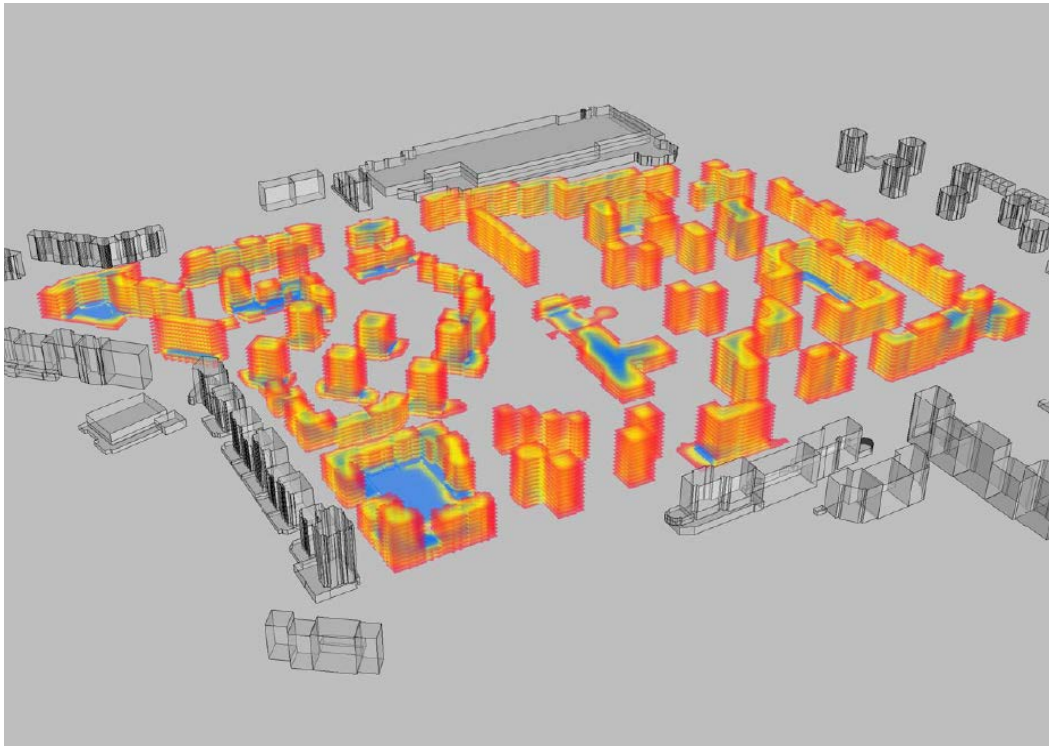


An approach on modelling urban form and energy performance in Lisbon, Portugal

IUPEA - International Urban Planning and Environment Association Conference, 31 May - 3 June, Lisboa, Portugal

João Fumega – IST and CEG (University of Lisbon)
Samuel Niza and Paulo Ferrão (IST-University of Lisbon)

GHG Emissions in urban areas

Urban areas contribute to GHG emissions through 3 vectors: direct, embodied and changes to atmospheric chemistry and albedo (OECD, 2009:35)

Energy consumption in cities is mainly used for electricity, thermal energy and transportation. Buildings represent nearly 40% of the total energy consumption (Salat, 2012)

Urban areas account for between 71 % and 76 % of CO2 emissions from global final energy use and between 67 – 76 % of global energy use (medium evidence, medium agreement) according to IPCC (2014:927)

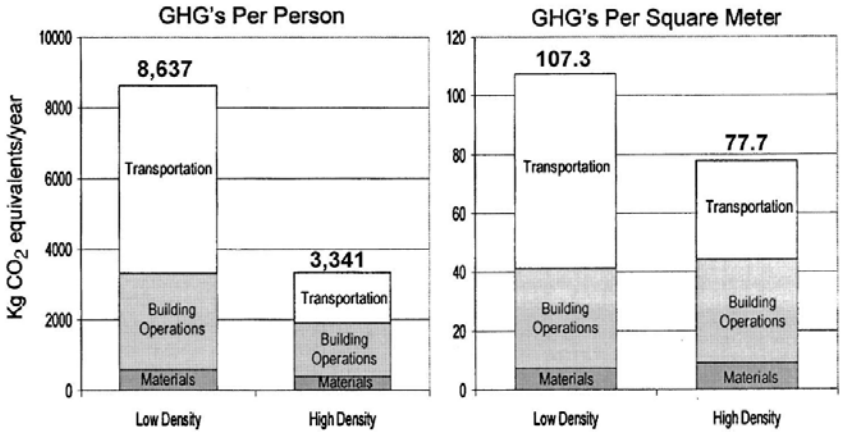


Fig. (up): Annual GHG emissions associated with low and high density development. Source: Norman, 2006

Urban Form

- Ferrão and Fernandez (2013:139-140) indicate that "[…] *urban form is a key element in the determination of prospects for urban sustainability*" due to:
  - Nature and intensity of resource consumption is highly dependent on the coupling of **population density and density of infrastructure and services**;
  - The **placement, scale and configuration** of the urban built environment affect the manner and intensity with which households, commercial spaces and industry consume energy and materials
  - The **dynamic interactions between buildings, open and green spaces, and urban infrastructure** and the corresponding concentration of heat and urban pollutants which originate unhealthy and energy intensive hot spots

- however "*morphological approaches to quantify energy consumptions and GHG emissions for the building sector remain rare*" (Salat, 2012:522)

Research on urban form on spatial metrics

- Urban research has focused its analysis in finding variables, developing models and tools with increased detail in order to better understand the complexity of urban systems

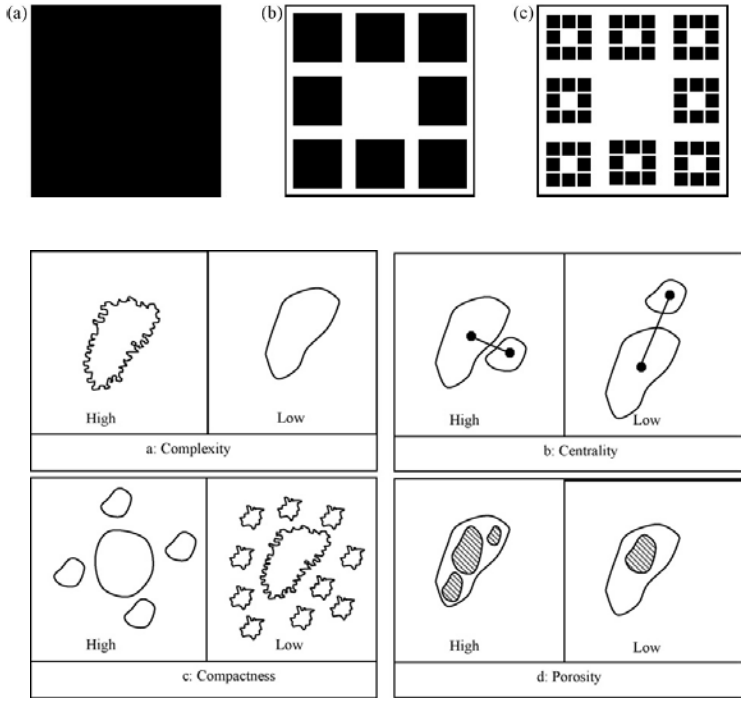


Fig. (up): First steps in generating a Fournier dust. Source: Thomas et al (2008:100). Fig. (down) metrics dimensions according to Huang and Sellers (2007:187)

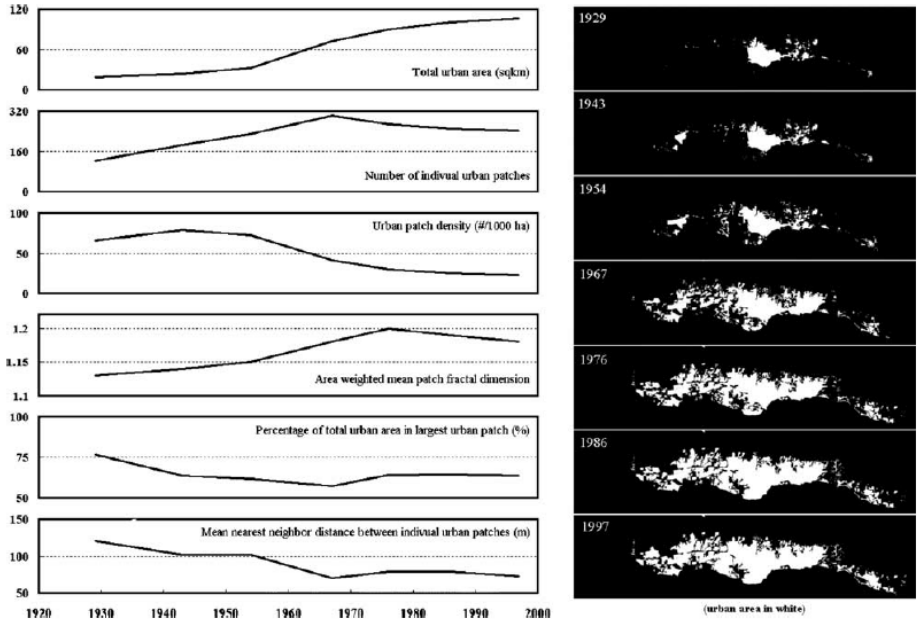
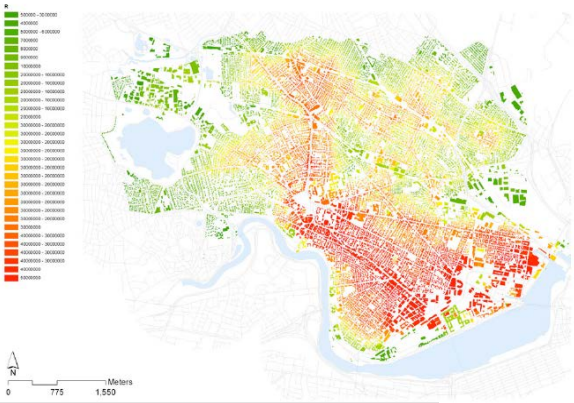
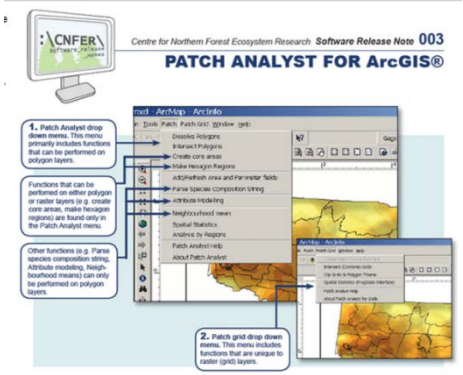


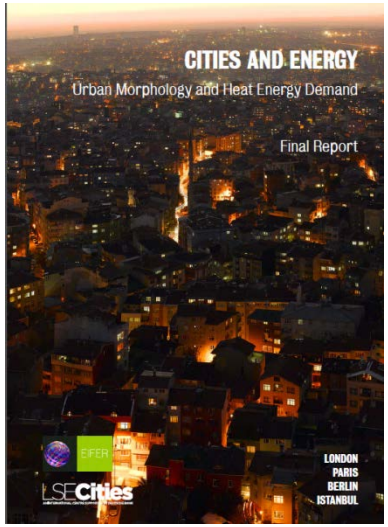
Fig. (up): Spatial metrics describing the spatial and temporal growth dynamics mapped from multi-temporal air photos in CA (1929-1997). Source Herold et al (2005:391)

Research on urban form





Tools



Reports

Fig. (Up): UMI tool developed at Sustainable Design Lab at MIT; Fig. (Middle). UNA tool developed at City Form Lab (Sevtsuk, A., Mekonnen, M., 2012); Fig. (below) Patch Analyst 5 (Rempel, R.S., D. Kaukinen., and A.P. Carr. 2012)

Case study: Lisbon urban form evolution

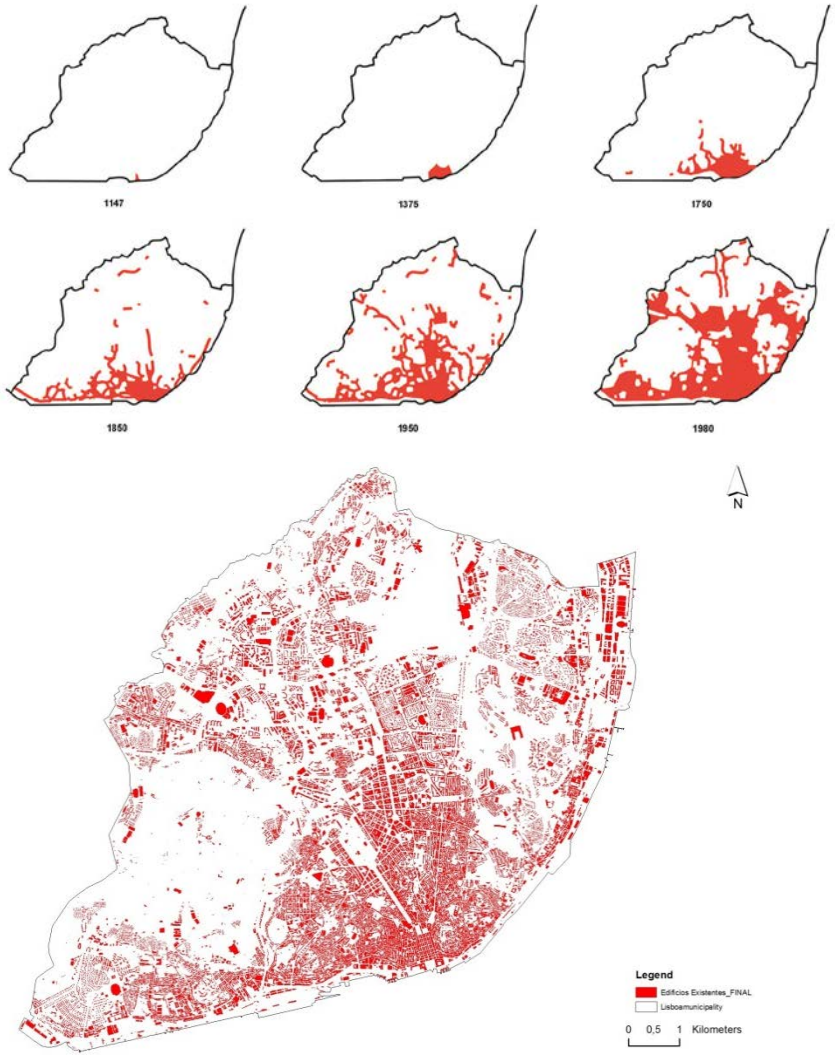
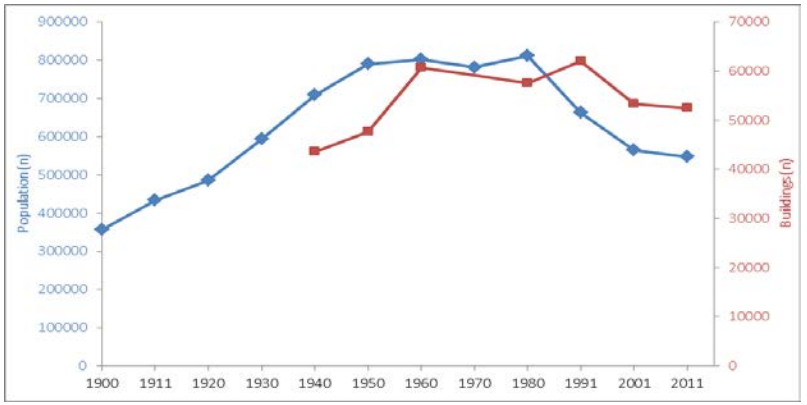


Fig.(up): Lisbon Metropolitan Area; Fig. (down): Urban structure in Lisbon from the 12th century till the present, Source: Marques (2003:22)



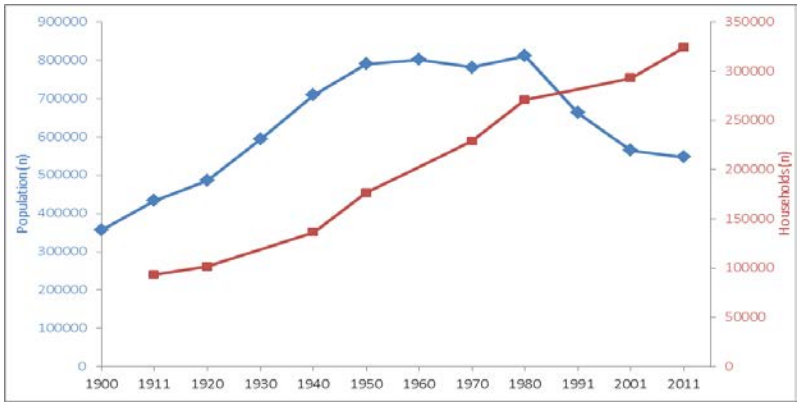


Fig. (up): Population and buildings evolution (number) through the 20th century in Lisbon. Source: Adapted from INE, PORDATA, Marques, 2003; Fig.(down): Population and households evolution (number) through the 20th century in Lisbon. Source: Adapted from INE, PORDATA, Marques, 2003

Lisbon: Predominant periods of construction

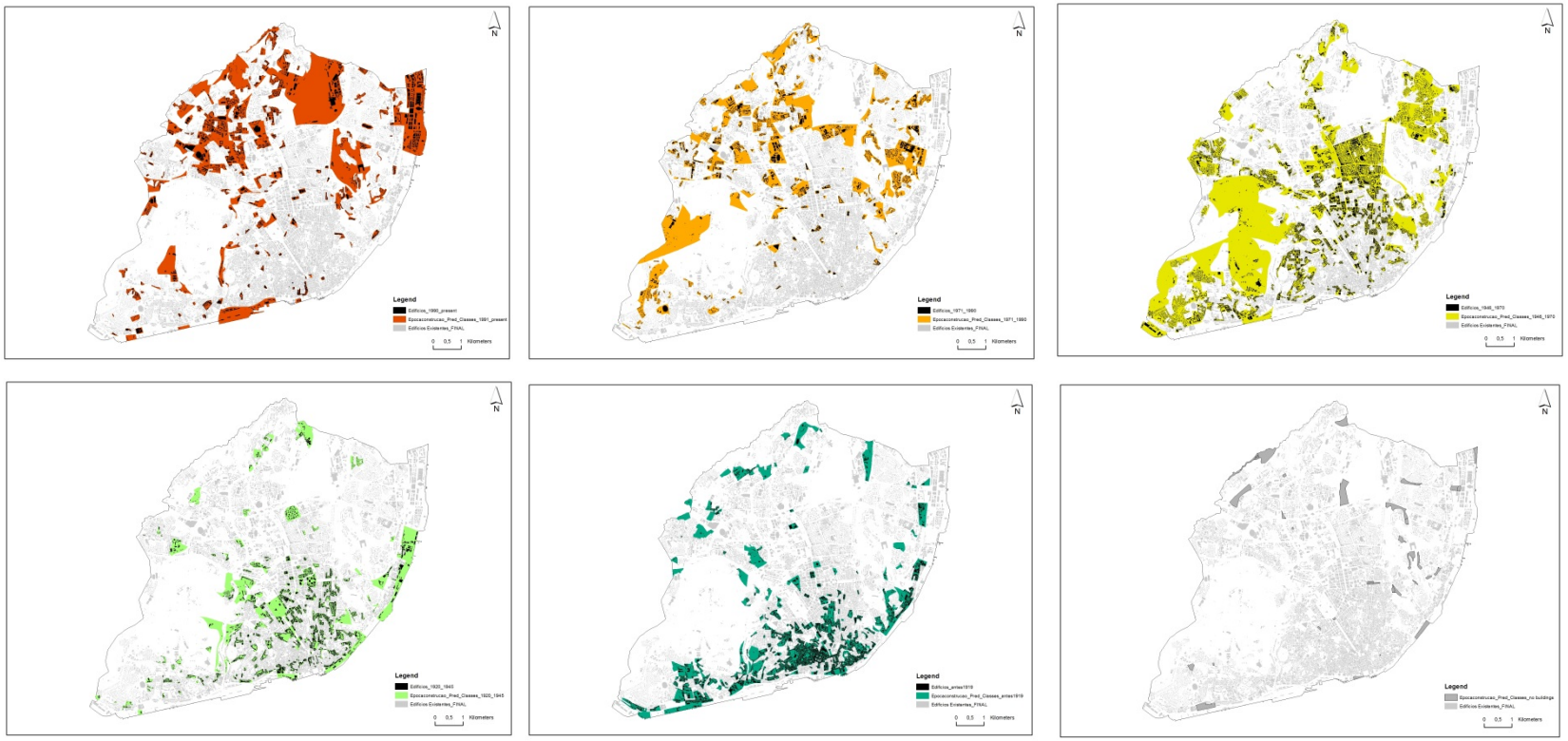
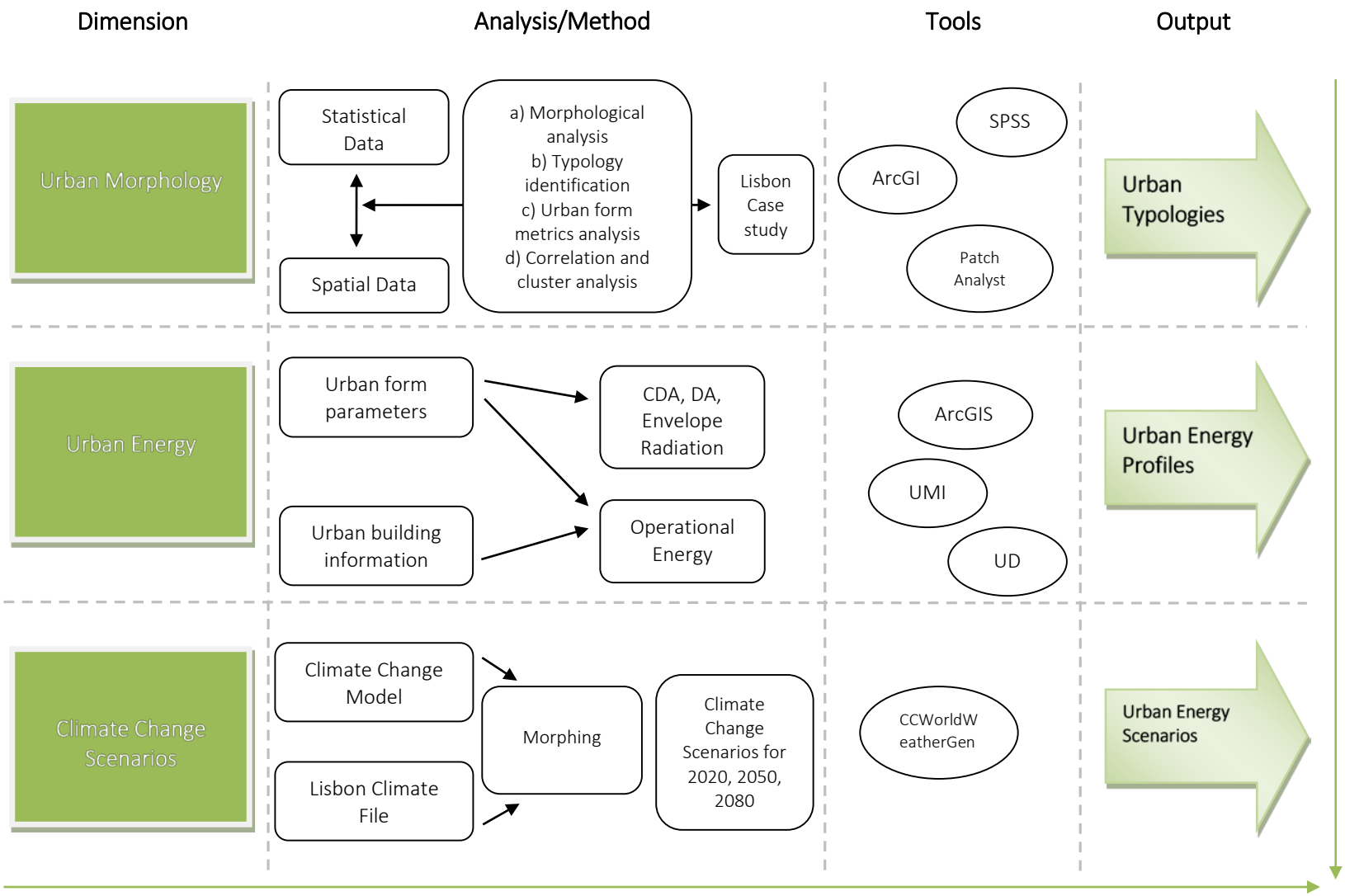
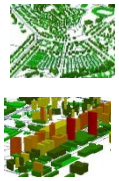


Figure (up): Distribution of buildings by the predominant period of construction classes in the city of Lisbon (with all classes and for each class): 1991-present, 1971-1990, 1946-1970, 1920-1945, before 1919, no buildings.
Source: Produced by the author (data from INE, 2011)

Methodology



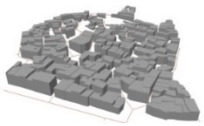
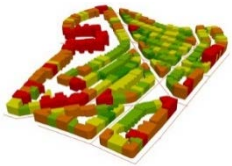
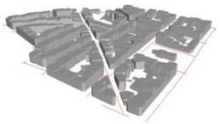
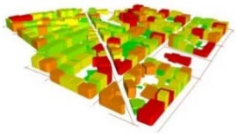
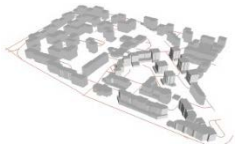
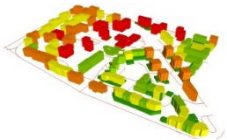
Urban Form Analysis: spatial metrics

Dimension	Spatial Representation	Description	Metrics	Definition
Complexity		Measures the building's design characteristics individually and as a whole at the neighborhood scale	- Mean Patch Fractal Dimension (MPFD)	Quantifies the degree of complexity of the planar shapes
			- Edge Density (ED)	Measures the number of edges of a certain shape
			- Surface-to-Volume Ratio (SVRatio)	The ratio of the envelope of a building (external facades and roof) to the entire volume of that building (sqm.)
Heterogeneity		Diversity of buildings sizes	- Patch Size Coefficient of Variation (PSCoV)	The variance in a certain area of the sizes of the shapes. It is a good indicator of the heterogeneity of buildings sizes across a typology
Compactness		Measures if the neighborhood is fragmented (clustered) with no or limited connection between its parts, or if there is a connection between buildings, therefore having a more uniform design	- Patch Density (PD)	A low patch density corresponds to highly dispersed areas, (low number of shapes per area), and a high shape density corresponds to more concentrated areas (a high number of shapes per area)
			- Average Near Neighbor (ANN)	A low ANN ratio corresponds to areas which are highly fragmented, and a high ANN ratio correspond to more compact areas
			- Coverage Ratio (CR)	The ratio of the sum of the building footprint areas to that of the sample area
Density		The vertical dimension of the neighborhood and the capacity to accommodate people, activities and transportation	- Floor Area Ratio (FAR)	Defined as the ratio of the sum of the areas of all building floors to that of the sample area
			- Average Height (AvHeight)	The average of the heights of all buildings in the sample area (m)
			- Road Density (RD)	Total road length dividing by total land area (m/sqm)

Urban Form Analysis: Typologies

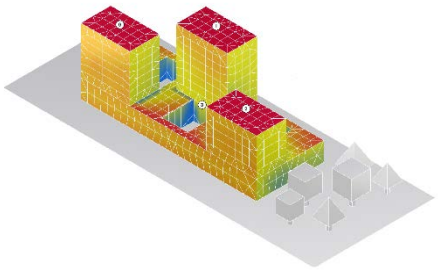
Typology/ Example	(1) Before 1919	(2) 1920-1945	(3) 1946-1970	(4) 1971-1990	(5) 1991-present
(1)					
(2)					
(3)					
(4)					
(5)					

Urban Form Analysis: new arrangement of urban typologies based on cluster analysis

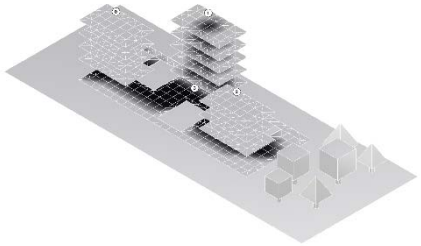
Cluster	Metric	Configuration	Height	Volume
CLUSTER 1 **Complex Urban Areas**	++ (1.00) Complexity -- (5.00) Heterogeneity + (1.67) Compaction + (2.33) Density			
CLUSTER 5 **Heterogeneous Urban Areas**	- (3.33) Complexity ++ (1.00) Heterogeneity -- (4.67) Compaction - (4.00) Density			
CLUSTER 2 **Elongated Urban Areas**	+ (2.00) Complexity - (4.00) Heterogeneity = (3.00) Compaction - (4.00) Density			
CLUSTER 3 **Compact Urban Areas**	= (3.67) Complexity = (3.00) Heterogeneity ++ (1.33) Compaction ++ (2.00) Density			
CLUSTER 4 **Modern Urban Areas**	-- (5.00) Complexity + (2.00) Heterogeneity - (4.33) Compaction = (2.67) Density			

Urban Energy Analysis: Metrics

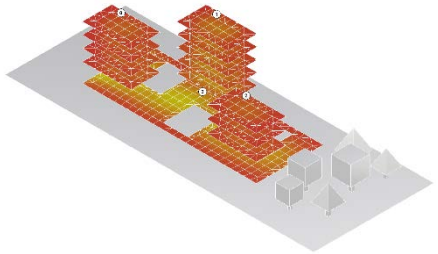
- **Passive Volume Ratio**: Ratti et al. (2004:772) "*Parts of buildings within 6 m of a façade present a significant reduction in energy consumption (almost 50%) compared with non-passive ones*"



- **Envelope Radiation**: the Envelope Radiation (ER) metrics assesses the accumulated solar radiation (MLux) for a given time frame, in this case for 1 year



- **Daylight Autonomy**: % of the floor area that exceeds 500 lux (value defined) for at least 50% of the time

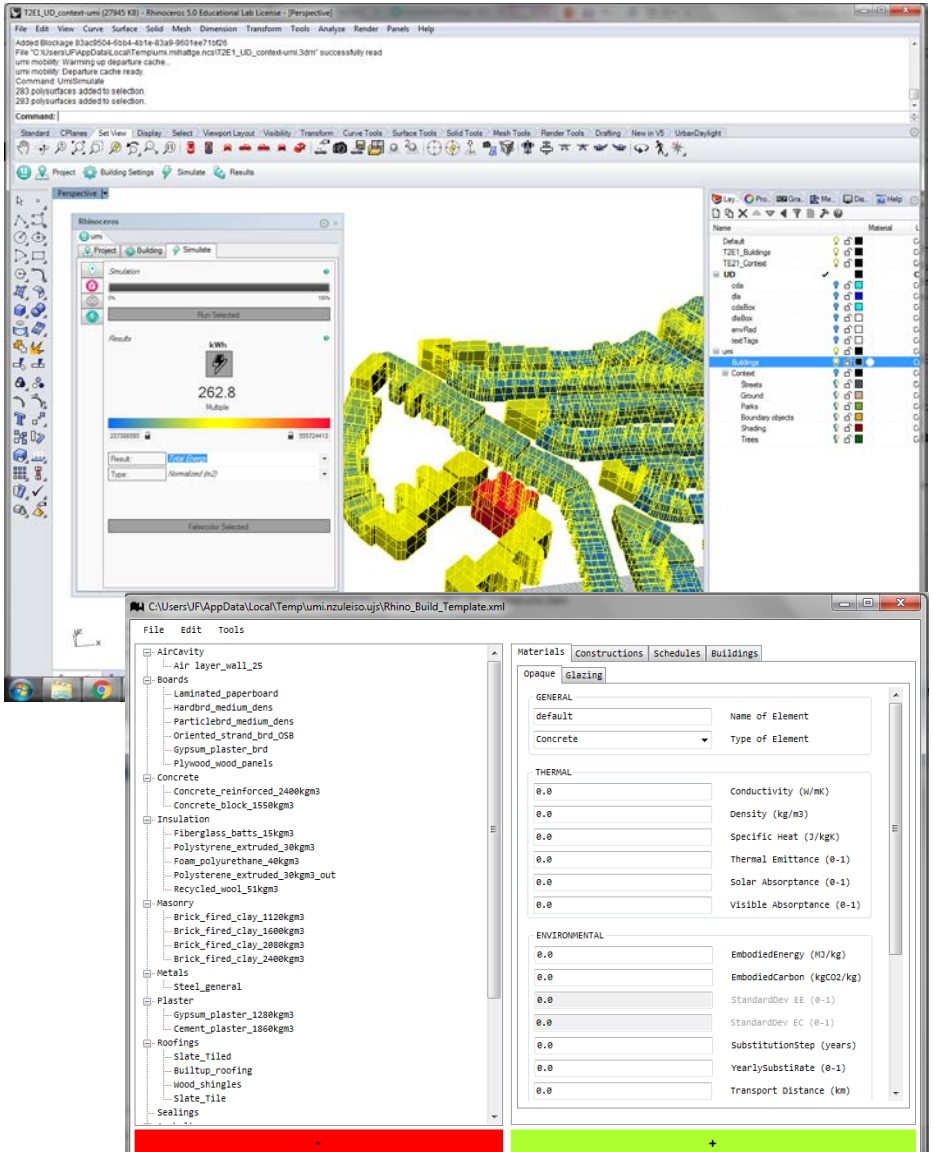


- **Continuous Daylight Autonomy**: % of the floor area that exceeds 500 lux for at least 50% of the time giving a partial credit for time steps below 500 lux.

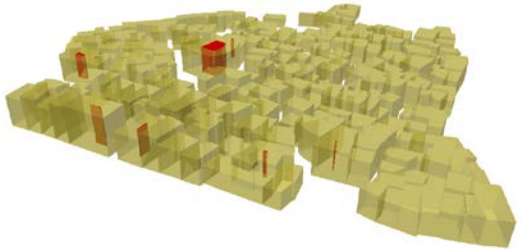
- **Operational Energy:** the amount of energy that is necessary for the building to run during 1 year. It takes into account the buildings specific characteristics, the shading of neighbor buildings and the blockage effect of contextual buildings.

Operational Energy: UMI Template and climate file

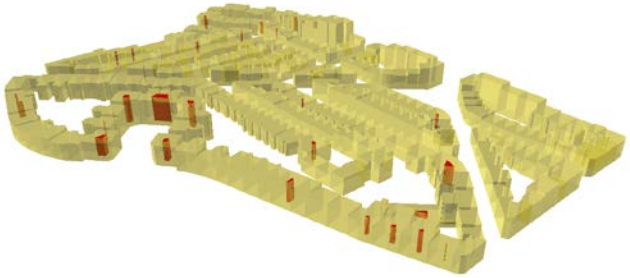
- The template file aggregates for each building general information; buildings construction materials; thermal loads; HVAC setting and lighting and shading;
- Template that was edited based on reference U-Values for a building in Portugal, Lisbon, according to ADENE;
- All typologies were given the same values, thus allowing to understand the effect of urban geometry on energy consumption, according to Ratti (2004) and Salat (2009)
- Climate file [epw.] used was the one for Lisbon (Lisboa 085360 - INETI))



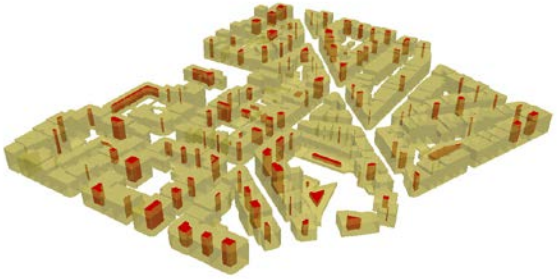
Urban Energy Analysis: Passive Volume Ratio



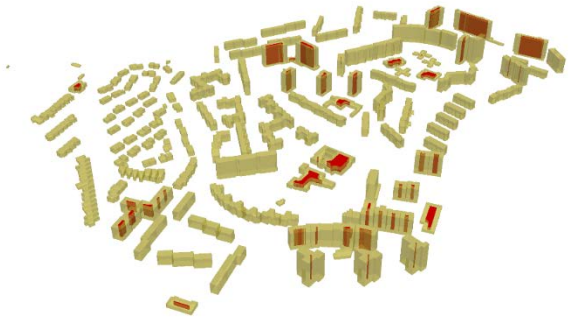
Complex Urban Areas (T1E1)



Elongated Urban Areas (T2E1)

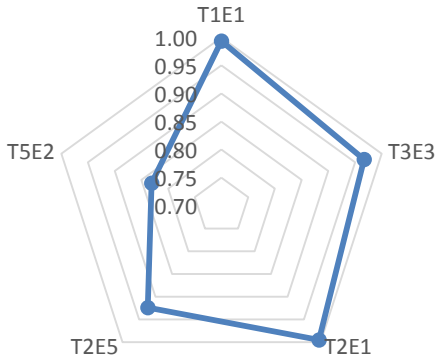


Compact Urban Areas (T2E5)

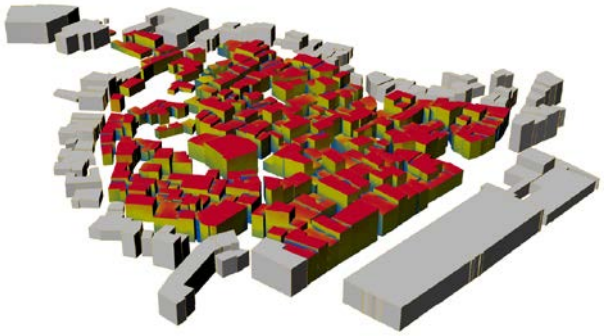


Heterogeneous Urban Areas (T3E3)

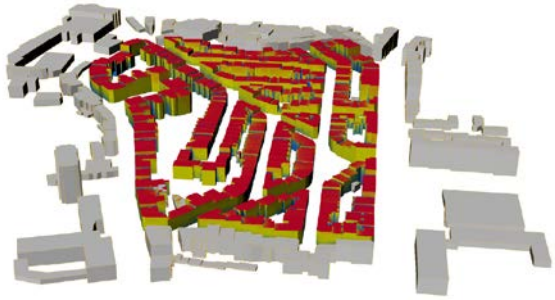
Modern Urban Areas (T5E2)



Urban Energy Analysis: Envelope Radiation (Mlux/envelope area [m2])



Complex Urban Areas (T1E1)

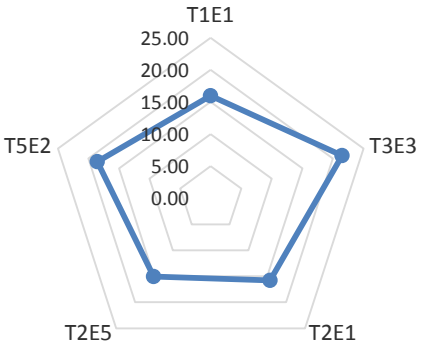


Elongated Urban Areas (T2E1)

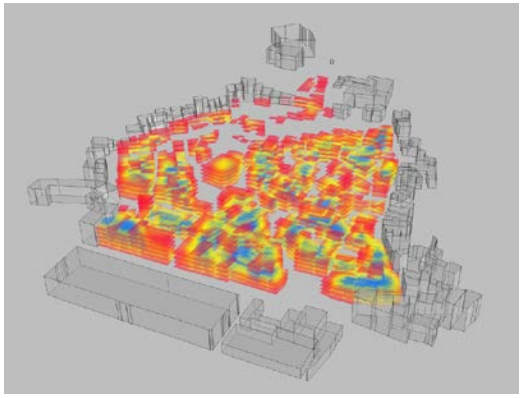
Compact Urban Areas (T2E5)

Heterogeneous Urban Areas (T3E3)

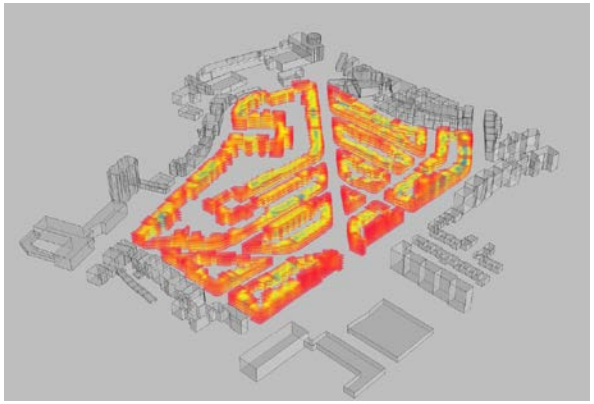
Modern Urban Areas (T5E2)



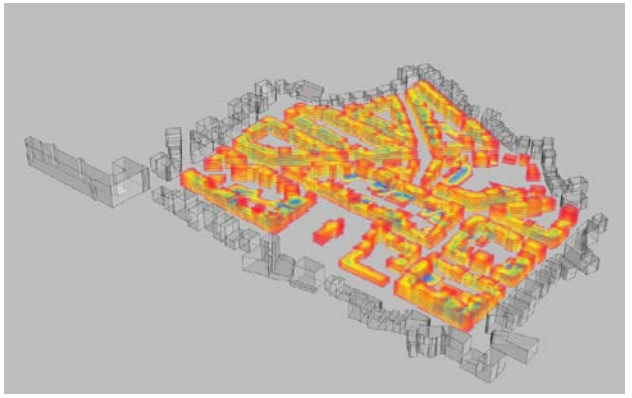
Urban Energy Analysis: Continuous Daylight Autonomy



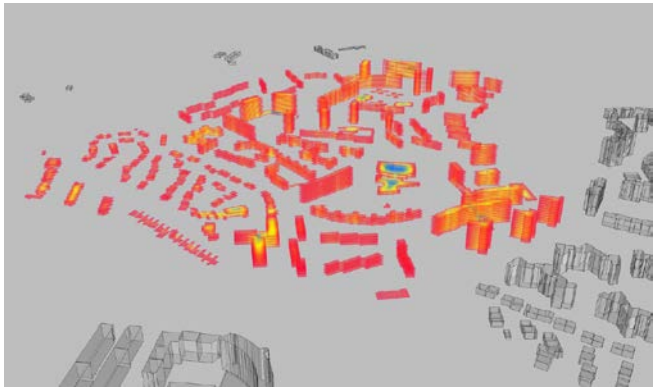
Complex Urban Areas (T1E1)



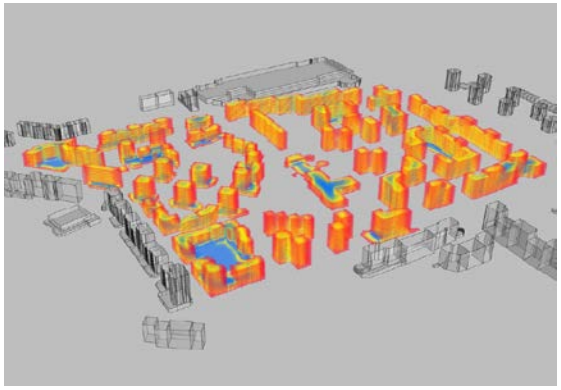
Elongated Urban Areas (T2E1)



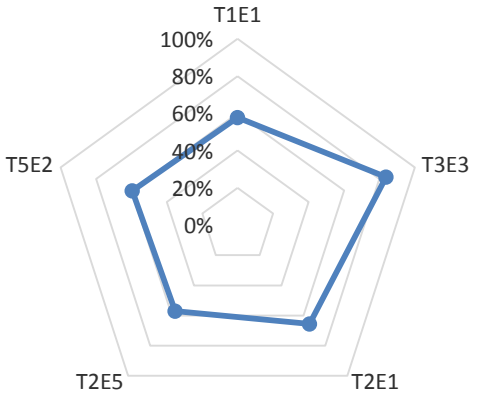
Compact Urban Areas (T2E5)



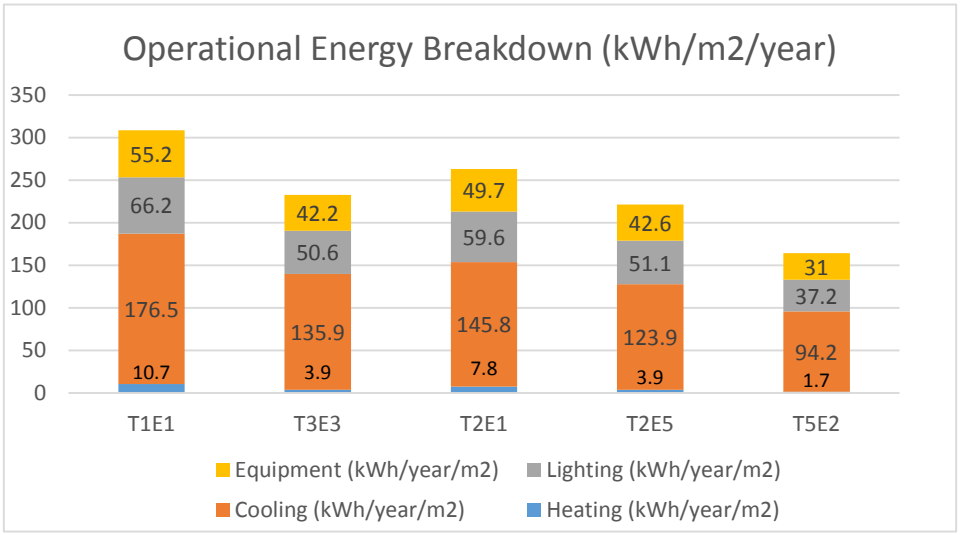
Heterogeneous Urban Areas (T3E3)

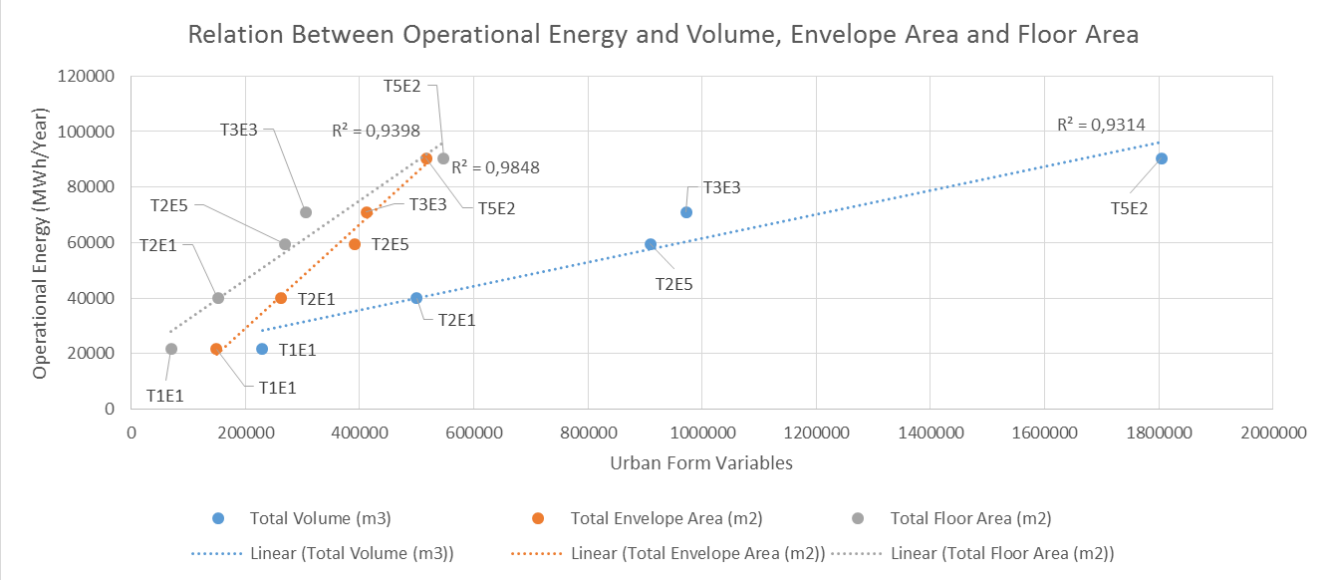


Modern Urban Areas (T5E2)

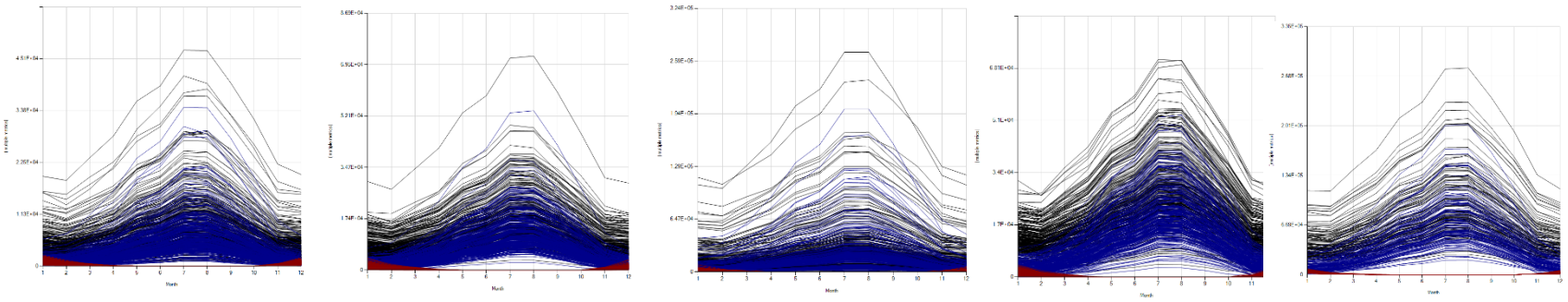


Urban Energy Analysis: Operational Energy





Urban Energy Analysis: Operational Energy (kWh/year)

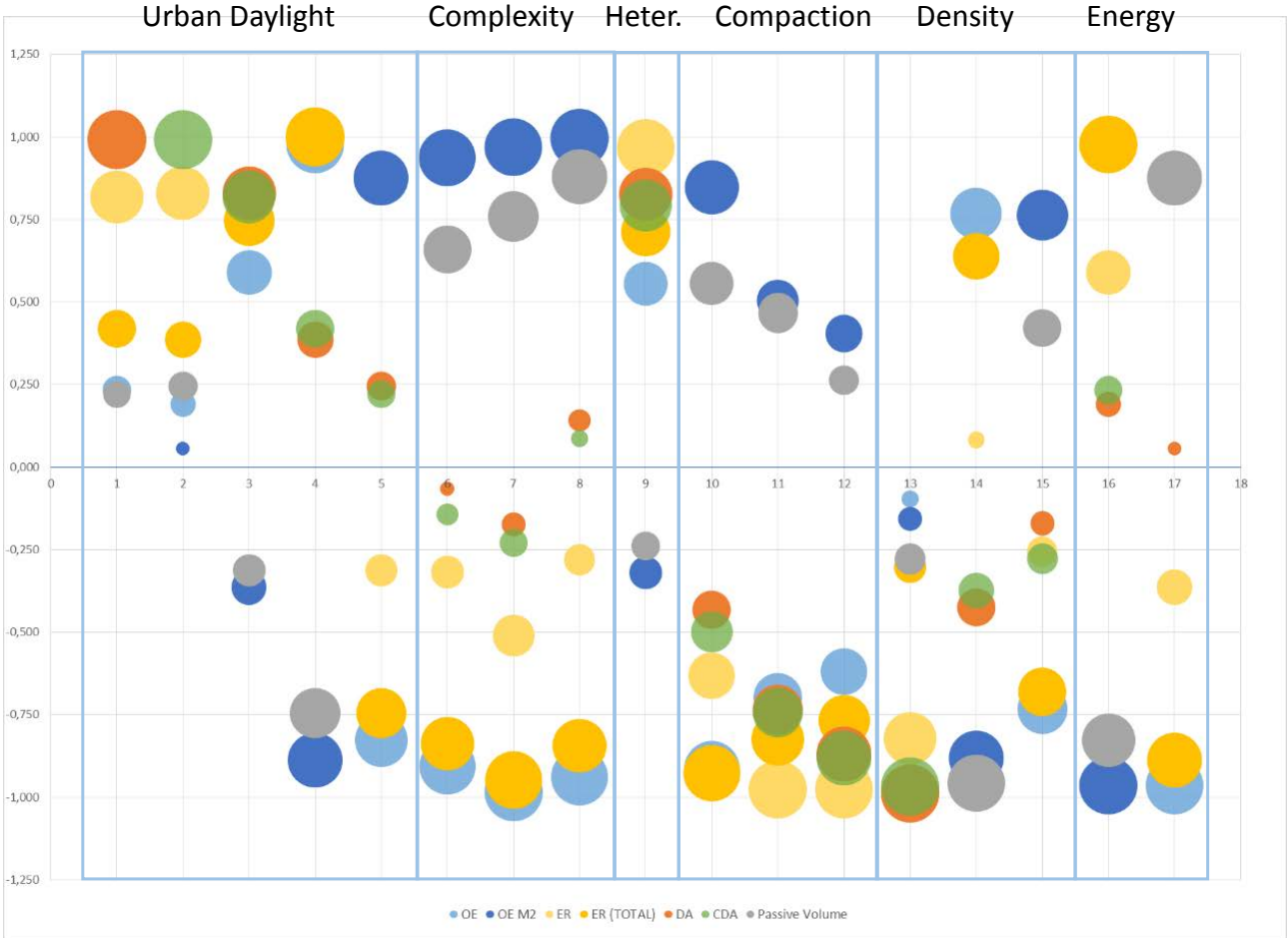


Total

Cooling

Heating

Correlations between urban form and energy



Complete set of correlations. Bubble size is equivalent to the correlation strength. X-Axis correspondence: A) 1- CDA, 2- DA, 3- ER (m2), 4- ER (total), 5- Passive Volume Ratio; B) 6- MPFD, 7- ED, 8- SVRatio; C) 9- PSCOV; D) 10- PD, 11- ANN, 12- CR; E) 13- FAR, 14- AVHeight, 15- RD; F) 16- OE, 17- OE (m2)
Source: Produced by the author

Conclusions

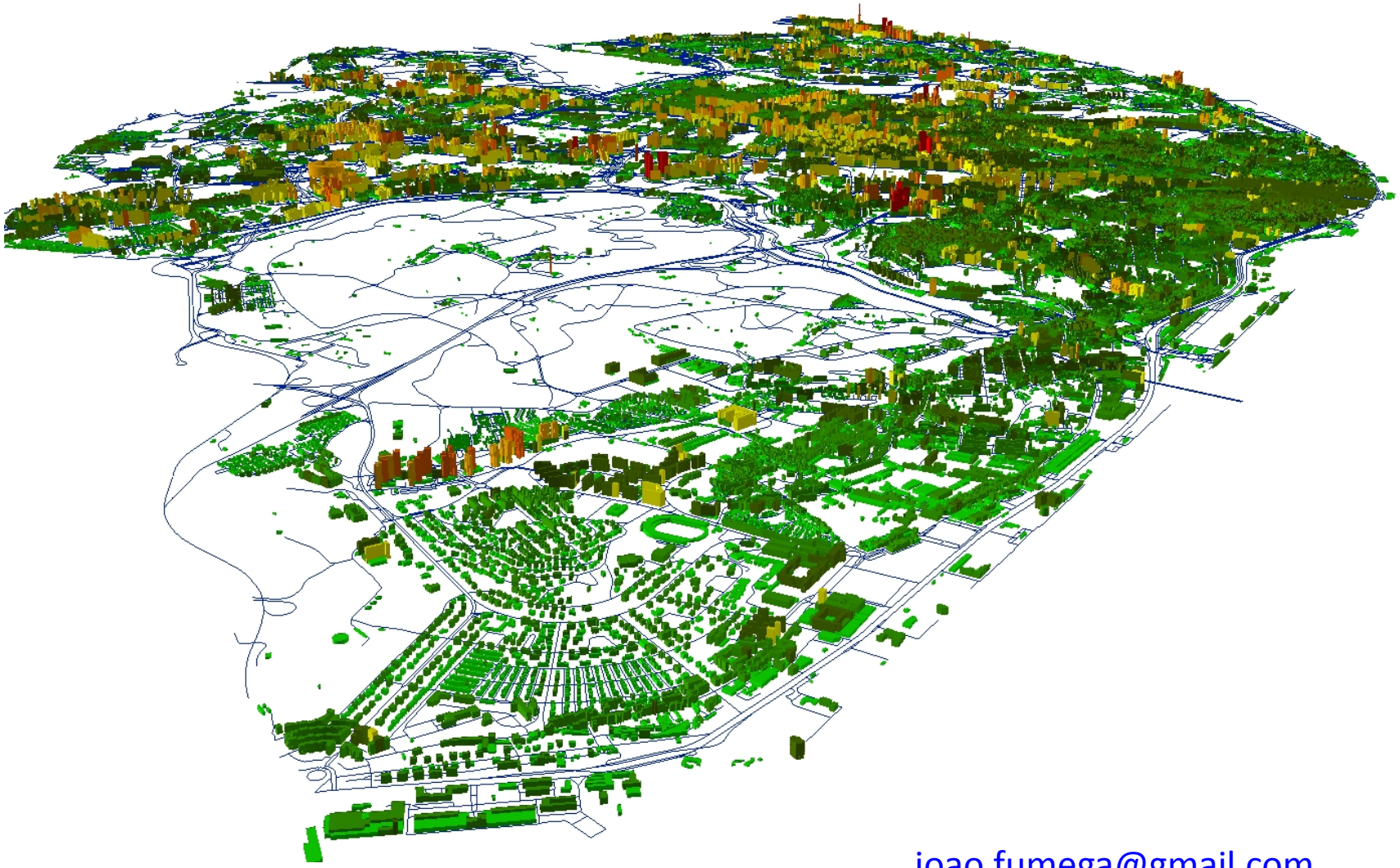
- When displaying the complete set of correlations between urban daylight metrics and operational energy and urban form metrics, and among urban daylight metrics and operational energy, it is possible to understand some tendencies:

  - Urban daylight metrics correlate mainly with themselves, also with operational energy
  - Urban complexity is positively correlated with operational energy
  - Heterogeneity is positively correlated with envelope radiation
  - Urban compaction is negatively correlated with urban daylight, particularly envelope radiation
  - Urban density is negatively correlated with daylight autonomy and passive volume
  - Operational energy (m2) correlates positively with envelope radiation, and to some degree, with passive volume ratio

Conclusions

- The following conclusions refer to the typologies presented and also to the specific climate of Portugal, Lisbon:
  - Urban daylight access is critical for understanding energy demand;
  - Typologies with a high passive volume ratio consume more energy;
  - Typologies with very complex urban forms tend to consume more energy, this can also be related with urban daylight access;
  - Typologies that have a more heterogeneous urban form, allow more solar exposure and therefore a higher envelope radiation;
  - On the other hand, compact and dense typologies have lower levels of daylight access.
- This way, the typologies that performed better are the ones that have medium to low levels of complexity and heterogeneity and medium to high levels of compaction and density
- This is a complementary approach for analyzing urban form, being that a context analysis together with a historical and socio-economical anaylisis should always be made.

Thank You.



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