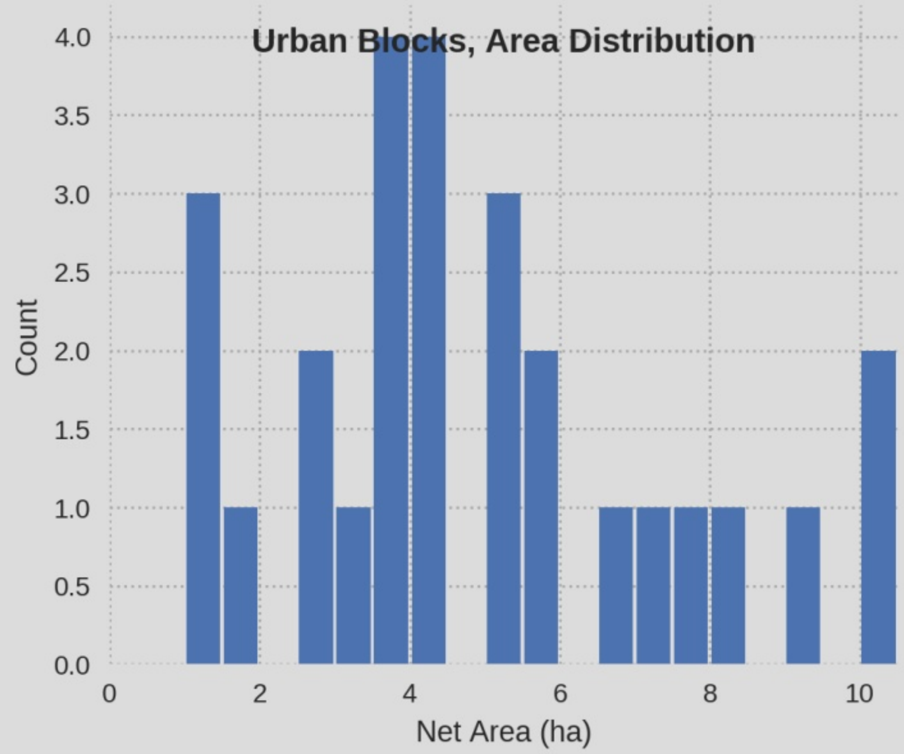
Appendix 11.4
ESDA of sample areas

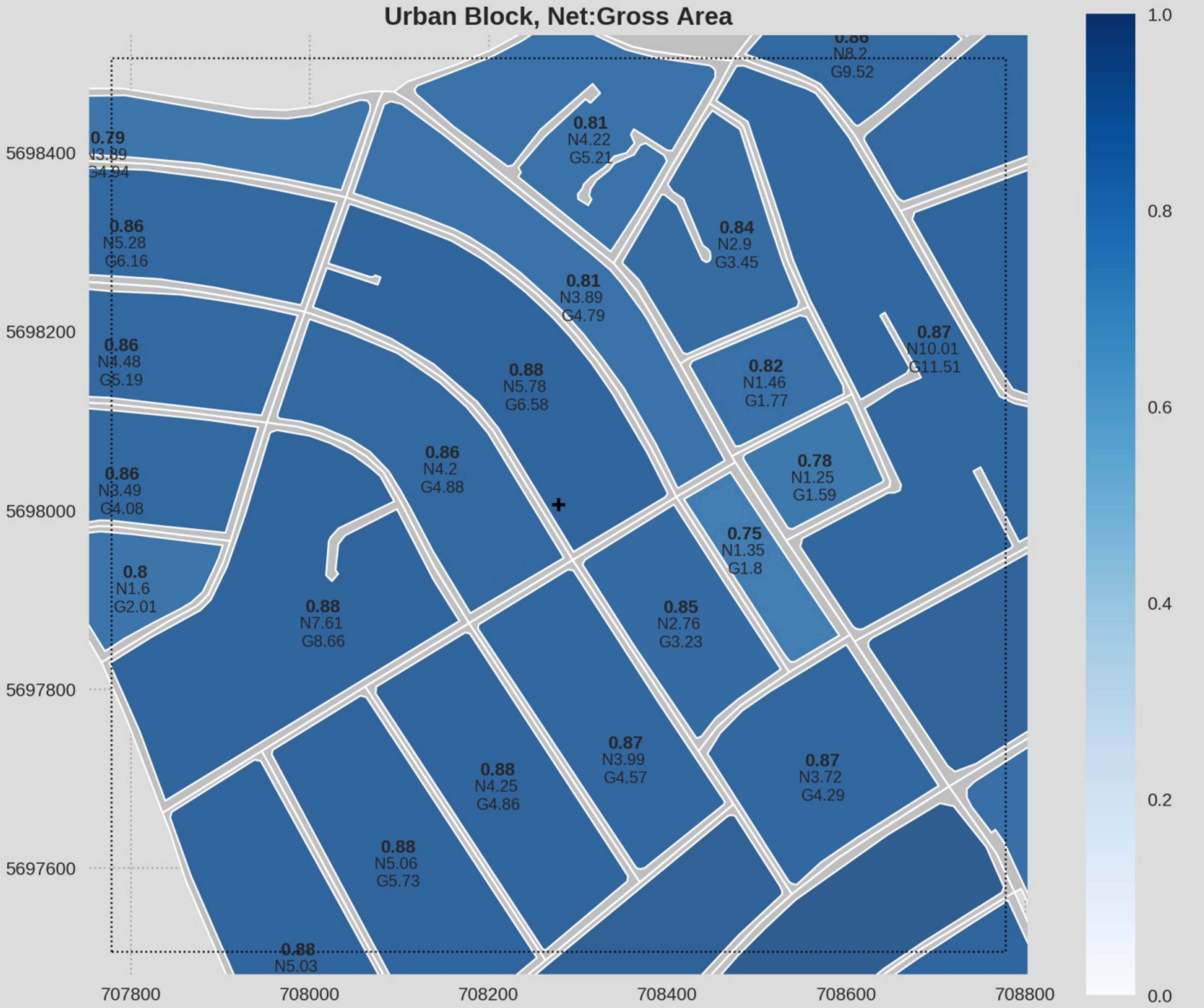


Nicholas James Owen Bristow
MA in International Planning and Sustainable Development, University of Westminster
August 2019

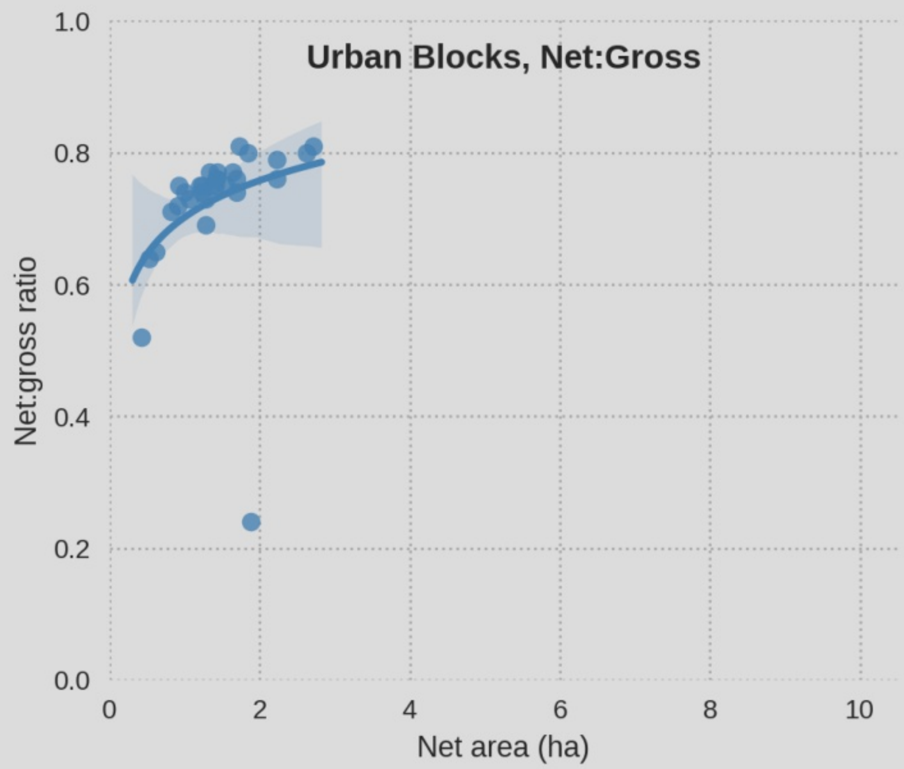
## Bromley - Urban Blocks - Net:Gross

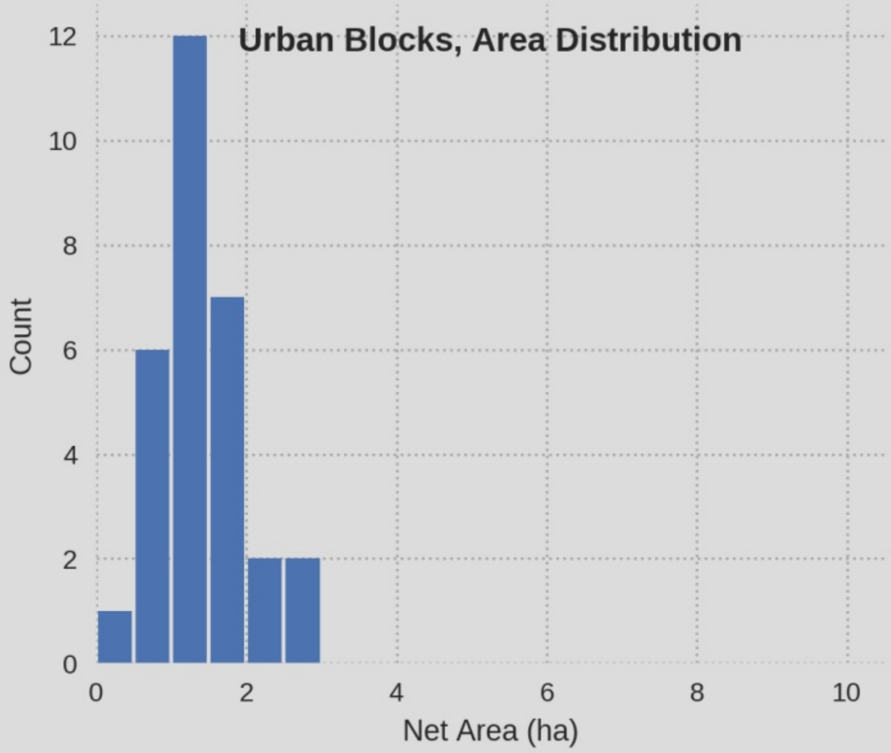


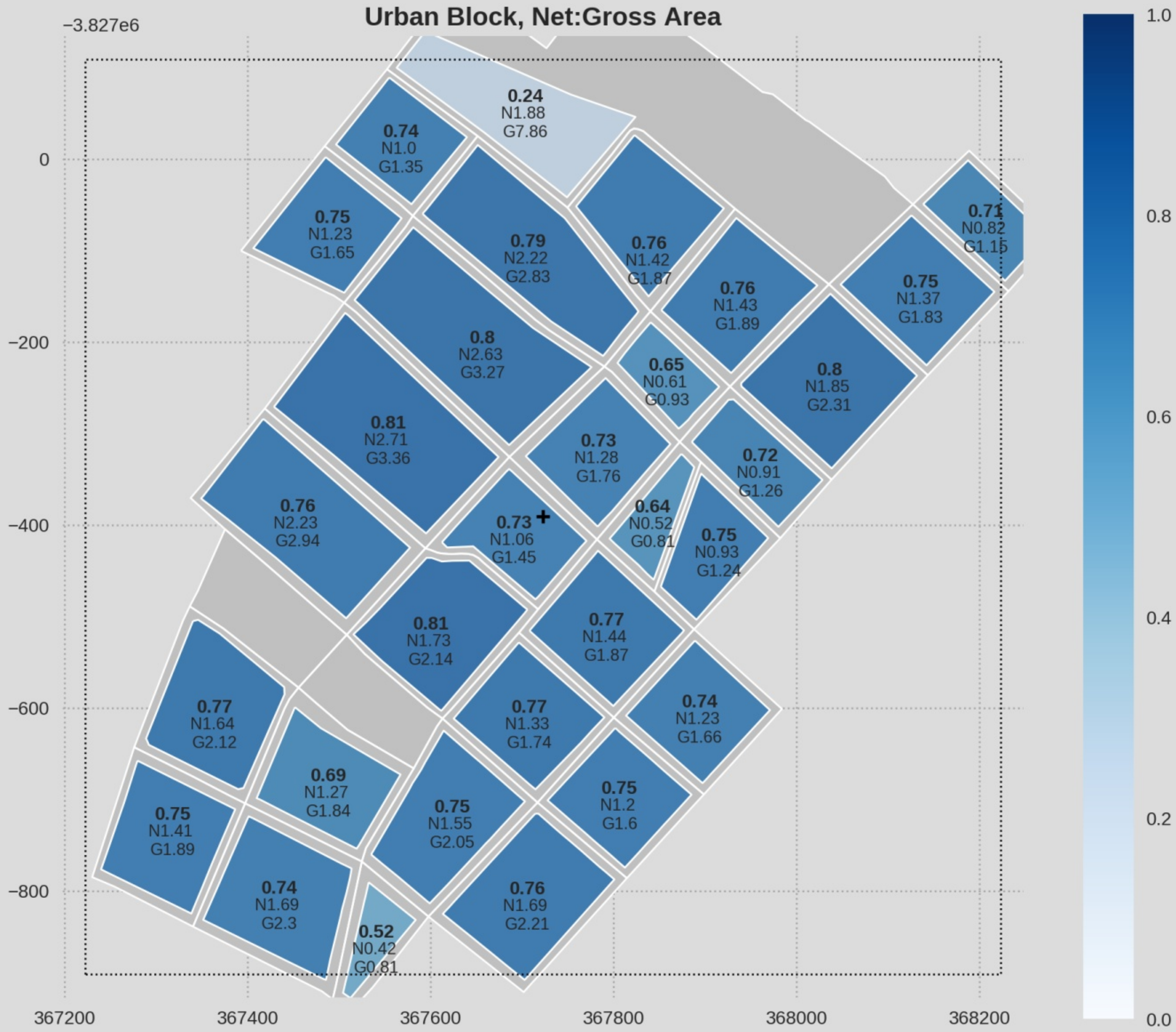



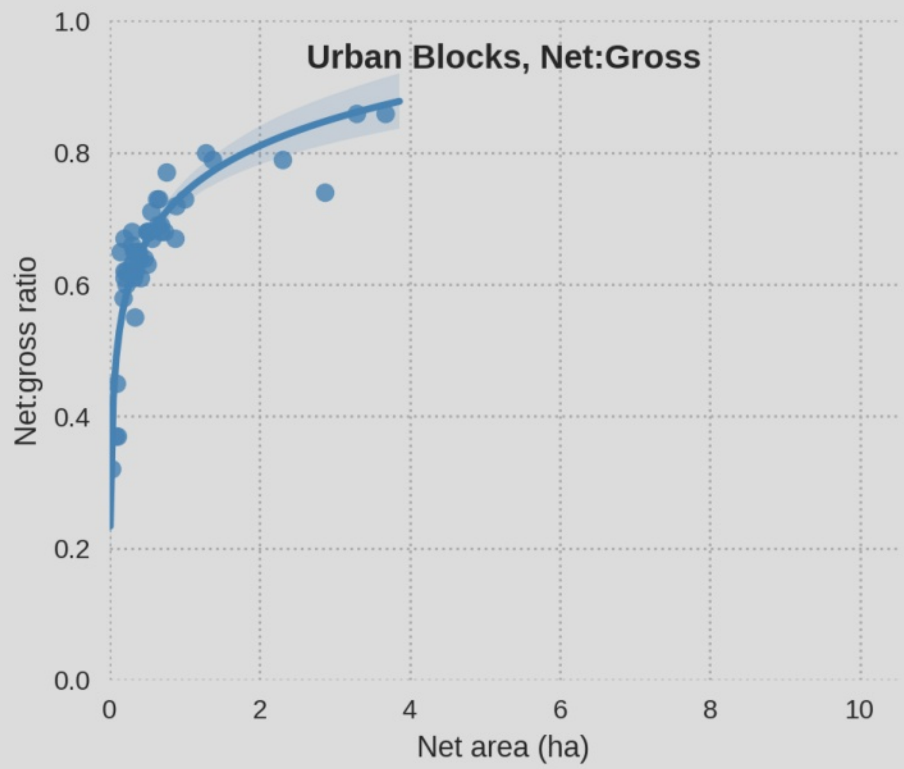
## Buenos Aires - Urban Blocks - Net:Gross

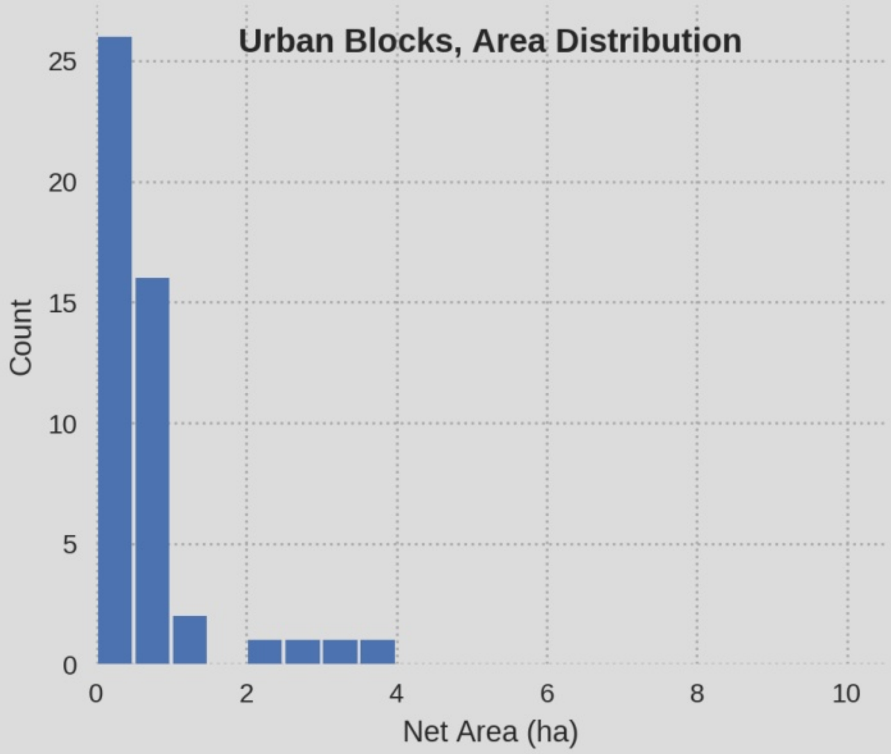


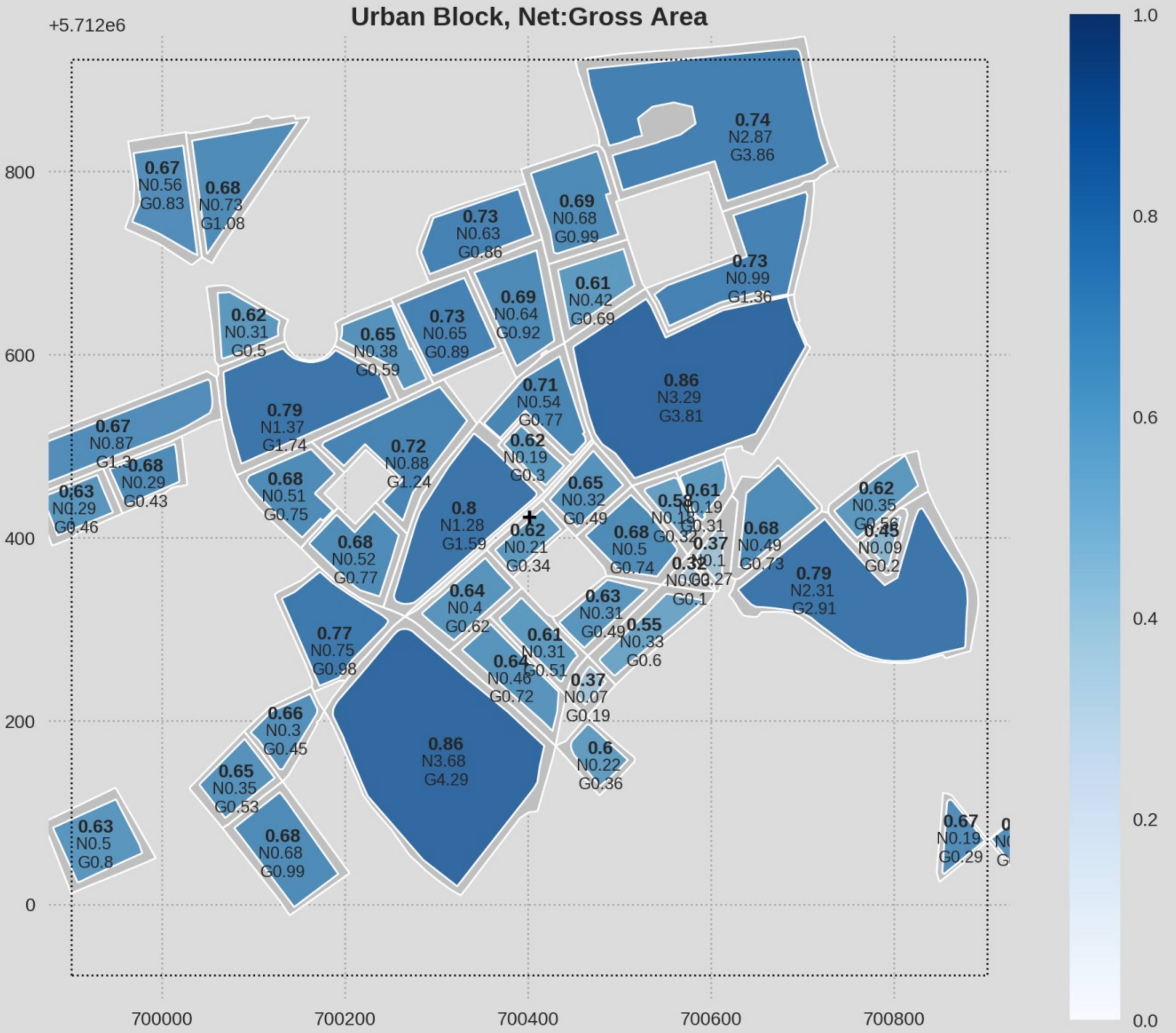



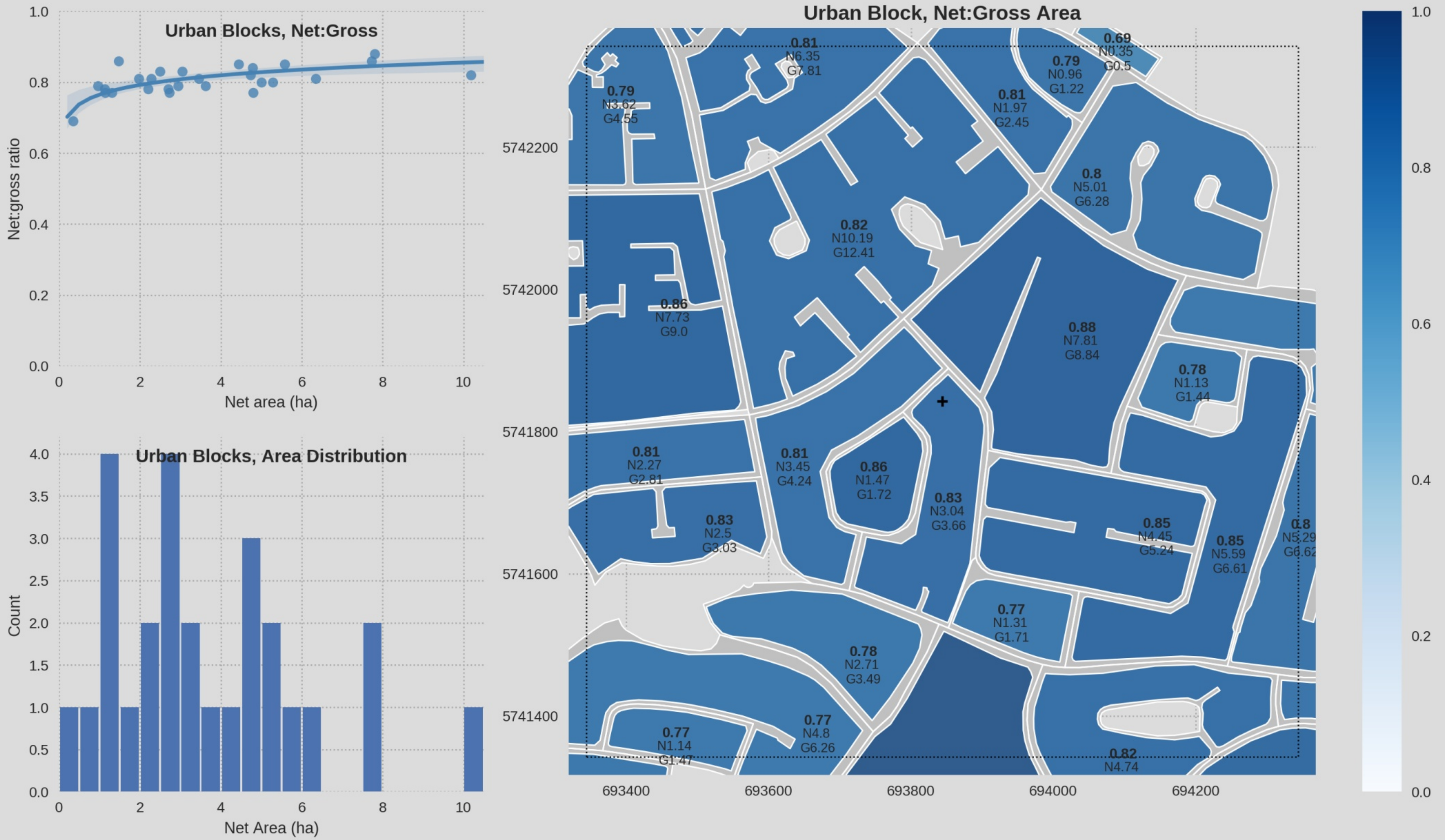
# Clerkenwell - Urban Blocks - Net:Gross



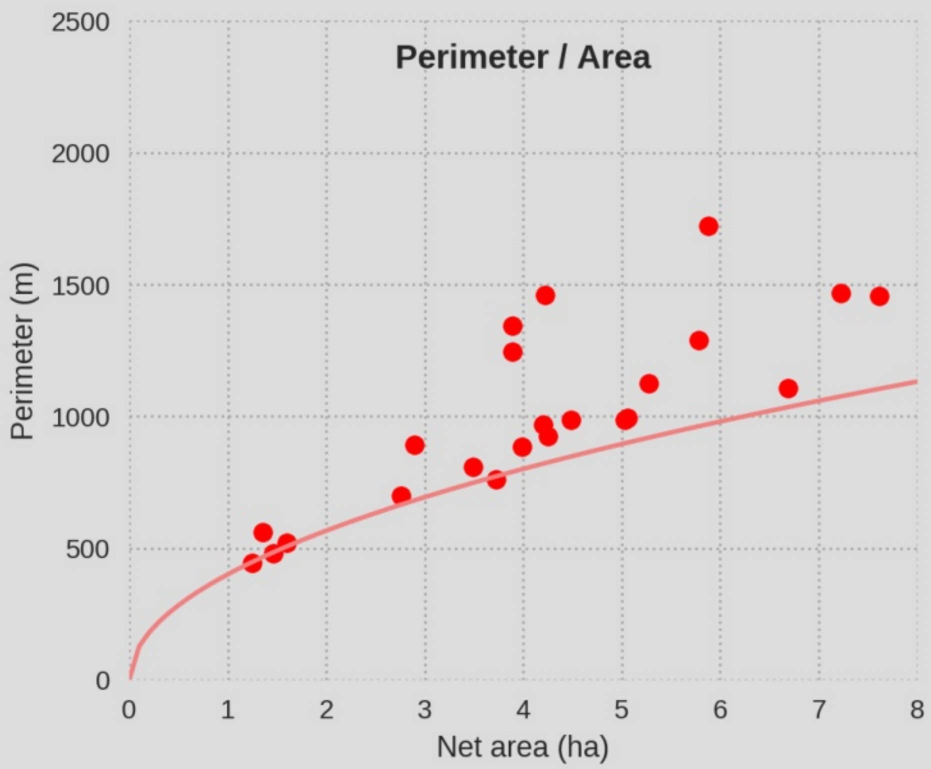



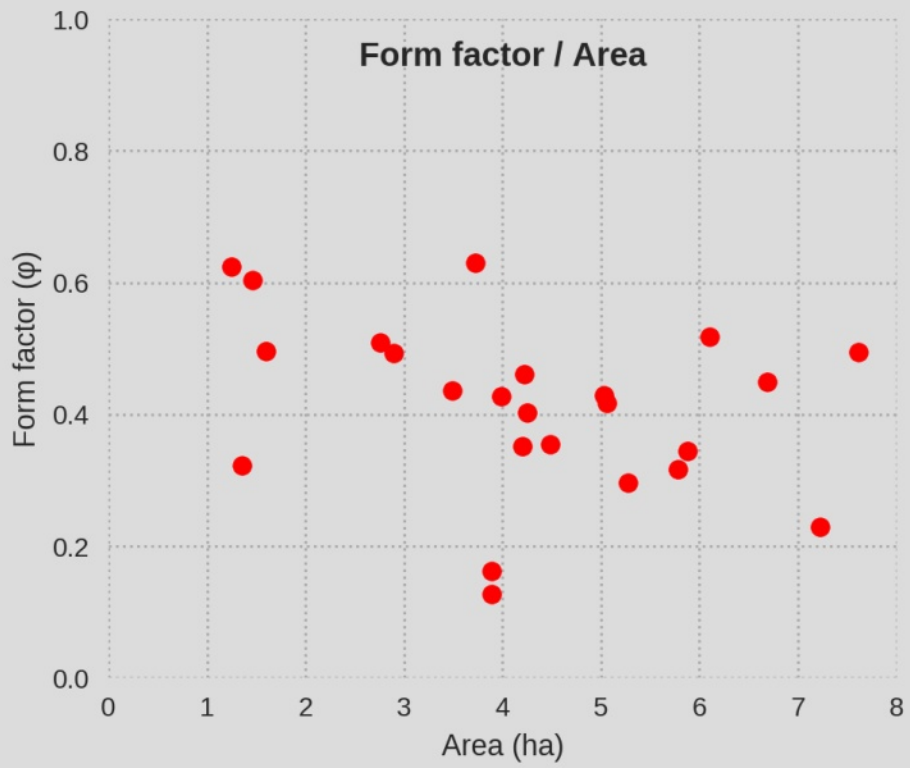



## Welwyn Garden City - Urban Blocks - Net:Gross

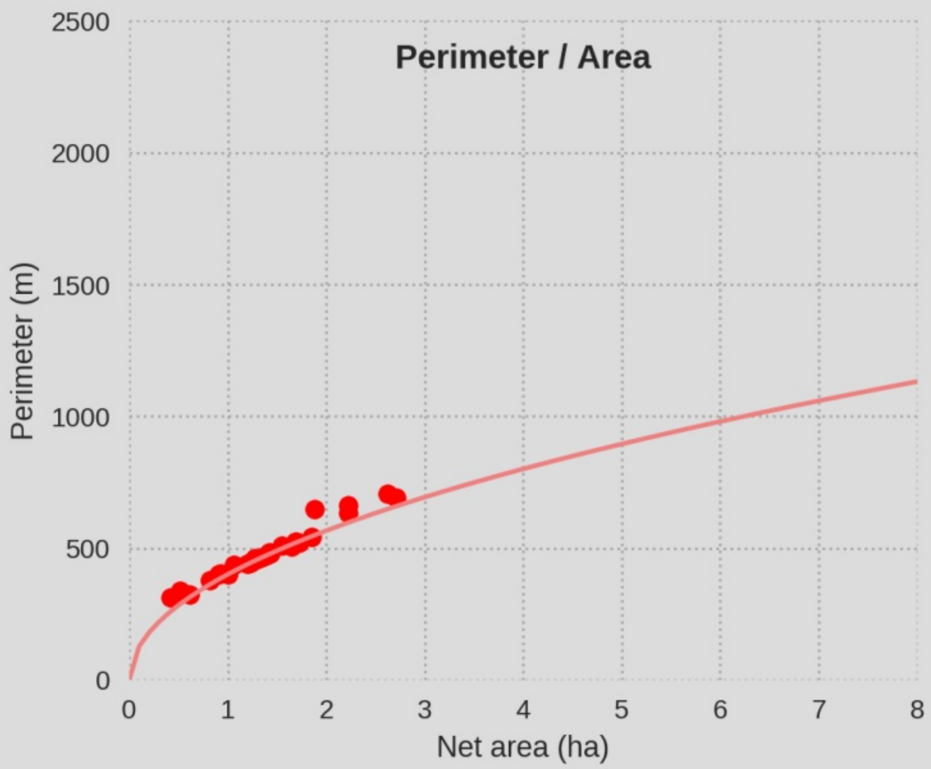


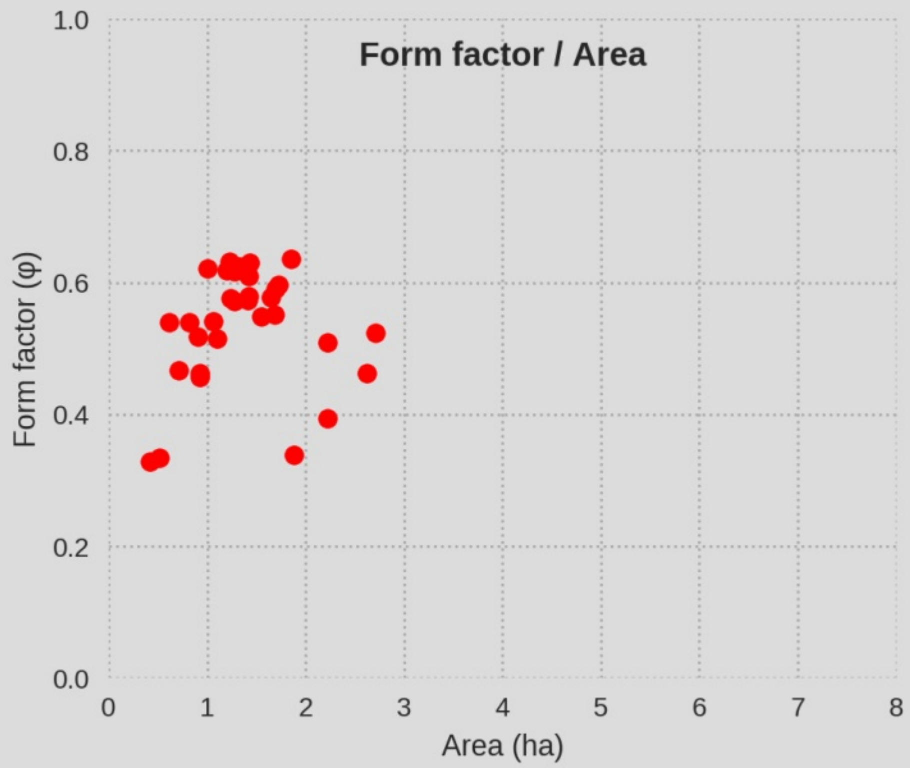
# Bromley - Net Urban Block - Perimeter:Area Ratio

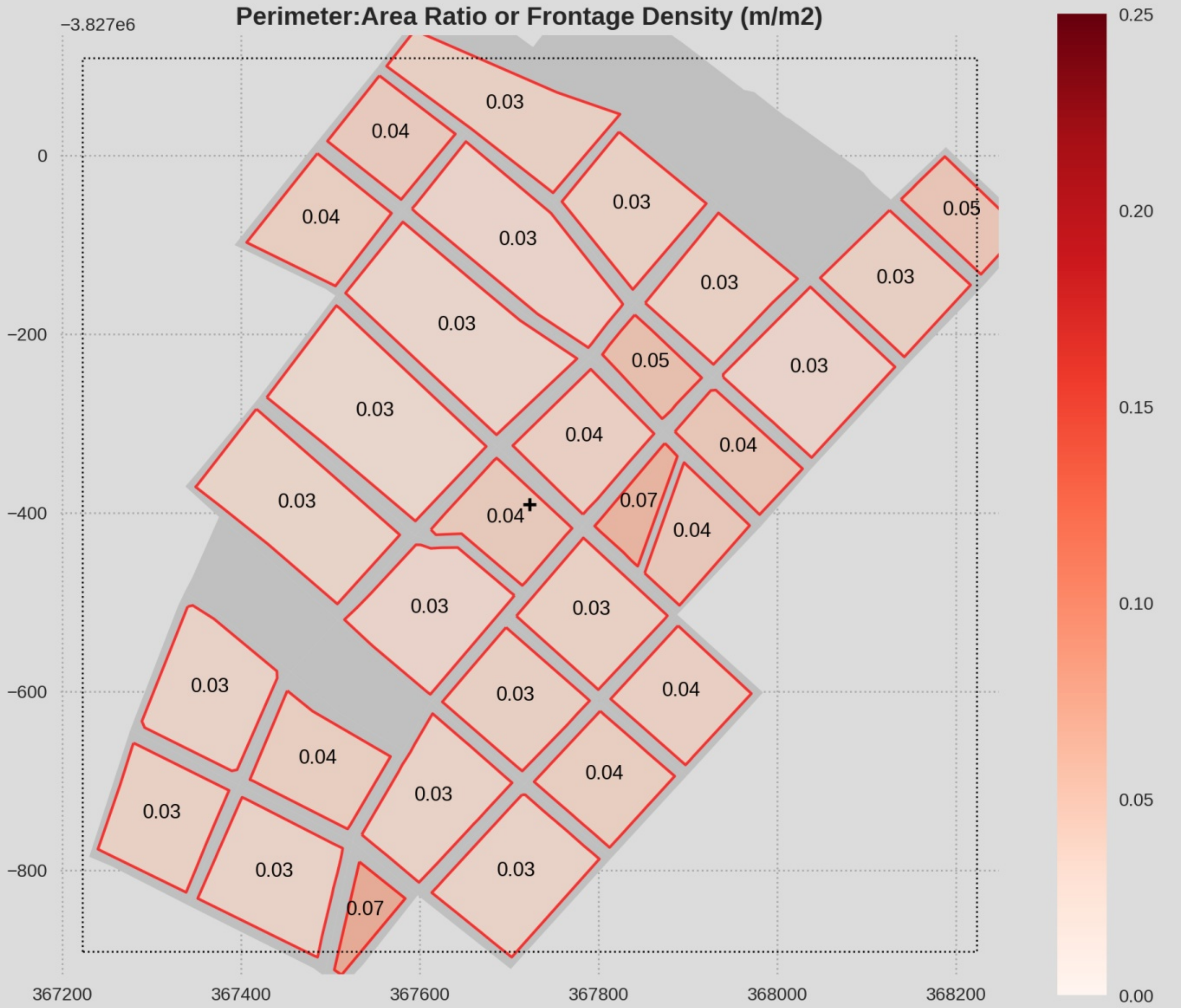


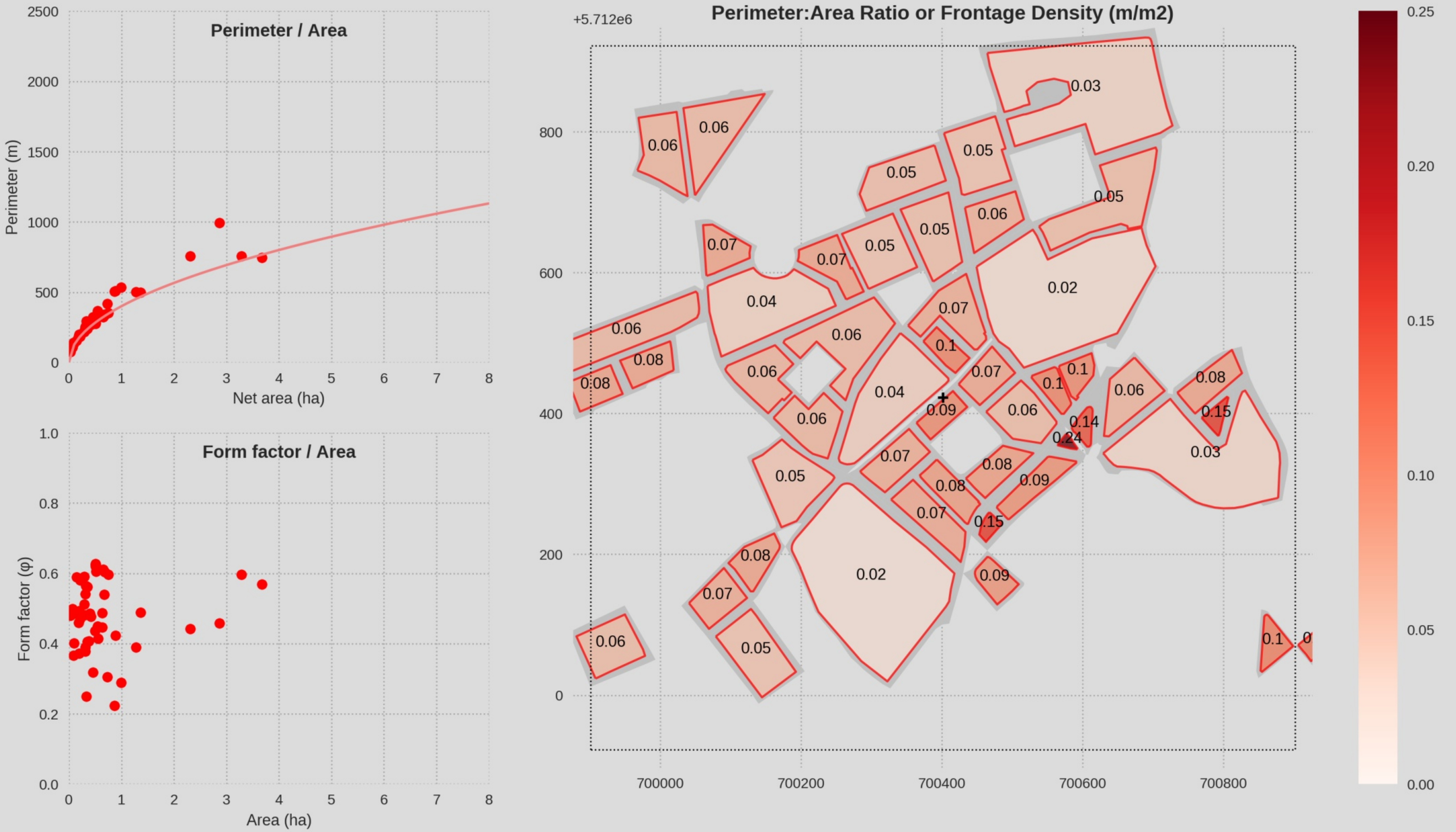

## Buenos Aires - Net Urban Block - Perimeter:Area Ratio



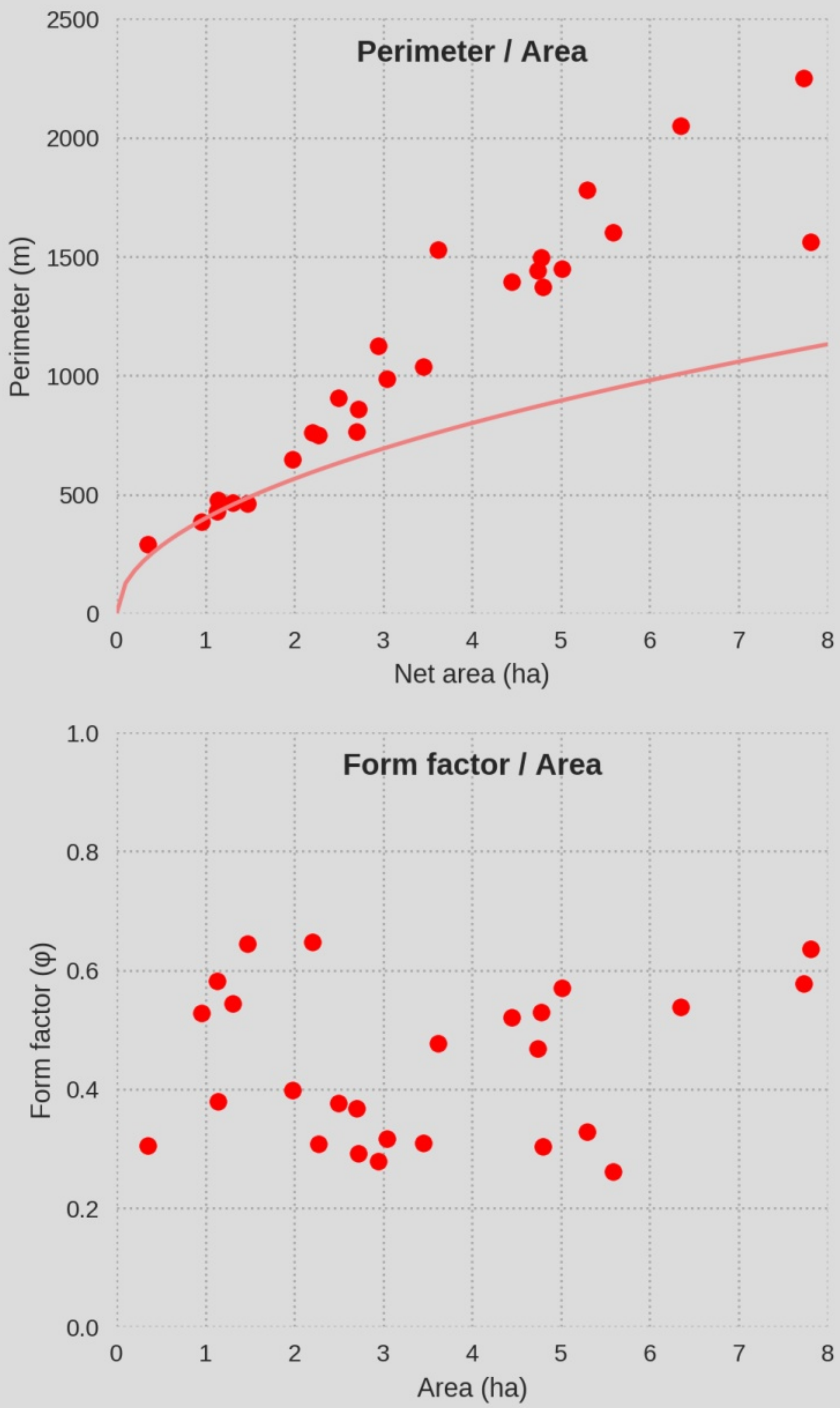



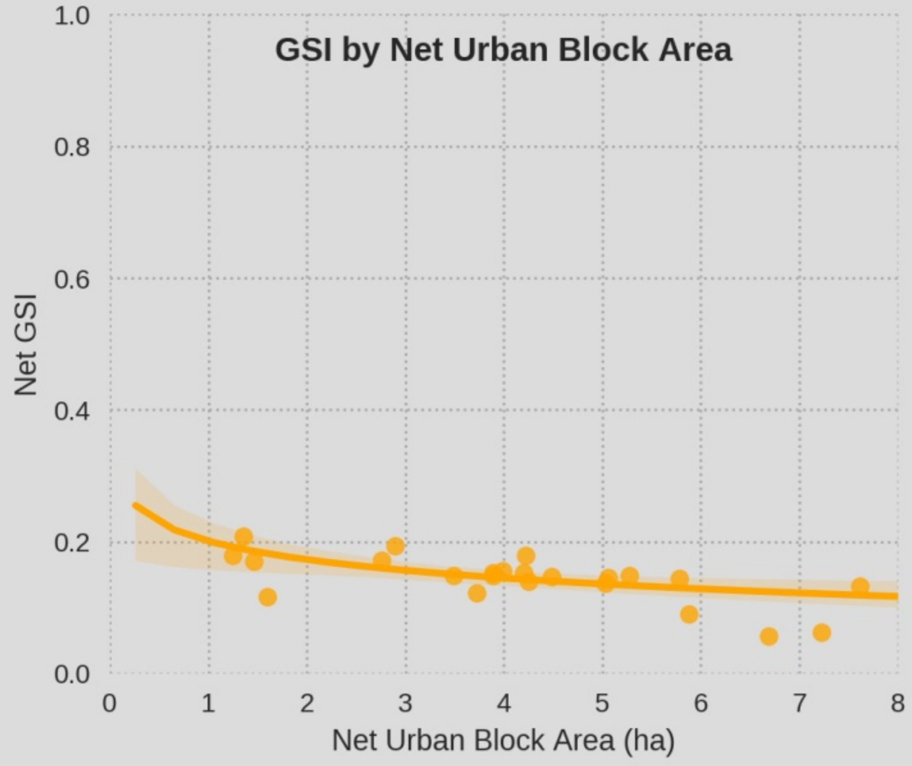
## Clerkenwell - Net Urban Block - Perimeter:Area Ratio

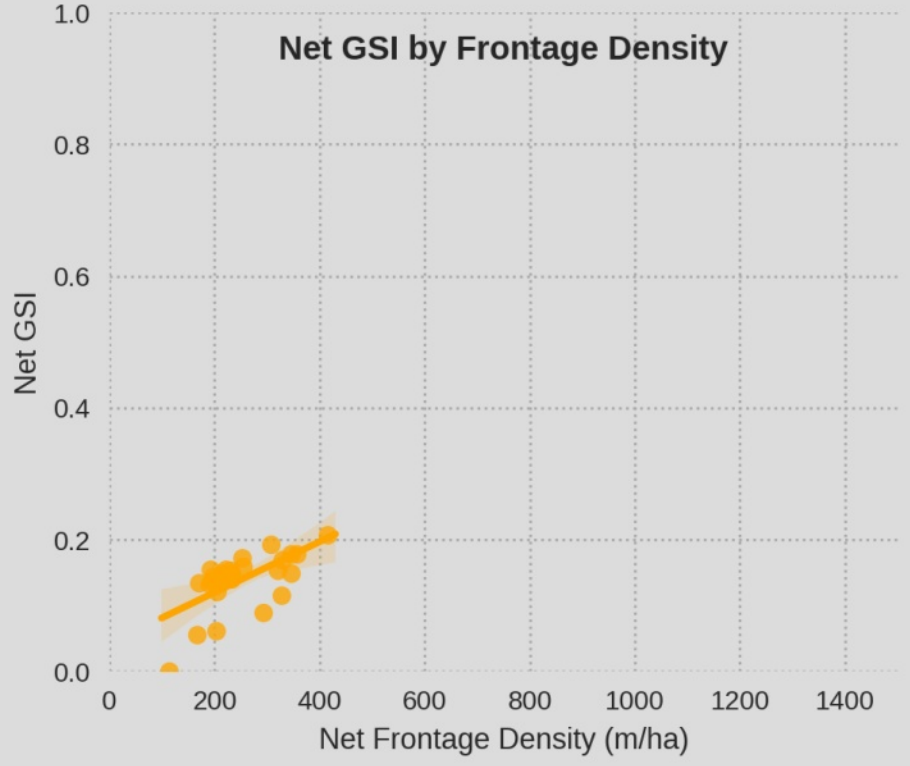


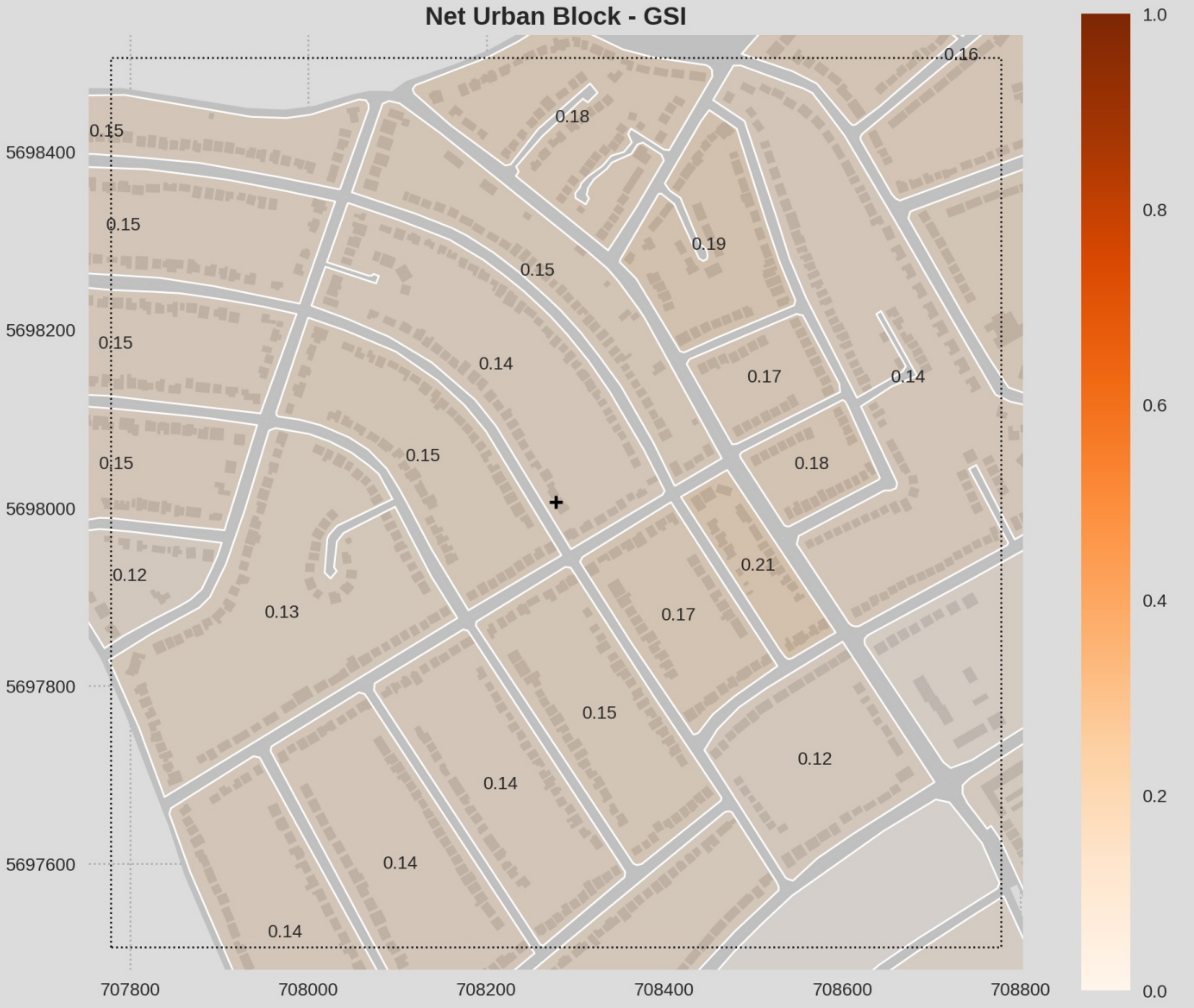
## Welwyn Garden City - Net Urban Block - Perimeter:Area Ratio



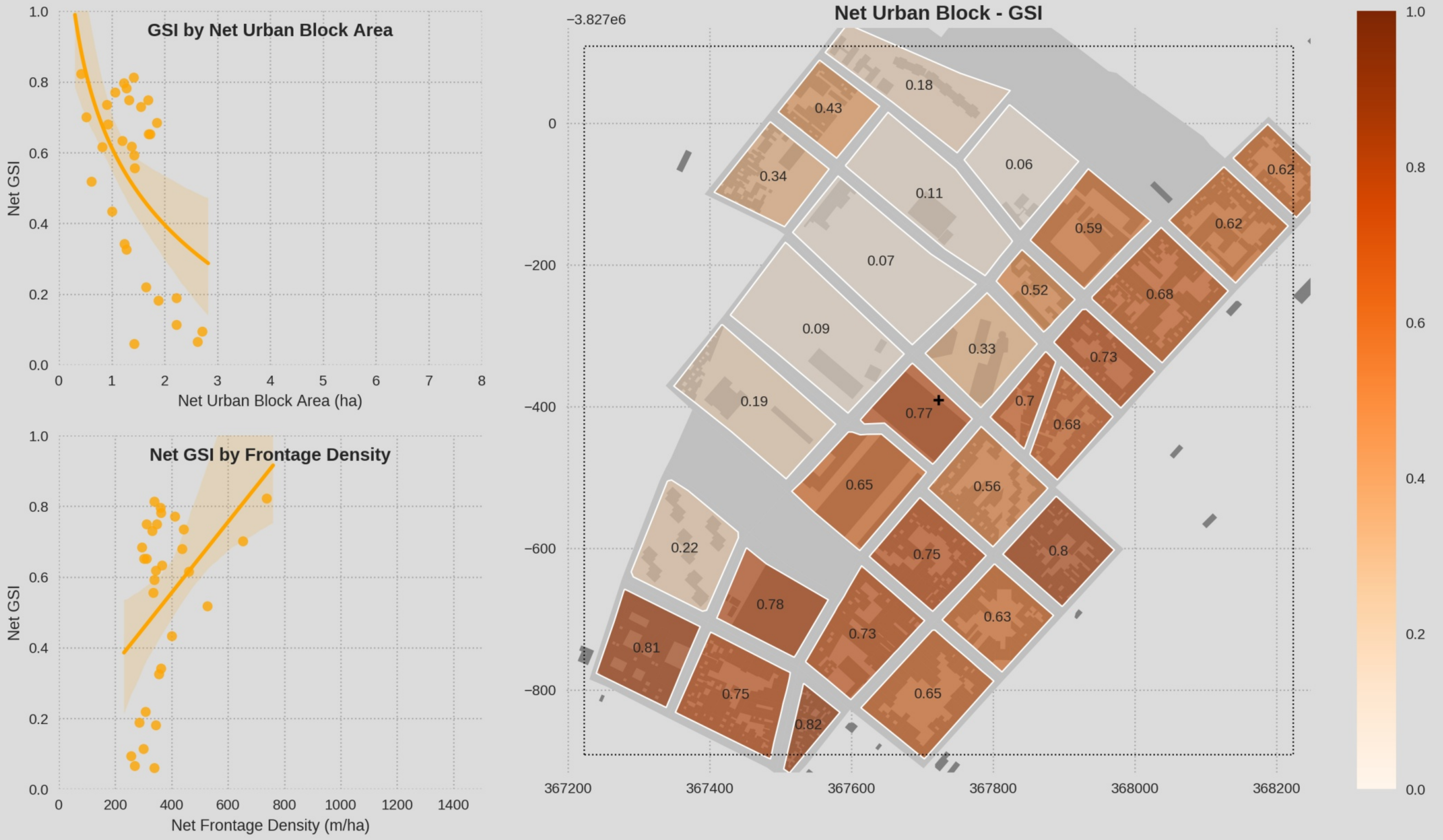

## Bromley - Net Urban Block - GSI



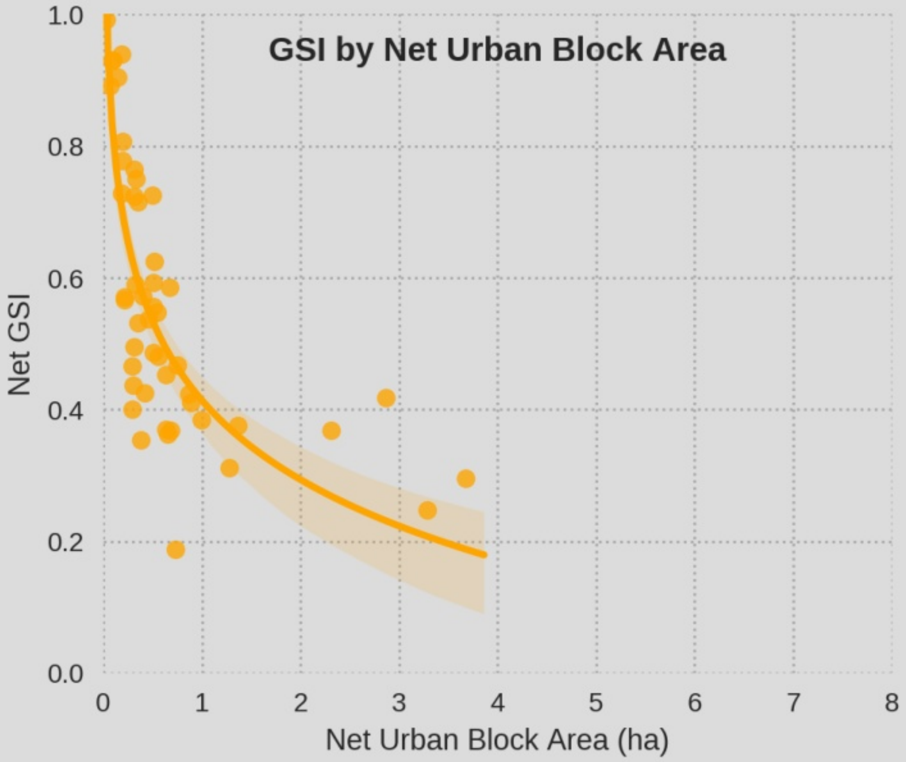



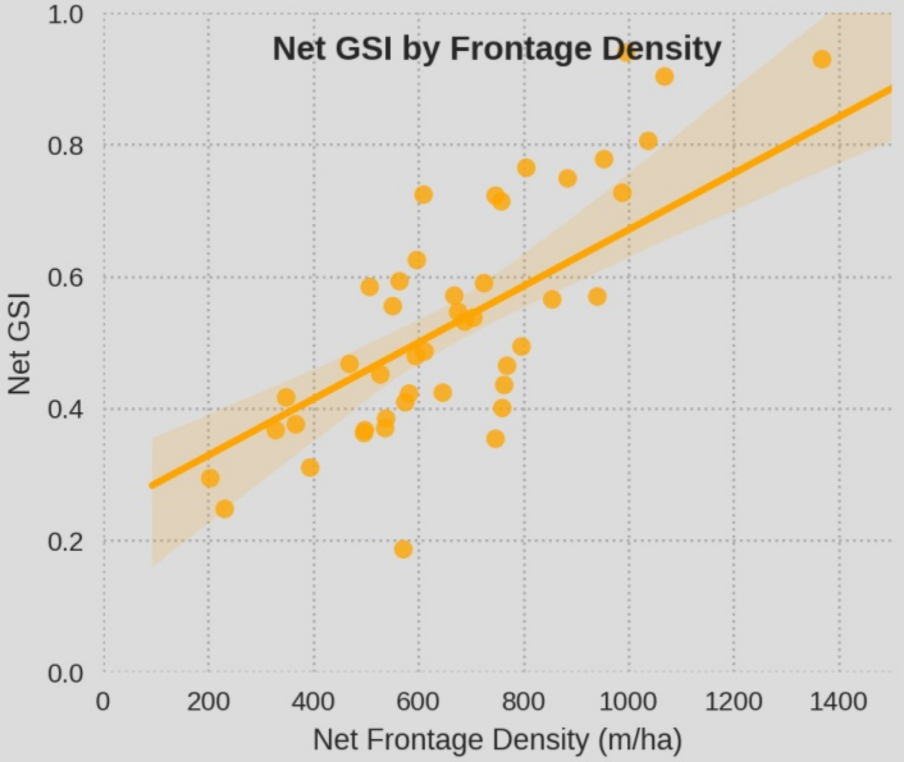



## Buenos Aires - Net Urban Block - GSI

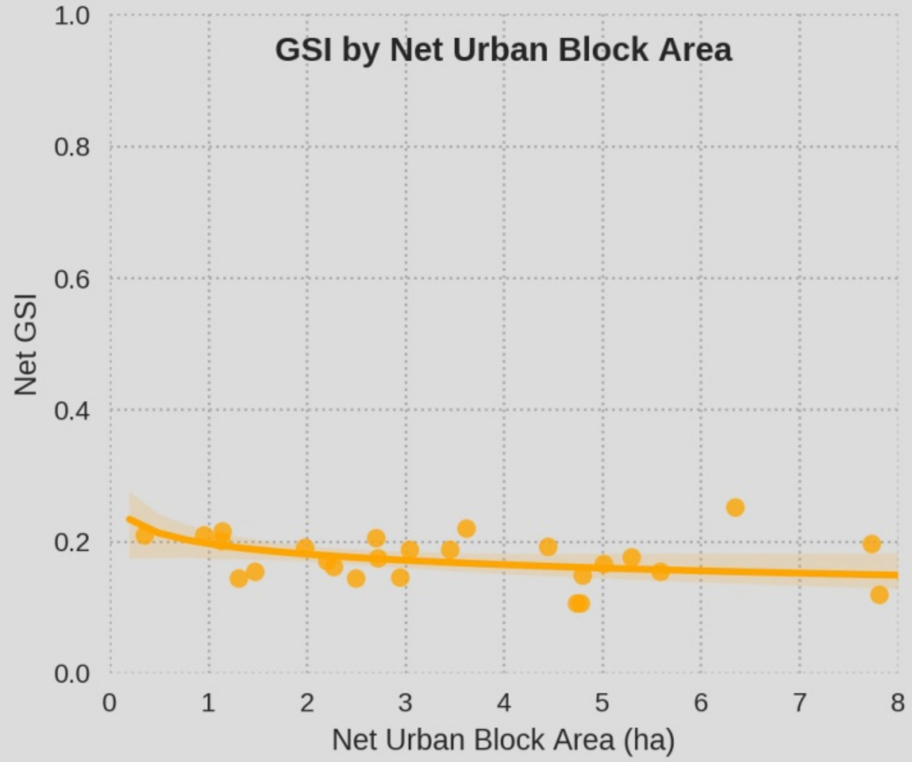


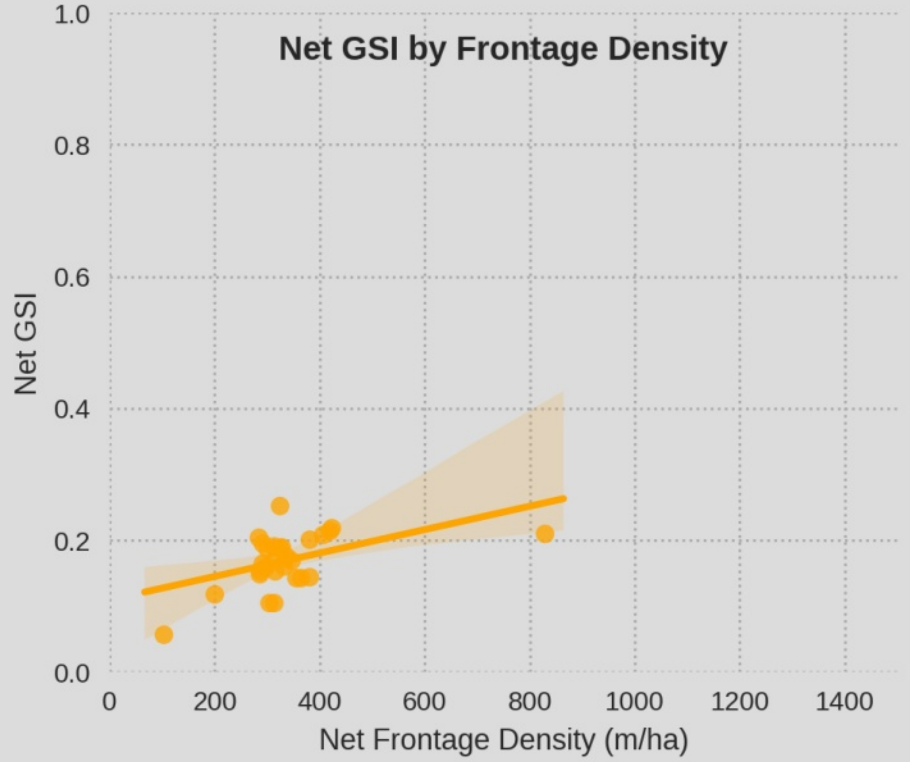
## Clerkenwell - Net Urban Block - GSI



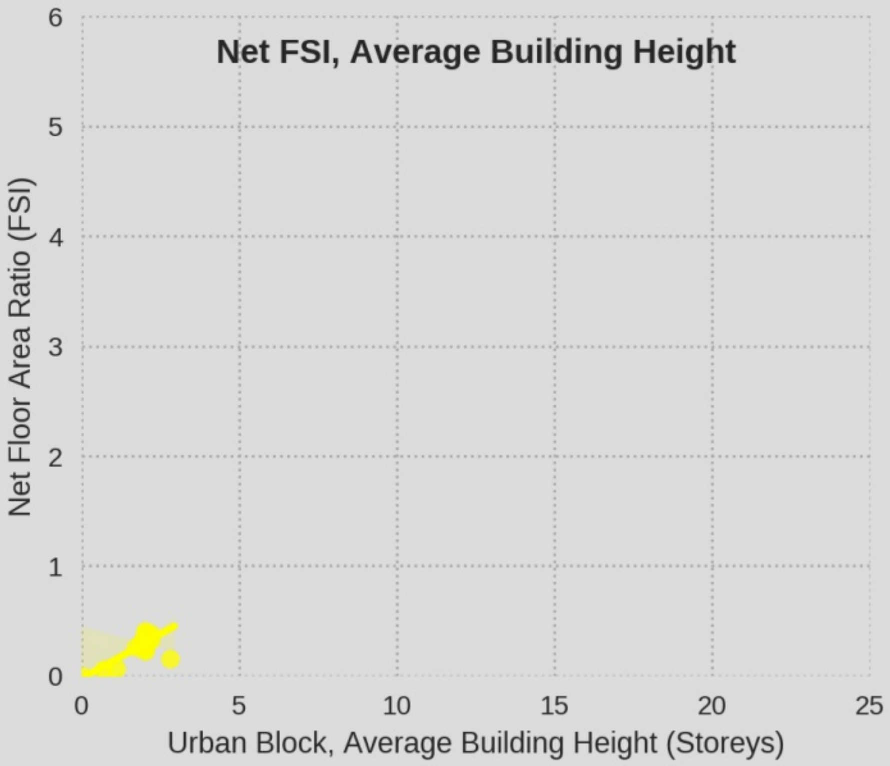



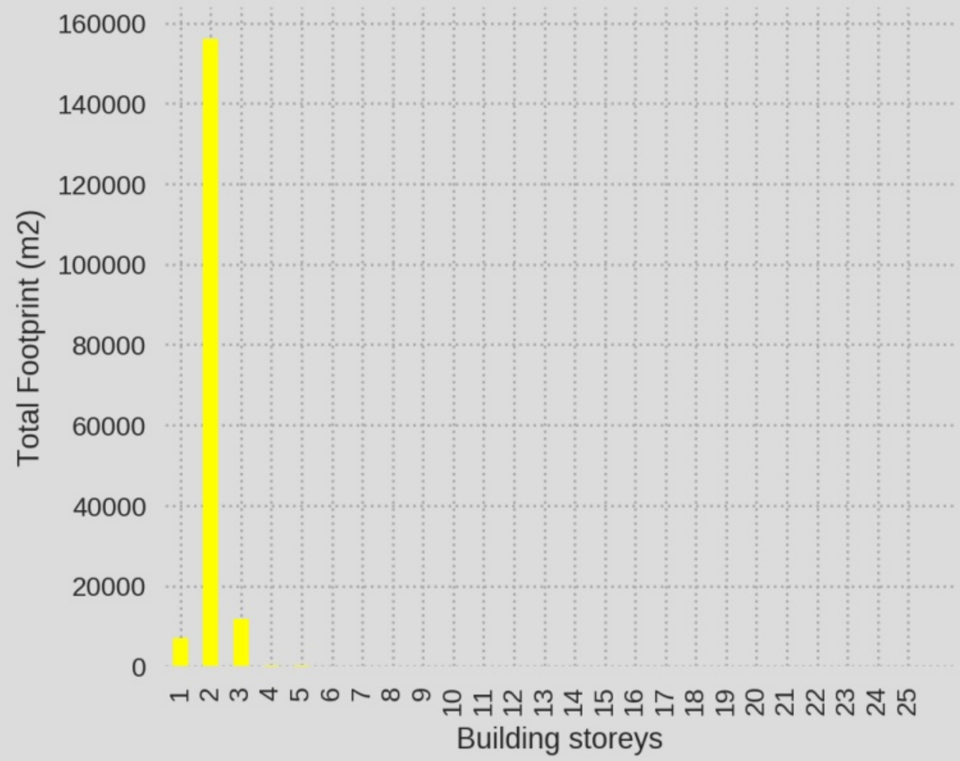

## Welwyn Garden City - Net Urban Block - GSI

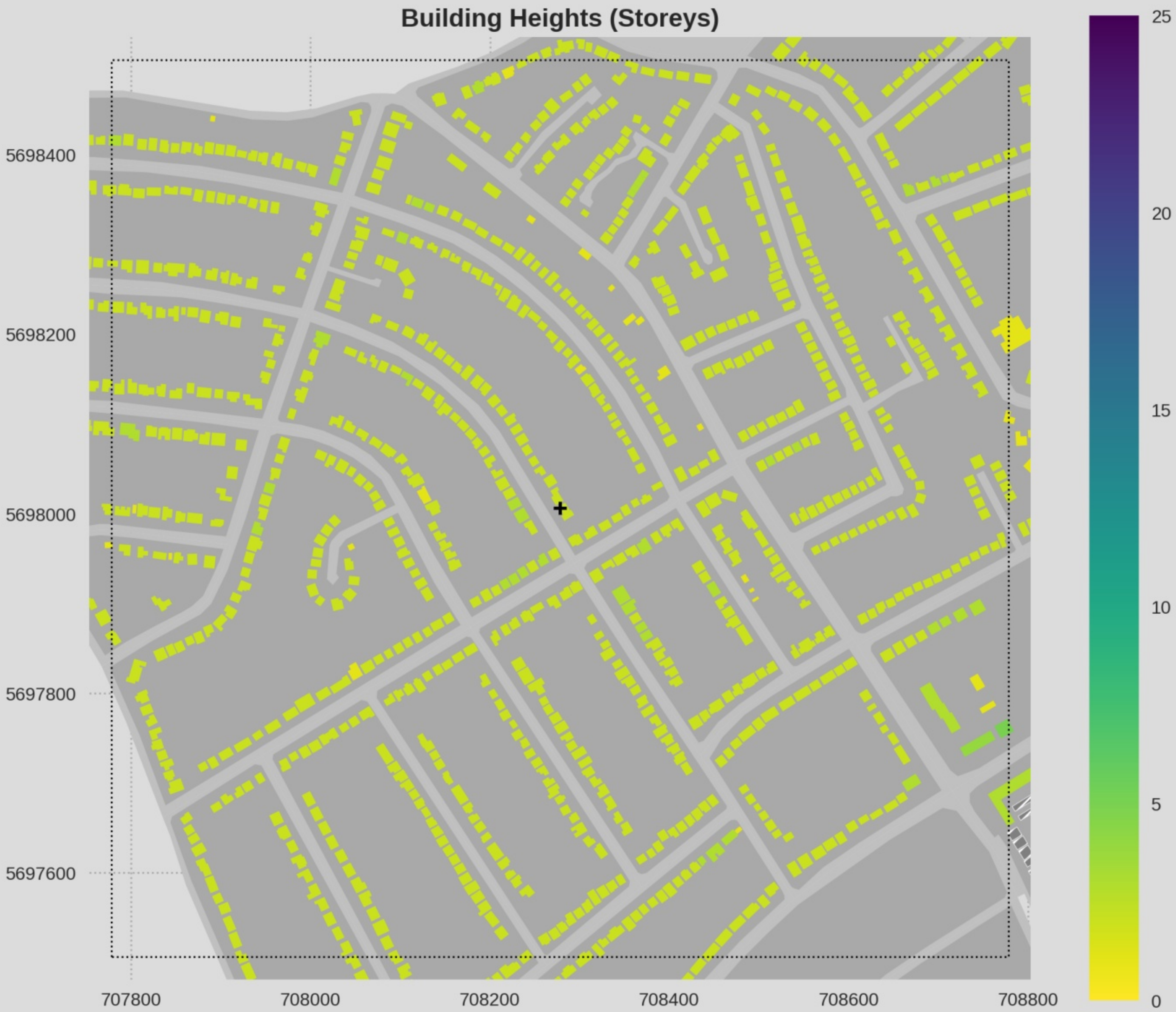


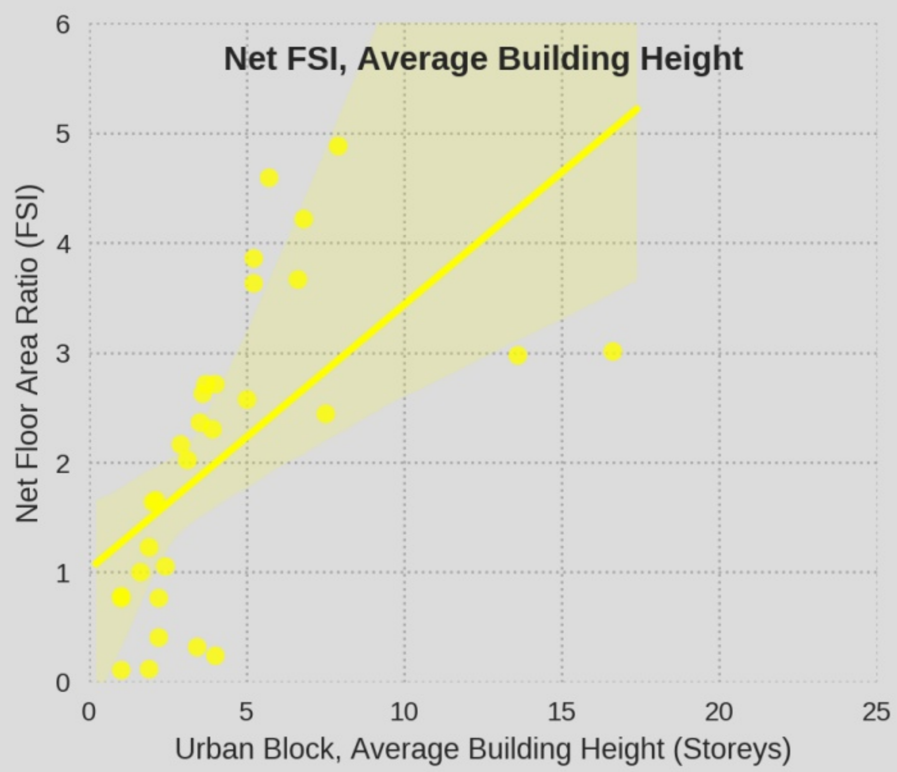

# Bromley - Building Heights

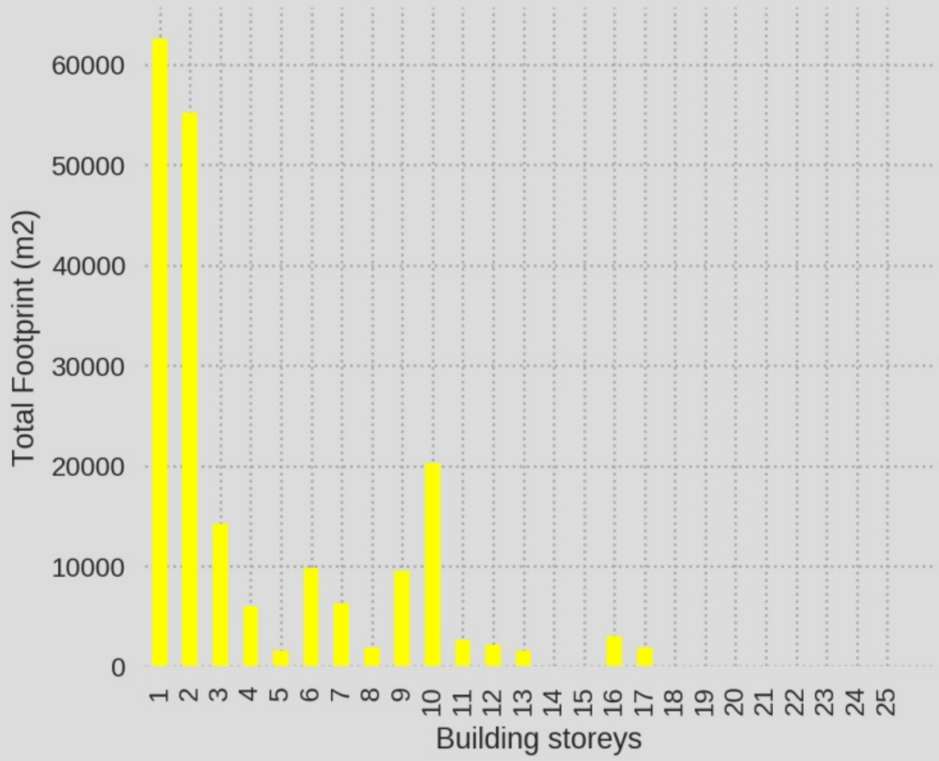


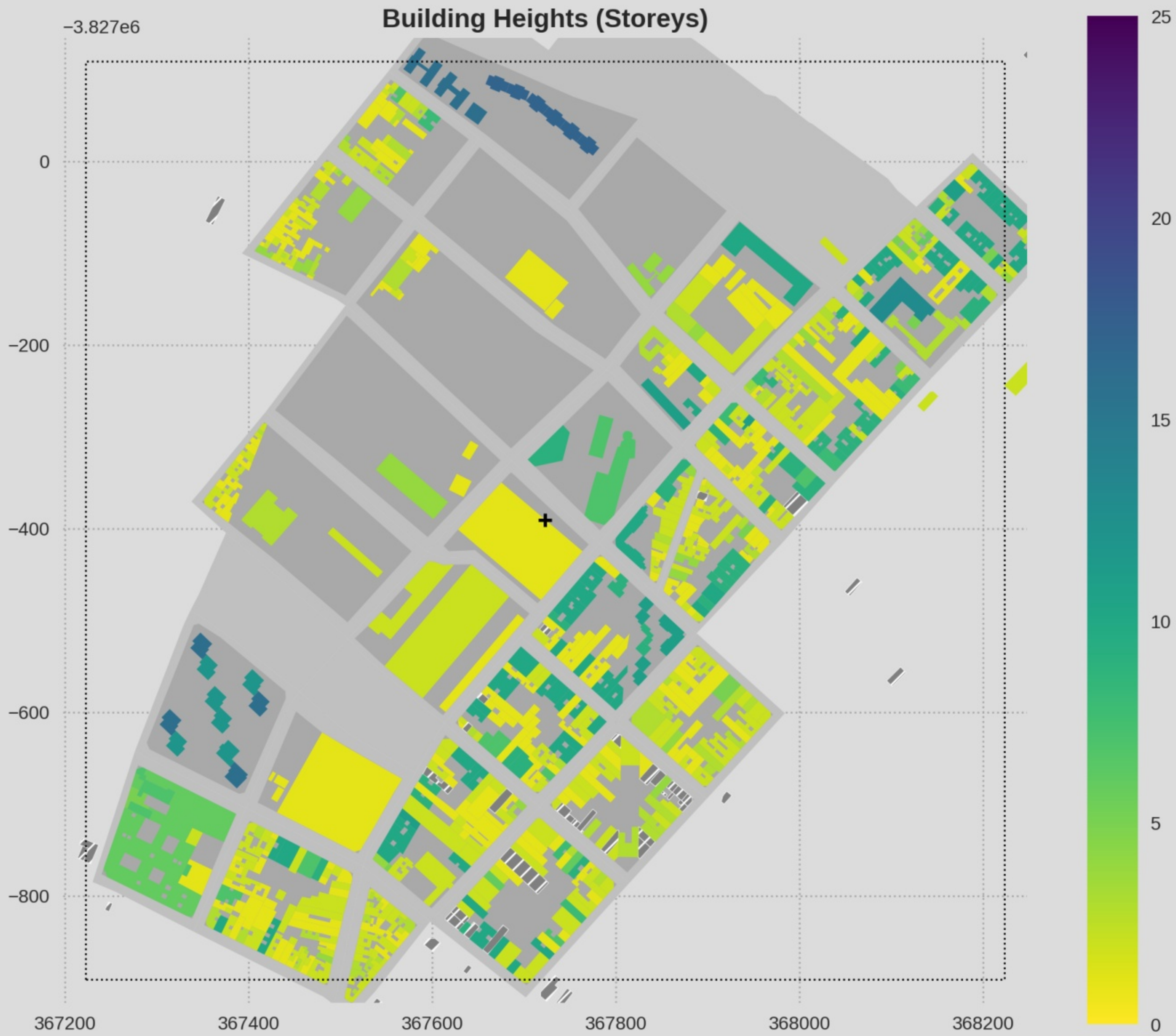



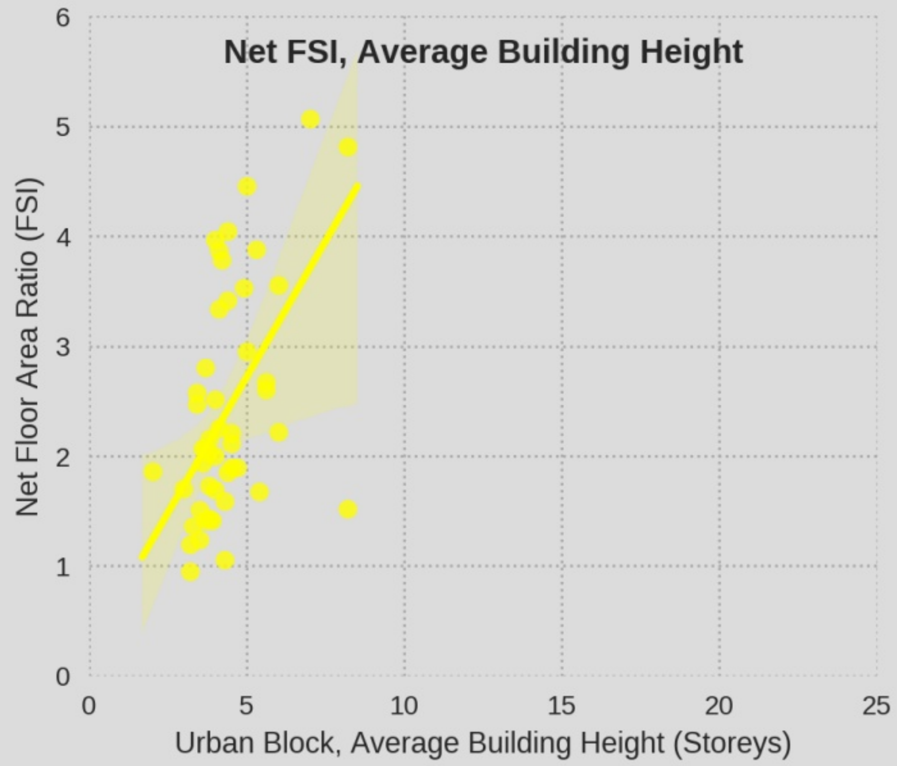
## Buenos Aires - Building Heights

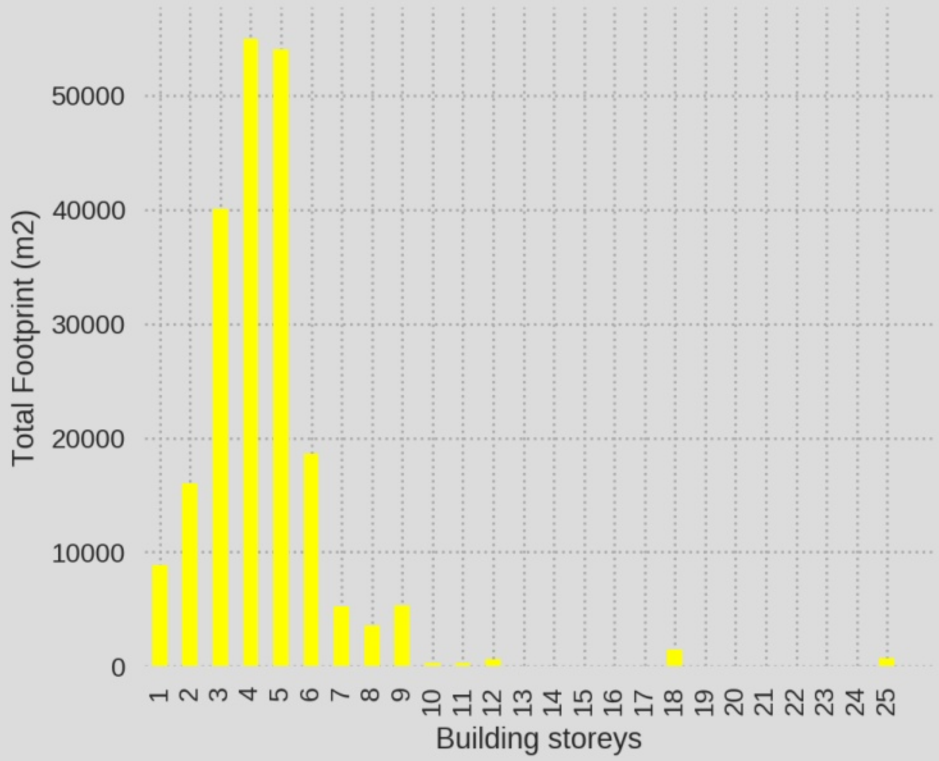


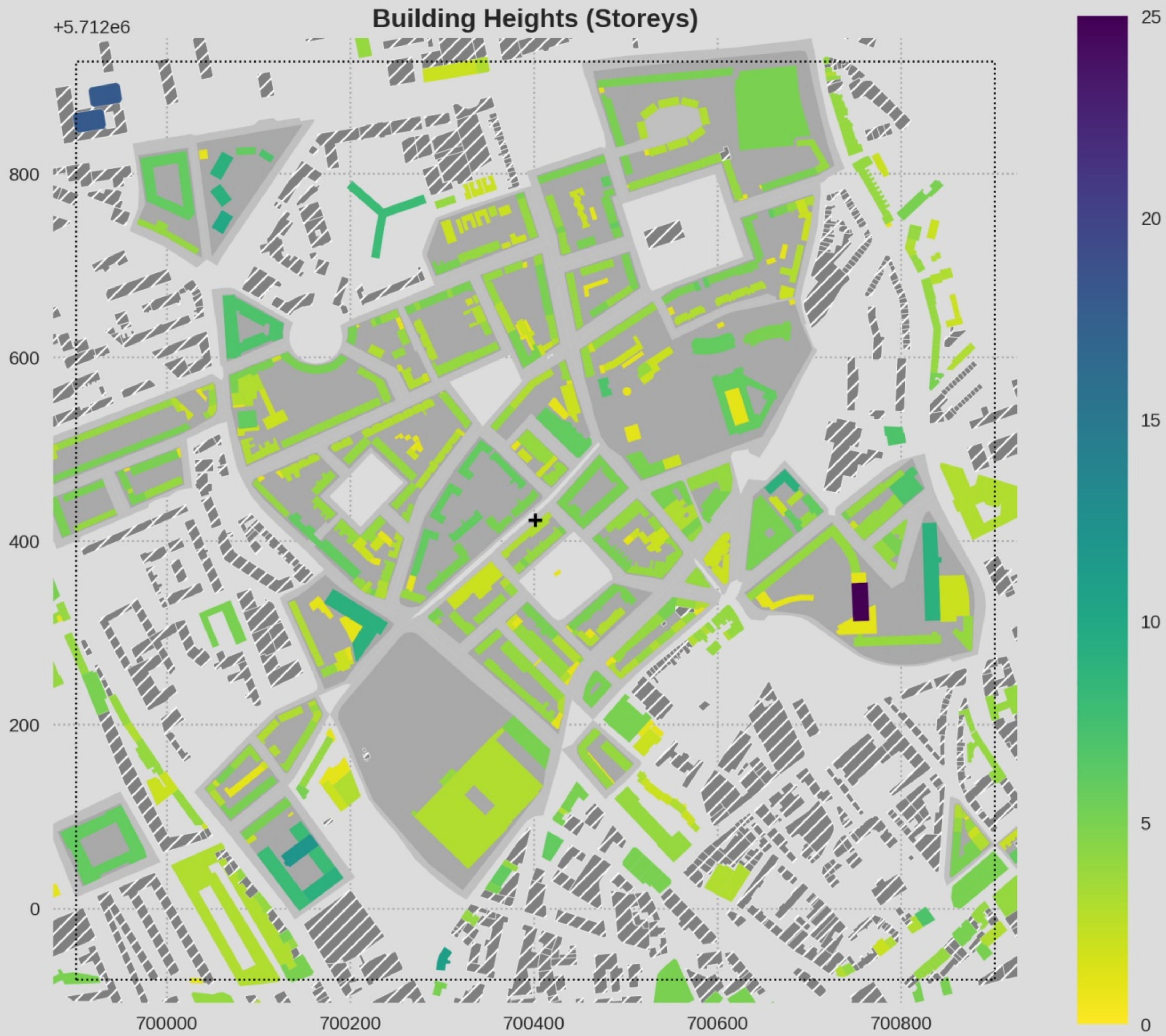



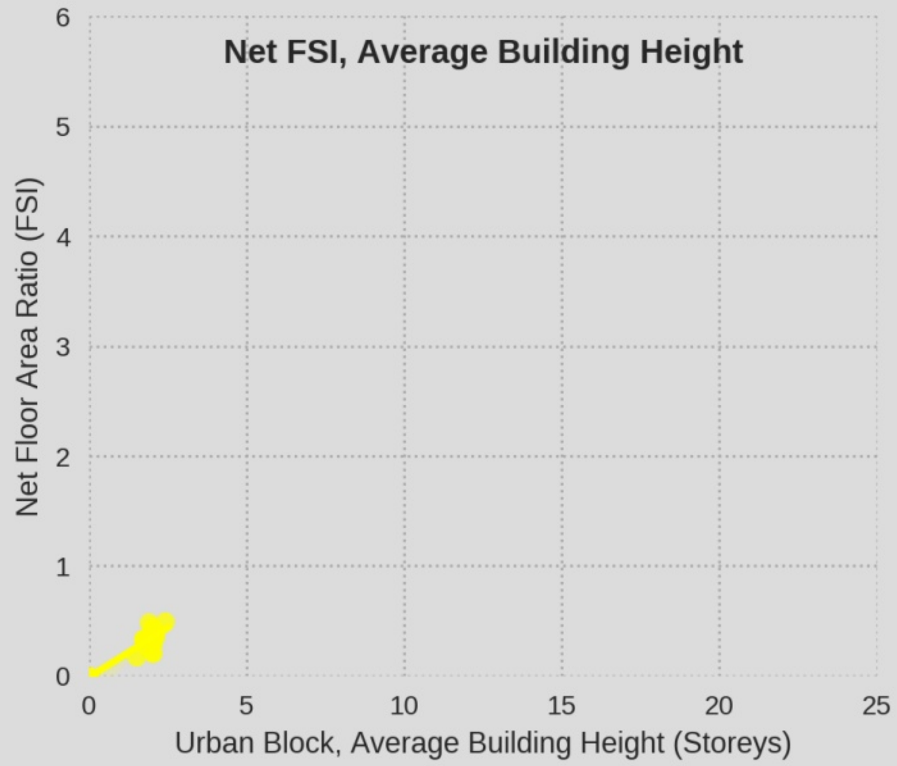
## Clerkenwell - Building Heights

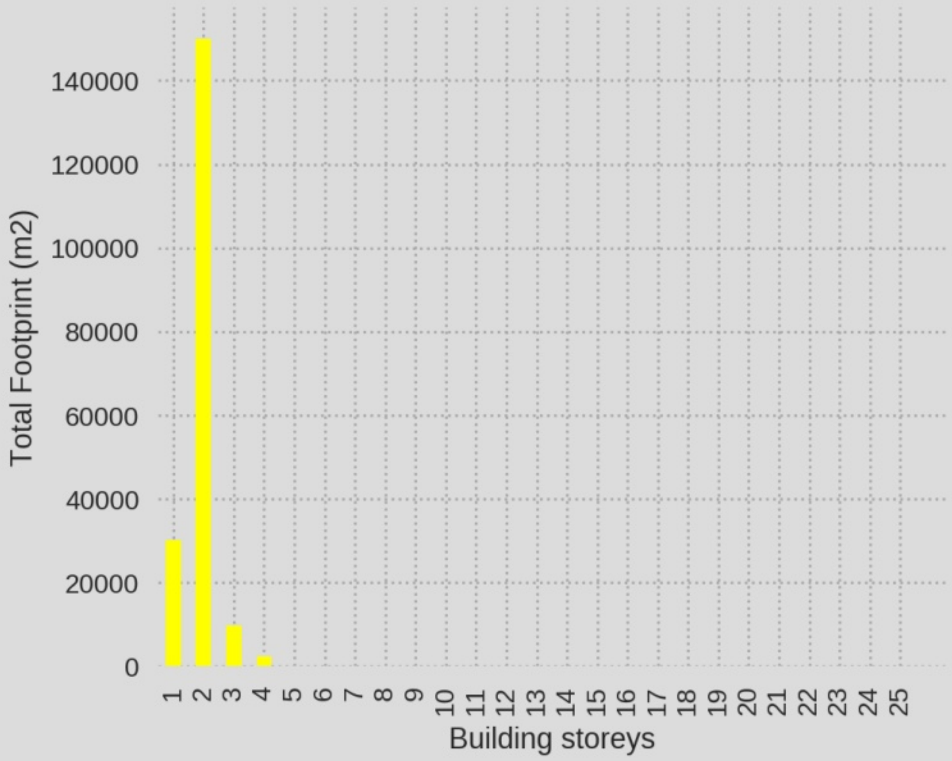


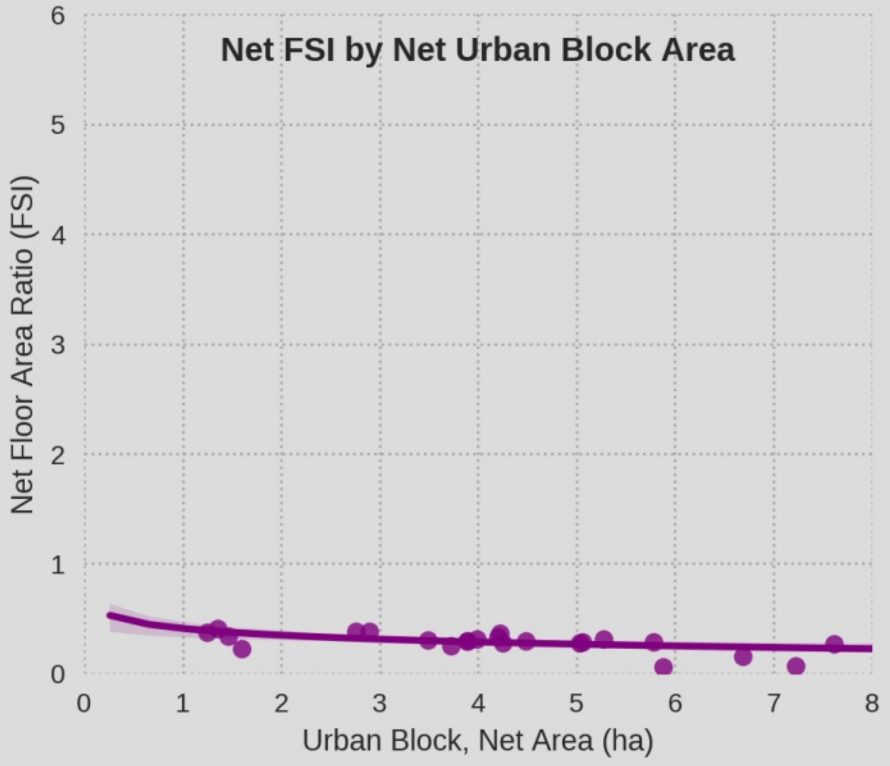



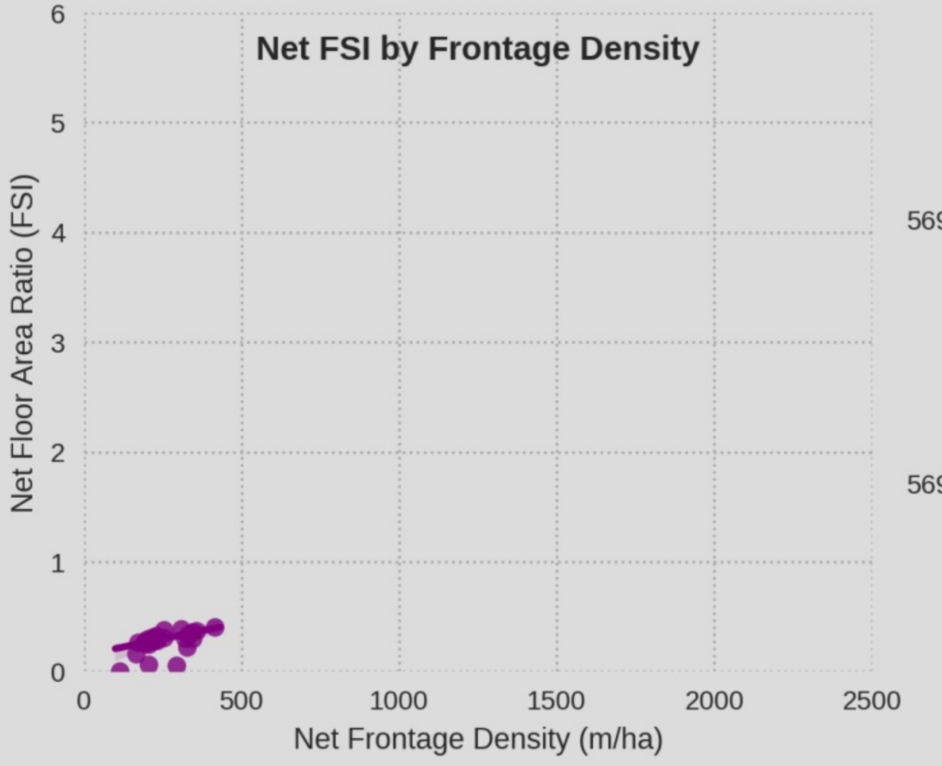
## Welwyn Garden City - Building Heights

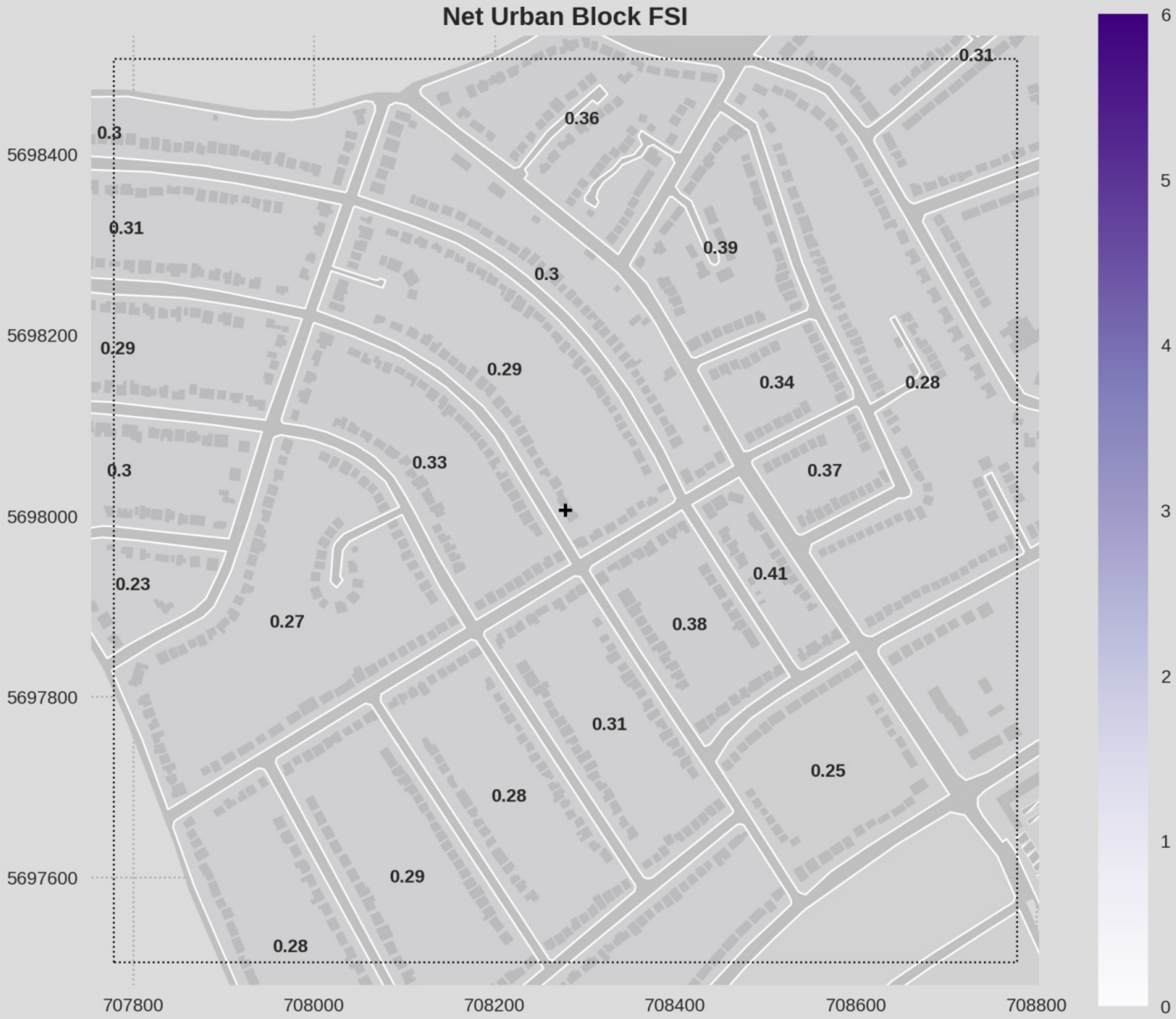


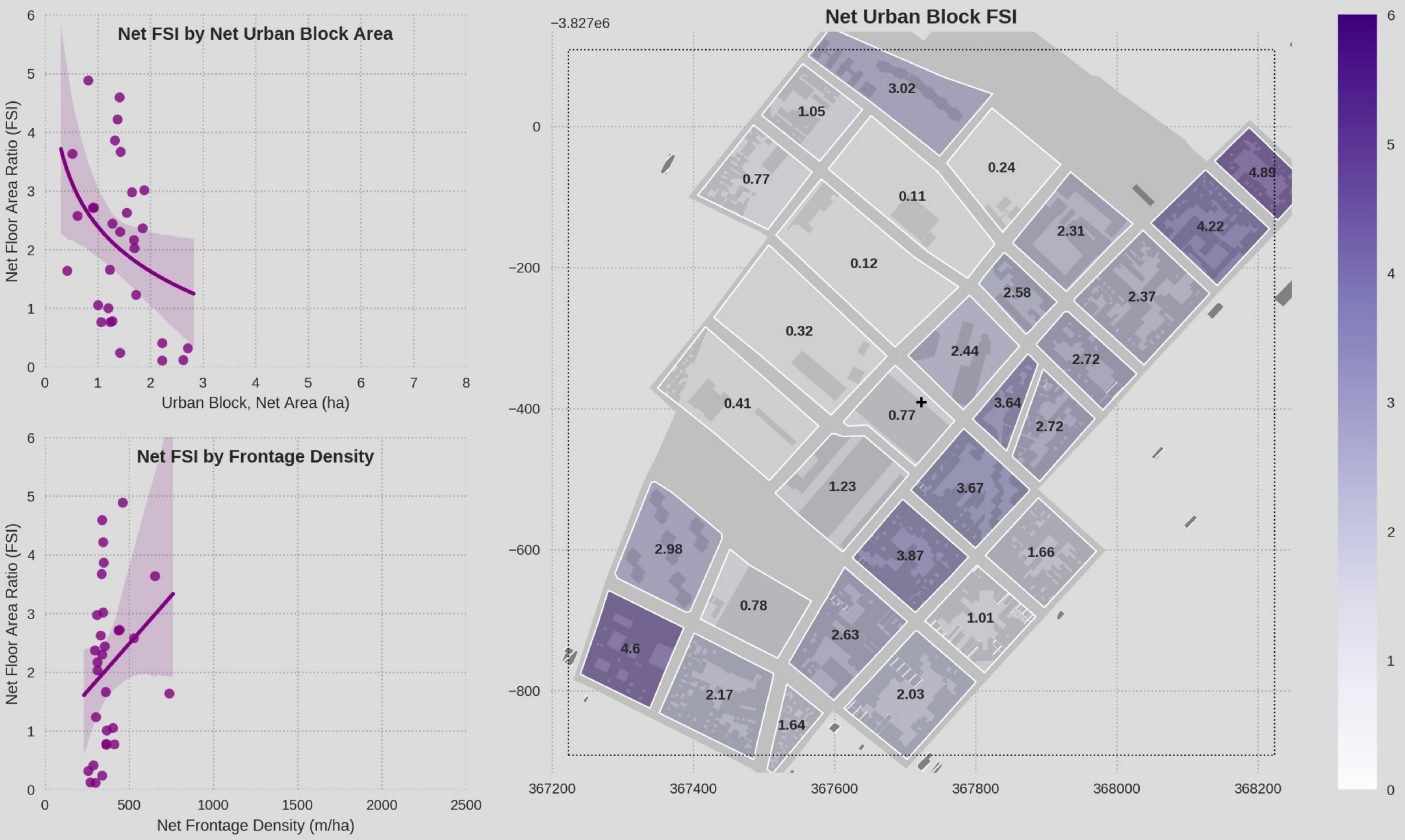

## Bromley Net Urban Block - FSI



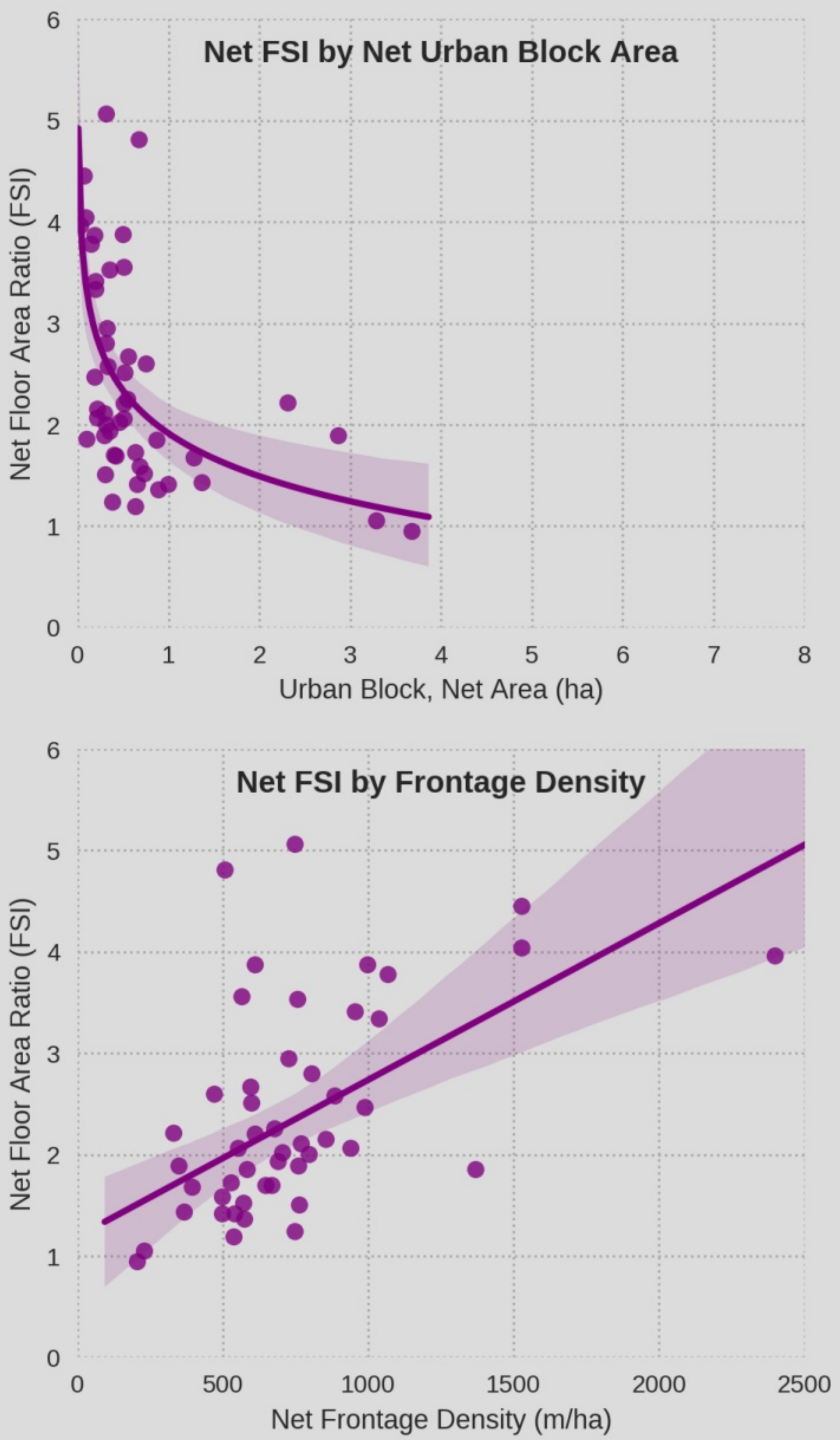



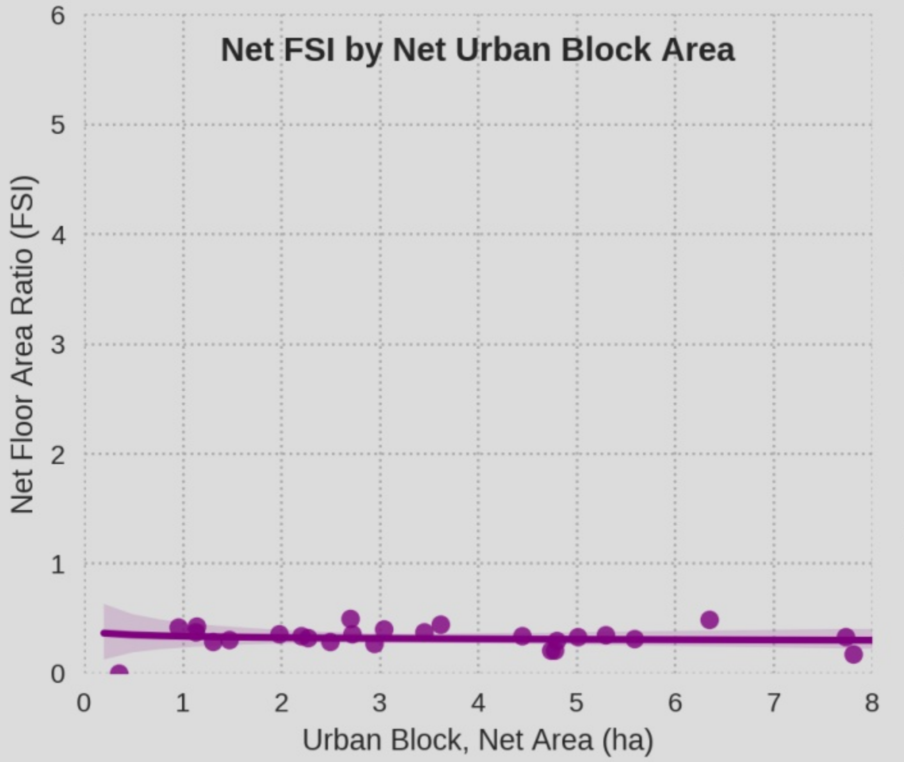
## Buenos Aires Net Urban Block - FSI

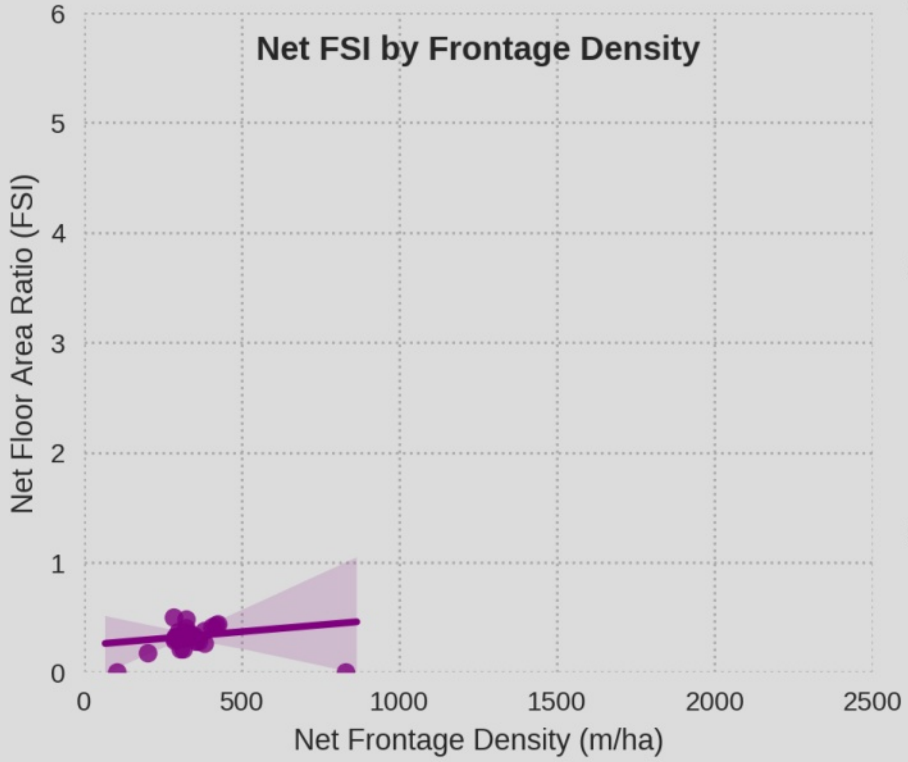


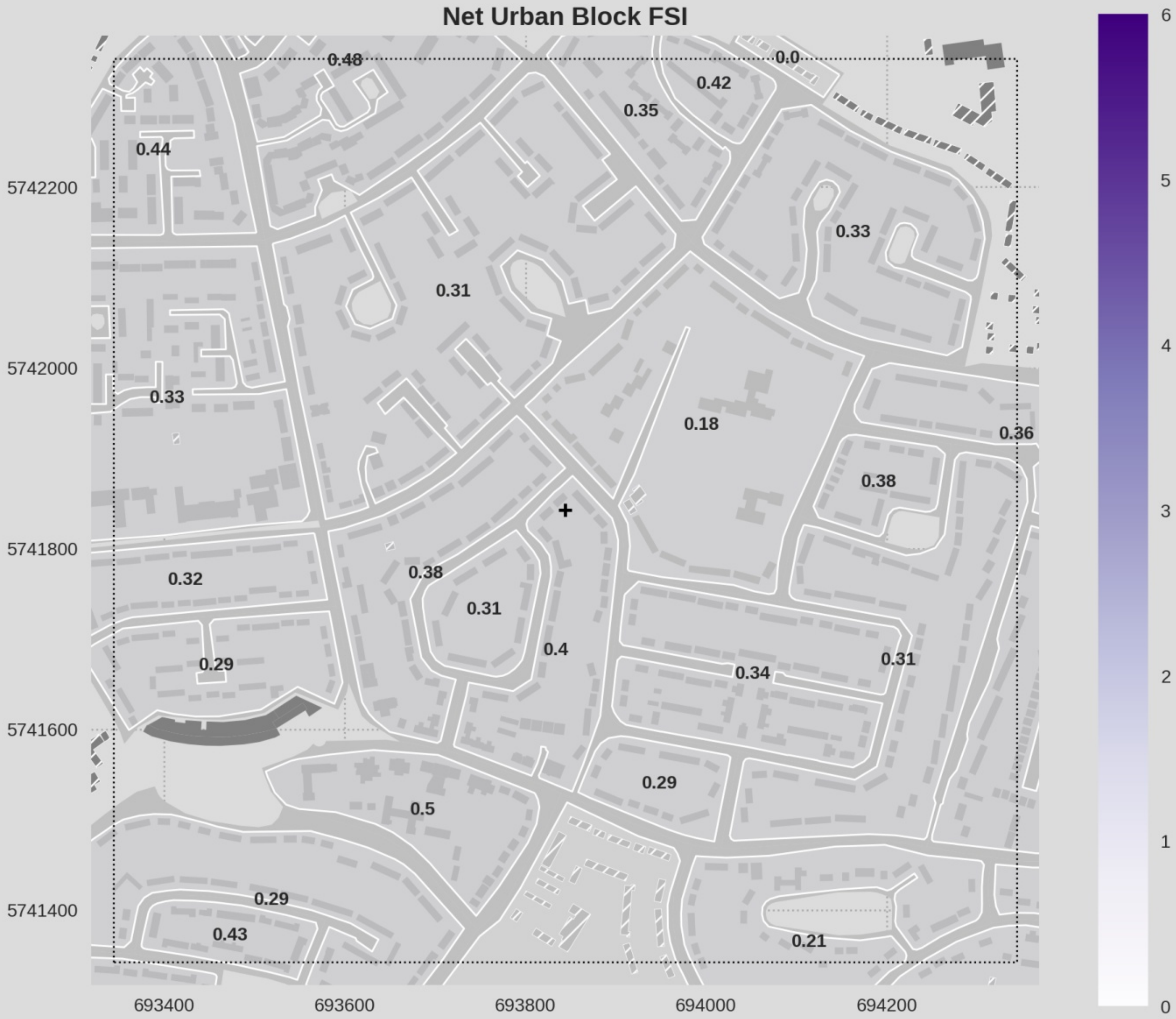
## Clerkenwell Net Urban Block - FSI



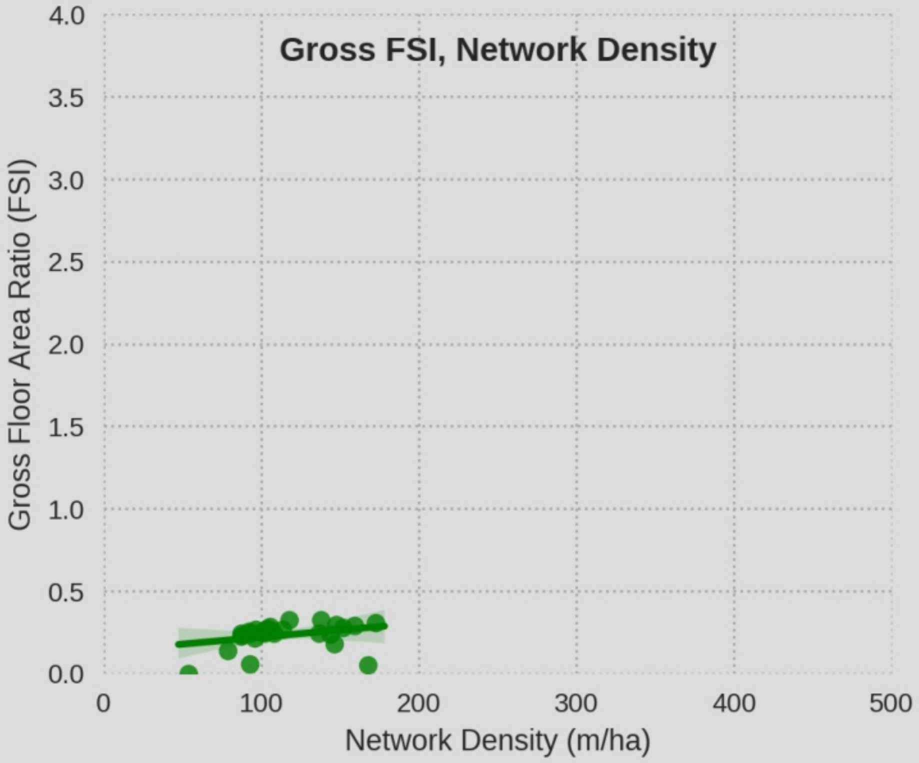

# Welwyn Garden City Net Urban Block - FSI

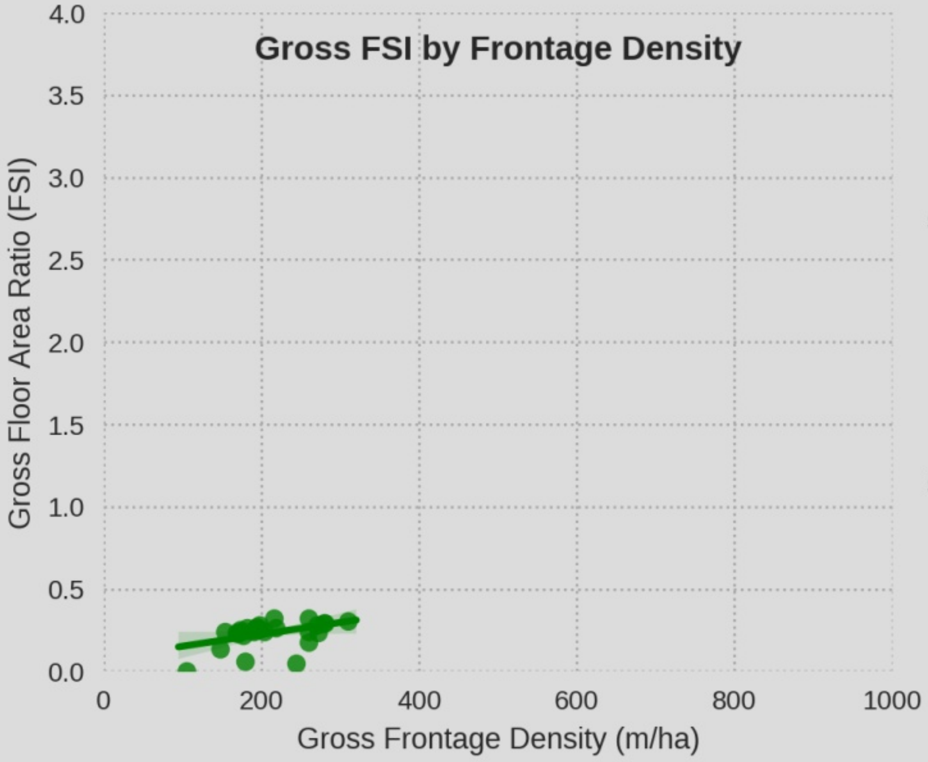


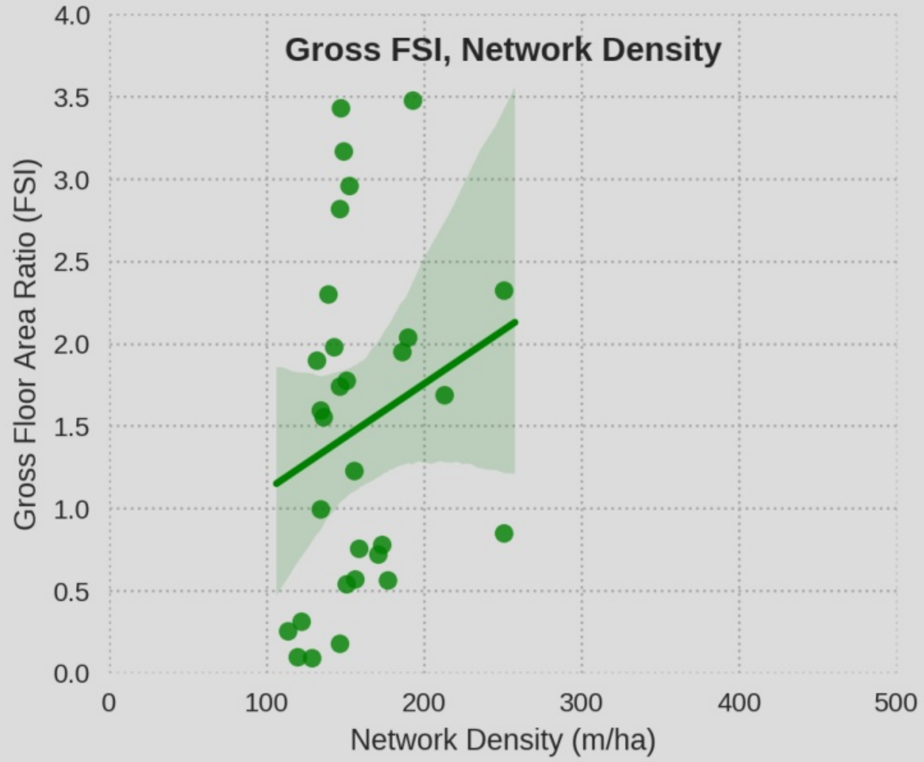



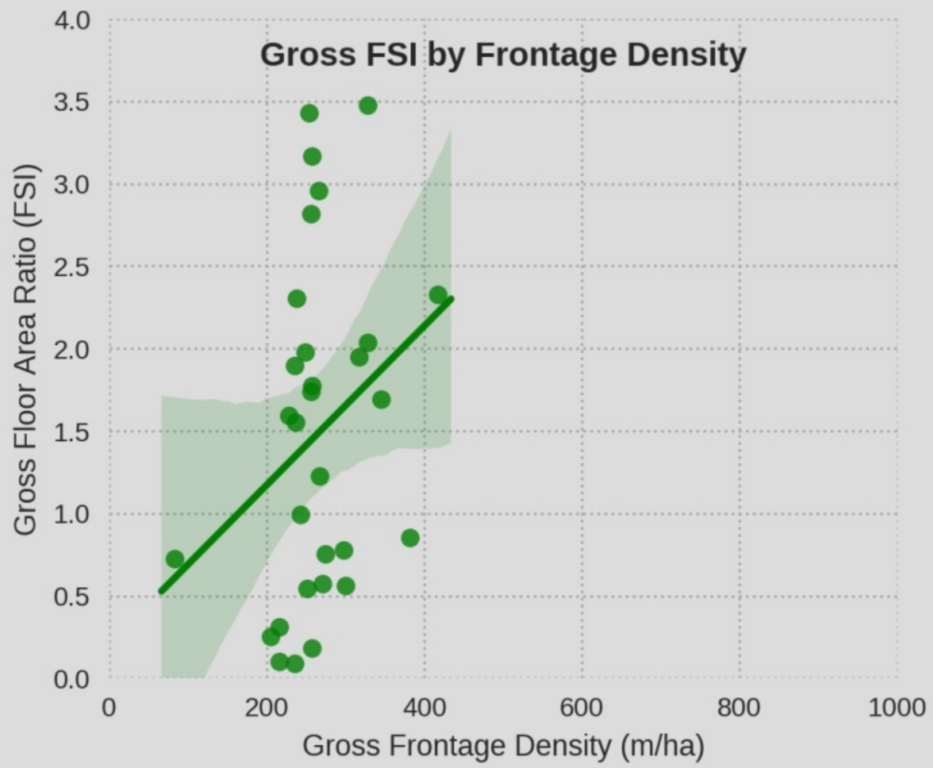
# Bromley - network density

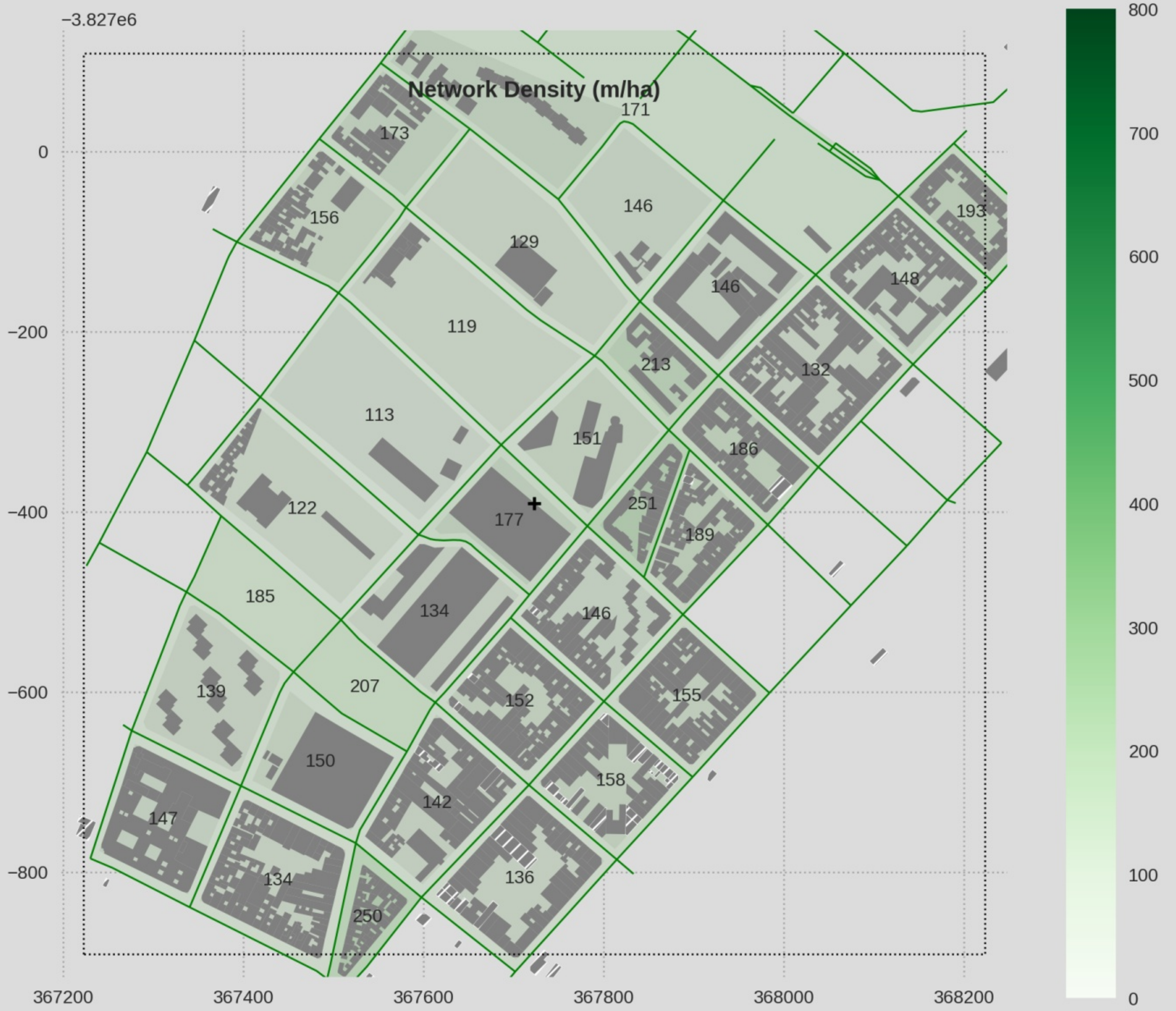


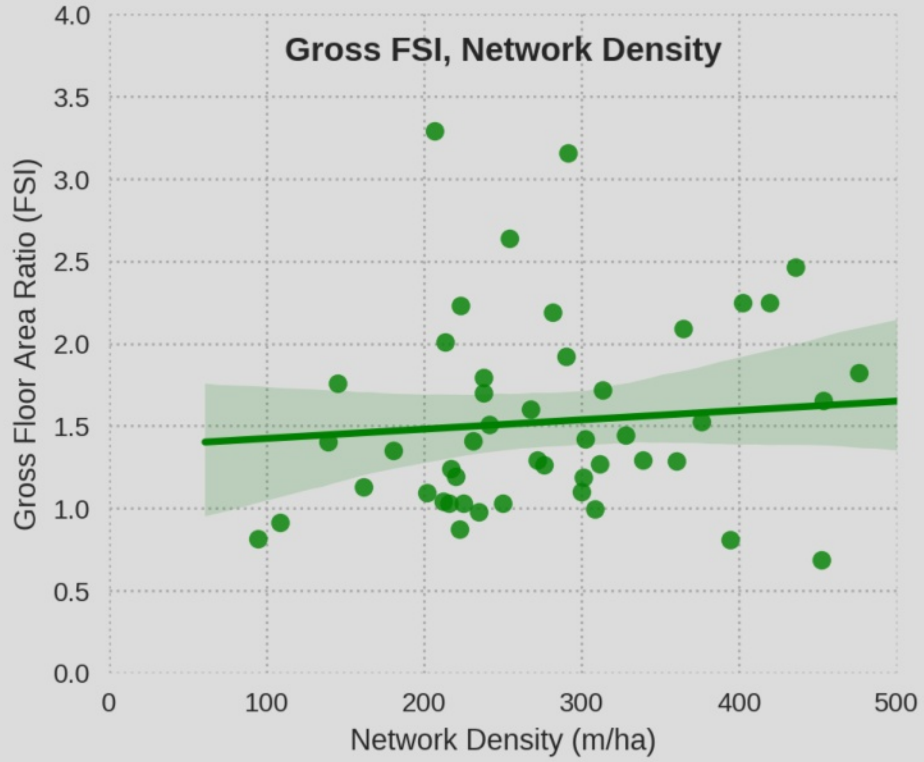

## Buenos Aires - network density

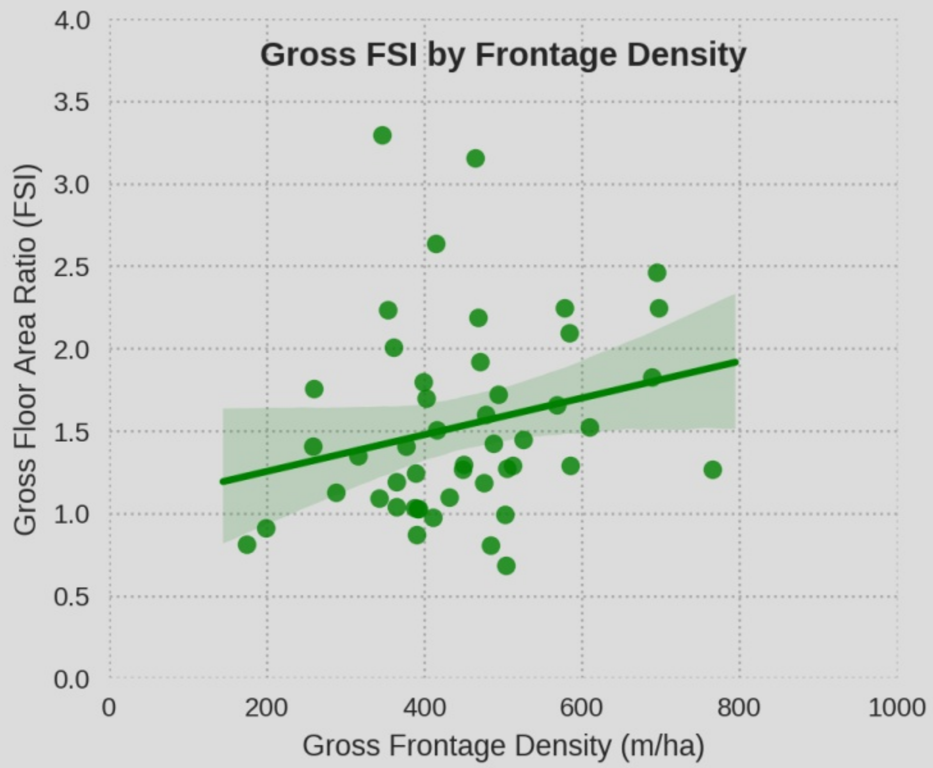


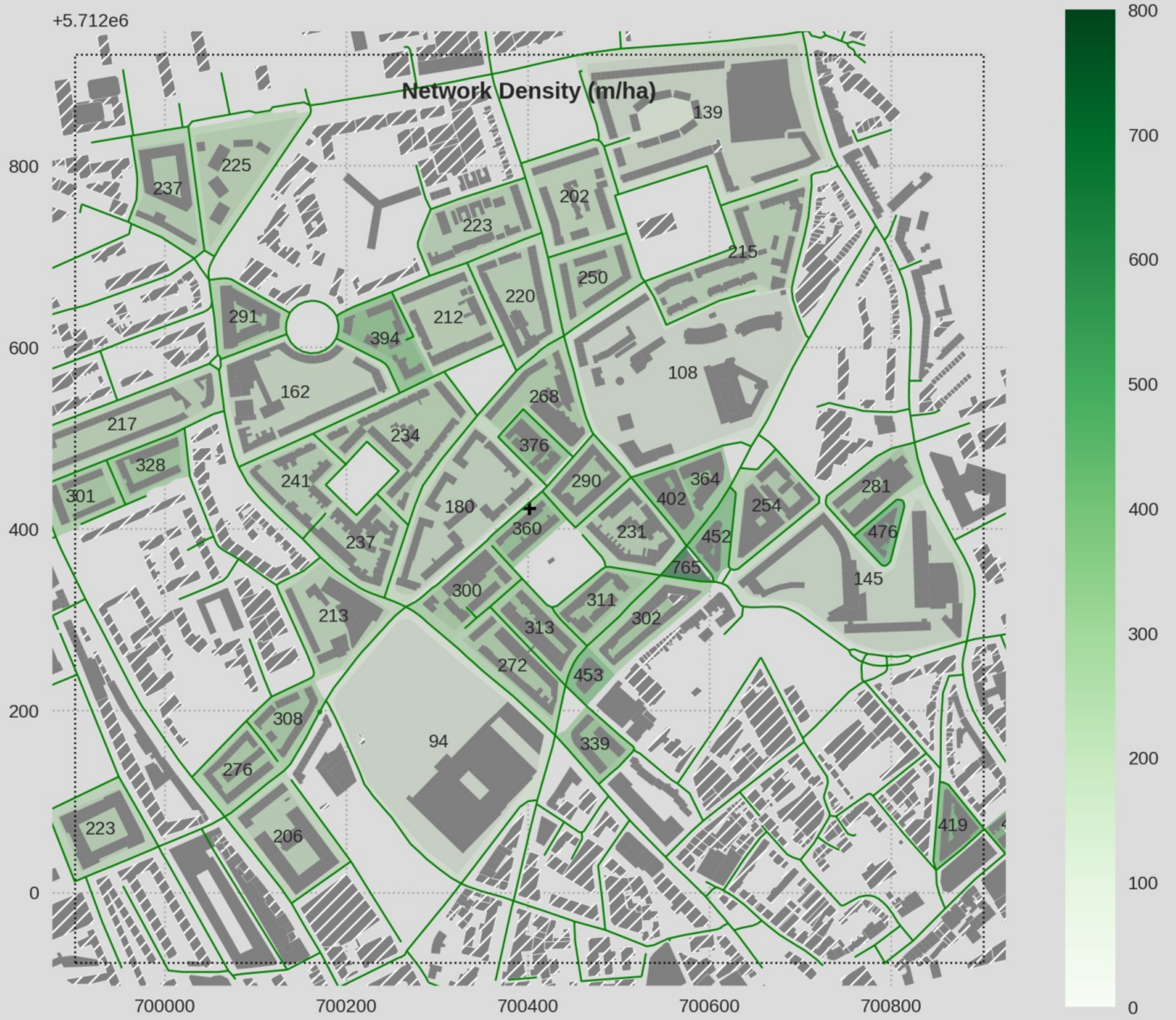



# Clerkenwell - network density



## Welwyn Garden City - network density