Energy and urban form:
A top-down assessment tool

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ABSTRACT: This paper explains the development and validation of a tool to estimate energy demand in cities, neighbourhoods or urban samples from morphological parameters such as density (GSI and FSI), compactness (Comp) and Orientation Ratio. The tool can additionally perform sensitive analysis of building-related attributes at urban scale, including floor height, glazing ratio, insulation, thermal capacity or albedo. The calculation process is based on a notional grid that retains the critical characteristics of the original urban fabric to determine energy demand. Then, it applies a 14-steps routine to obtain loads for heating, cooling and lighting. The whole process has been automatised using a spreadsheet, so that calculations are instantly performed. The model incorporates different specifications and default values for different building types and it provides output results accordingly. The outputs are given as useful load per square meter of construction (built up area) for each building type or as average primary energy per land area. Unlike most energy tools, this application starts from urban scale parameters. Estimations for large urban areas can be quickly performed from a top down approach. Applications of the model have been developed in three different formats: "Spreadsheet", which provides the most accurate results while allowing a great flexibility. "Regional diagrams", which take a graph format and finally, a GIS integrated tool to produce city-wide energy density maps.
Keywords: energy, urban morphology, GIS, cities

INTRODUCTION

The debate about the less unsustainable city forms has taken a prominent place in the field of urban studies in the last two decades. A number of arguments have been used either to praise or to undermine the characteristic configurations in which cities have evolved. These have been repeatedly defined by quantifiable attributes, such as density or compactness, which drove the discussion to the comparison between antithetic models: high density versus low density, compactness versus sprawl, etc.

The criteria to evaluate the goodness of city form have ranged from business minded terms such as economic advantage and competitiveness to more user-oriented concepts like liveability or urbanity. However, urban metabolic studies in the late seventies and early eighties [1] had raised the awareness about the resource voracity of towns and cities and hence energy, water or waste became main priorities in the attempts to improve urban efficiency.

Research was then asked to provide new analytical techniques and objective energy estimations to assist propositions of new buildings and cities. In the last decades, thermodynamic processes at building scale have been described and simulated with great accuracy. Many energy packages are currently available to test the performance of design solutions for individual or multiple buildings (e.g. Energy Plus, EDSL TAS, ESP-r and many others). However, none of them has been developed at urban scale, in the traditional sense that urbanism has understood cities, as global entities, rather than a collection of buildings. Most of the existing energy models are not applicable to urban planning because they have been developed at building level. When these models are employed to analyze wider areas, with several buildings, they quickly become unmanageable because every building has to be drawn up and modelled individually. This bottom-up approach is so far unrealistic for city-wide assessment due to time and computing limitations. Moreover, the high complexity of a model does not imply greater accuracy as structural uncertainty can effectively lead to the magnification of errors [2].

In this paper, a top-down methodology to perform large scale comparative energy analysis is proposed. This method consists on the adaptation of well established calculation procedures to planning practice, in such a way that inputs are extracted from the characteristic parameters of the urban fabric rather than from individual buildings. It should not be regarded as an ultimate assessment tool but as an instrument to explore and compare the performance of existing or proposed urban configurations. The model relies on several mathematical hypotheses which were used to simplify the geometric description of urban typologies with few key parameters. Both the model and the assumptions have been tested against alternative energy software tools and results showed a strong correlation. It has been noticed that the accuracy of the model is higher for moderately dense urban areas than for suburban or garden-city like environments. However, the large distance between constructions that characterize low density dilutes the "urban effect" and building interaction, hence bottom up energy models can be still deemed effective in those cases.

PRECEDENTS

Two precedents have to be acknowledged as having a special influence on the development of this application: the LT method and the Energy Index. They share some common characteristics such as simplicity and ease of use as priorities. Although they were developed some fifteen years ago, they are still useful as their strength is based on the intuitive associations that can be drawn in a quite straightforward interaction. Both models are still being applied, either as background model embedded in broader software packages (i.e. LT in Climatelite) or as consultation spreadsheet for preliminary assessments and to set performance targets (EI). The description of these precedents goes beyond the scope of this paper. However, detailed explanations can be found in references [3] and [4].

The main learning outcome extracted from LT model and Energy Index lays in the potential of simplification to develop manageable environmental design supporting tools. Simple models produce reasonable results from relatively few input parameters and some predefined assumptions. Urban morphological studies can benefit from a tool that provides information about energy performance in this way. If the analysis is circumscribed to variables that are familiar to urbanists, the evaluation becomes simpler and energy aspects can be integrated in planning decisions.

PARAMETER VALUES

The use of models has a long tradition in urban planning. The systemic approach to urbanism emerged in the fifties and reached a great projection in the sixties, before it fell into abeyance in the early seventies. Douglas Lee, the same who had written the celebrated obituary of urban models in 1973 [5], qualified his earlier remarks in 1994 [6], when systemic approach was being reinvented. He also pointed out some sort of guidelines that would facilitate the full potential of models to be delivered. Those observations were observed in this model and can be summarized as follows:

1. The most important attribute of a model lays on its "transparency". Big "black box" models are to be avoided as they do not allow a direct investigation of the points of disagreement.

2. The balance between theoretical basis, objectivity and intuition should be a major aim. Overemphasis on any of those aspects may lead to loss of contact with reality, empty-headed empiricism or erratic problem solving.

3. Models shall start from the clear definition of the problem to be addressed and the selection of the most adequate method to solve it. The opposite of this was the application of methods just because they needed to be tested or because were novel.

4. Build only very simple models. The modeller has the capacity to discern what to disregard in building the model. Complex models do not work better and they cannot be understood by others [6].

Two of the most important objectives that were considered in the elaboration of the urban energy model described in this paper have been simplicity and legibility. For this reason, much work has been devoted to the extrapolation of knowledge and relevant factors from buildings to the urban scale. In this transition from building to urban scale two essential prerequisites were taken: first, the input parameters had to be limited and familiar for urban professionals and, second, the characterization of urban fabric by these parameters had to be univocal and systematic.

The identification of relevant parameters was inspired by classic morphological studies and recent multivariable definitions. Classic morphological studies were, however, more concerned on qualitative typological analysis than on the quantitative definition of urban form. In planning practice, quantitative standards had been a common instrument since the second half of the nineteenth century, when the industrial revolution brought about massive migrations and the earliest problems of urban overcrowding. During the twentieth century, density was probably the most widely used indicator for both describing structural problems and regulating the growth of cities. Density is still a poor indicator that hardly reflects the spatial properties of the urban fabric. To overcome the ambiguity and potential bias of density, the Floor Space Index (FSI) was proposed in 1948 as a common measure in Europe [7]. The FSI indicates the total floor area that is built over a delimited region (a plot, block or city zone) per unit area.

However, a number of different urban typologies are defined with the same FSI. The measure of land coverage is a complementary indicator that gives, together with the FSI, a univocal definition of urban form. It expresses the proportion of land that is occupied by buildings. It has been extensively used in planning since Cerdá's plan for Barcelona (he had prescribed plot coverage of 50%). Every combination of FSI and coverage can be related to a specific urban typology, limiting the range of possible variations.

The model described in this paper uses FSI and GSI as main input parameters. The research hypothesis is based on the assumption that the combination of these two variables together with the compactness of the urban fabric contains enough information to make meaningful estimates of energy performance on large urban areas. Thus the main input parameters are:

- **Floor Space Index (FSI).** It represents the gross built up area per land unit. It includes all uses and floors above ground level. It is measured in m^2/m^2 and it is a typical descriptor of density in urban plans.

$$FSI = TFA / A$$

FSI: Floor Space Index (m^2/m^2)
TFA: Total Gross Floor Area (m^2)
A: Gross Area of the land unit (m^2)

- **Coverage or Ground Space Index (GSI).** It illustrates the proportion of land that is occupied by buildings. In this indicator, only the building's footprint is computed and divided by the total land area.

$$GSI = GFA / A$$

GSI: Ground Space Index (m^2/m^2)
GFA: Total Ground Floor Area of all buildings (m^2)
A: Gross Area of the land unit (m^2)

- **Compactness Ratio (Comp).** This parameter is not so common in urban planning but it is important in buildings' performance. It is defined as the proportion of external envelope in relation to the floor area. A similar variable is used at building scale to illustrate the degree of exposure of the internal spaces to the external environment. A large envelope to floor proportion would enhance heat flow and, depending on climate and materials, penalize energy consumption.

$$Comp = Env / TFA$$

Comp: Compactness Ratio (m^2/m^2)
Env: Total External Envelope Area (m^2)
TFA: Total Gross Floor Area (m^2)

The model also takes into account other parameters that are initially assigned default values to allow quick estimates. However, they can be altered according to the analyst judgment. They have been considered as secondary parameters due to their relative influence in dense urban areas, the large margin of error that is possible in the measurement of the parameter or because they refer to building elements rather than to urban typologies:

- **Orientation Ratio (Or).** The orientation ratio refers to the proportion of elevations that are orientated in each direction, assuming that every urban typology has two main axes. This has been proved consistent in the 28 urban samples that were analyzed in the development of the model. More specifically, the Orientation Ratio is defined as the proportion between the area of the elevations oriented to the main axis to the elevations oriented to the secondary axis.

- **Typical Floor Height (fh)** The floor height is used to calculate the average building height in meters. The proportion FSI/GSI will provide an estimate of the average number of floors for the whole area. The mean height can then be obtained by multiplying that number for the typical floor height.

- **Glazing Ratio (Gr).** The Glazing Ratio is defined as the proportion of façade that is taken by windows and glazed elements. In building assessments, the position of windows in each orientation has to be specified. In urban assessments, it can be assumed that the distribution of openings is homogeneous in all façades of the sample if no detailed account has been provided.

- **Construction type (Ct).** The type of materials and construction systems can be inferred from the age of the buildings in each part of the city. The insulation level has a significant effect in energy studies. The influence of form in heating and cooling loads will tend to diminish when buildings become highly insulated.

- **Thermal capacity (Tc).** The thermal storage capacity indicates the potential to accumulate excessive heat and release it sometime afterwards. It will be used to take account of dynamic heat flows by its correlation with the utilization factor, which is the ratio of useful solar heat gains to the total solar gains.

- **Albedo(ρ)** The albedo represents the reflectance of external surfaces and it is used to calculate reflected component of solar radiation and daylight factor. A high albedo typically corresponds to a clear surface and it means that solar reflectance is greater. A default value of 0.2 is used as it is typical in urban surfaces.

These parameters are complemented with details regarding the location and specific context of the study area, including climate and latitude. If land use and building types breakdown are known, they can be also included and computed as input parameters.

THE MATHEMATICAL MODEL

The strategy devised for the urban energy model consists of a fundamental hypothesis and two main calculation stages.

Hypothesis: The average energy demand for heating, lighting and cooling from buildings in a moderately dense, regular or irregular, urban area is analogous to the demand of a notional regular grid which has retained, from the original urban fabric, information of the following parameters:

- Built footprint (GFA)
- Total built up area (TFA)
- Envelope's Area (Env)
- Buildings' perimeter (P)
- Proportion of façades facing the main orientation quadrant to façades facing secondary orientation quadrant (Pn-s/Pe-w)
- Average obstruction angle in two main axes (θ)
- Built volume (V)
- Average building height (h)
- Average number of storeys (f)
- Glazing ratio (Gr)
- Construction type (Ct)

Stage 1: The first step in the calculation process consists on the transformation of the real urban fabric into the notional characteristic grid that preserves all the aforementioned parameters. This is done through a series of predefined algorithms that were theoretically inferred and validated with real samples and the aid of GIS.

Stage 2: The second step consists on the calculation of the energy demand for heating, cooling and lighting, as associated to the notional grid. For this process, a simplified energy model is used and adapted to urban characteristics. The calculation procedure contains fourteen steps which are embedded into a spreadsheet for ease and speed. A GIS application has been also produced. So far, the GIS is based on the Regression Analysis validated with the spreadsheet tool.

NOTIONAL GRID

The characteristic notional grid is a geometric simplification of the urban fabric that retains the key spatial parameters that influence energy consumption. It allows comparative analysis of urban energy behaviour without complex modelling. The transformation from the irregular, heterogeneous fabric into an analogous regular structure simplifies the calculation of average loads. Instead of individual predictions, which would be eventually averaged, this strategy takes a top-down approach. It starts by averaging the geometrical attributes and performing the energy calculation for a building that represents the mean geometric values of the whole sample (fig. 1). The average building would then represent the urban fabric that is being analyzed. This approach is similar to Quetelet's concept of average man in statistical science:

"If the average man were determined for a nation he would present the type of that nation; if he could be determined from the ensemble of men, he would present the type of the entire human species"[8]

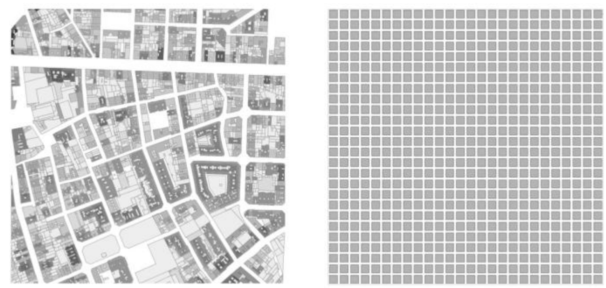

Figure 1: Urban sample (left) and its correspondent notional grid (right)

To obtain the characteristic notional grid of a real urban sample, a series of algorithms have been developed. In order to retain the key environmental attributes, the following conditions were established:

- The area of the real sample and the notional characteristic grid are equal
- All blocks in the grid are equal
- Each block has the same GFA/P ratio than that calculated for the whole urban sample
- Each block has the same proportion of its perimeter facing the primary orientation quadrant and the secondary orientation quadrant than the whole urban sample
- The built up area and the total perimeter of the grid are the same as for the urban sample

If the previous requirements are met, it can be demonstrated that the following statements will be valid (fig.2):

- The obstruction angle (θ) in the two main axes of the grid is analogous to the average obstruction angle in those axes in the real sample
- The distance between blocks in the two main axes of the grid is analogous to the average distance between blocks in those axes in the real sample
- The length of elevations facing the two main axes of the grid is analogous to the length of elevations facing those axes in the real sample

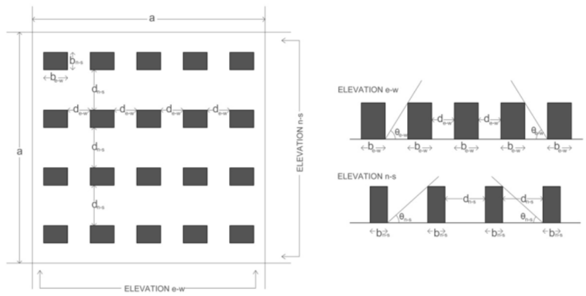

Figure 2: Notional characteristic grid. Main notations

CALCULATION SPREADSHEET

Once the notional grid has been obtained, a 14-step routine can be applied to obtain average loads for annual heating, cooling and lighting. The whole process, including the grid generation has been automatised using a spreadsheet (fig.3), so that calculations can be automatically performed. Al the algorithms are visible and the user can modify default values as well as adapt the routines. The minimum inputs are location (climate and latitude), GSI, FSI and compactness. If the latter value is not known, an empirical formula can be used to obtain typical compactness as related to GSI and FSI.

Urban Energy Index — **URBAN PARAMETERS**

Urban Energy Index						
Project Name						
Climate	12		Sample length	a	500	m
Latitude	52		Sample Area	At	250,000	m
Main axis (degrees from N)	30		Ground Space Index	GSI	0.23	m²/m²
Land Use:			Floor Space Index	FSI	1.15	m²/m²
Retail	10	%	Compactness ratio	Comp	0.98	m²/m²
Industrial	5	%	Orientation Ratio	Or	0.91	m/m
Facilities	5	%	Typical Floor height	fh	3.00	m
Office	20	%	Glazing ratio	Gz	35	%
Residential	80	%	Construction type	Ct	reference	
			Thermal capacity	Tc	Heavy	
			Albedo	ρ	Urban general	

BUILDING MODEL

Avg Lenght Main axis	14.69	Total Area	1,186 m²
Avg Lenght Secondary axis	16.15	Average Obstruction Angle Ma	25.16
Height	15.00	Average Obstruction Angle Se	23.29
Storeys	5.00	Heat Losses	
Distance Main axis	17.42	Internal Heat Gains	
Distance Secondary axis	15.97	Solar Gains	
Total floor Area	237.21		
Passive zone Area	201.18		

Figure 3: Calculation spreadsheet. The cells that can be modified are colored in light brown. The others are intermediate outputs, some of which are only useful for calculation purposes

Results are given as useful load per square meter of construction (built up area) for each building type. If different building types have been defined in the land use breakdown, aggregate values are given as average loads per unit of built up area and per square meter of land respectively (fig.4)

RESULTS

	RETAIL	INDUSTRIAL	FACILITIES	OFFICE	RESIDENTIAL	
Cooling Reference	61	52	26	48	15	kWh/m² year
Lighting Reference	99	75	41	45	42	
Heating Demand (Useful)	0	15	2	1	35	
Total	223	193	136	130	138	

AVERAGE URBAN ENERGY INDEX

Heating Demand (Useful)	29	kWh/m² built up area year
Lighting Reference	58	
Cooling Reference	32	
TOTAL	175	
Heating Demand (Useful)	15	kWh/m² urban area
Lighting Reference	29	
Cooling Reference	16	
TOTAL	87	

Figure 4: Calculation spreadsheet. Outputs

VALIDATION

The validation of the model has consisted on two different stages. First, the validity of the notional grid as to represent the relevant attributes of real urban fabric was assessed. A set of twenty eight urban samples was selected and simulated with two different methods: using a detailed model (all buildings being drawn up as they are) and using a simplified model (notional grid). Both simulations, detailed and simplified, were performed in Climatelite [9], an environmental modeling software tool that incorporates algorithms from LT. A close correspondence was found between the two modeling techniques, which supports the hypothesis that a simplified model can be used to perform rapid assessments in large urban areas (fig.5). In the second validation stage, the spreadsheet model was tested against simulations performed in Climatelite. The results from the spreadsheet were compared against the results obtained by Climatelite, using both detailed and simplified models. In general terms, the model compared well to the reference tool. Correlations ranged from r^2=0.75 to r^2=0.82 for comparisons against detailed and simplified Climatelite models respectively.

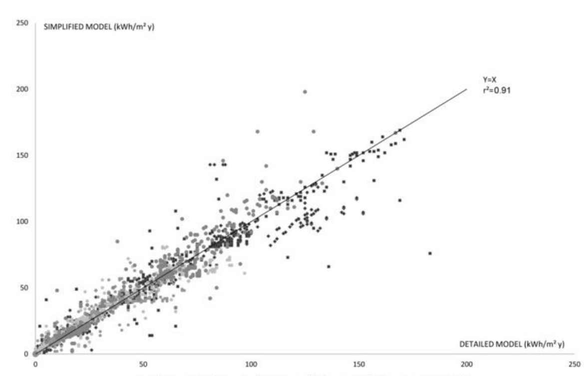

Figure 5: Scatter plot and correlation between results from simplified (notional grid) and detailed models (r^2=0.91).

APPLICATIONS

One of the possible applications of the model is the study of urban form and buildings' energy. Studies on this subject are typically based on parametric analysis in which the effects from urban parameters are evaluated one at a time (fig. 6). The impacts of different orientations, urban canyon or building depth can be tested in iterative simulations, in which a single parameter is varied while the rest of the model remains fixed. This use of the model is limited by the fact that only one aggregation can be analyzed at a time since results are obtained for every combination of FSI, GSI and compactness.

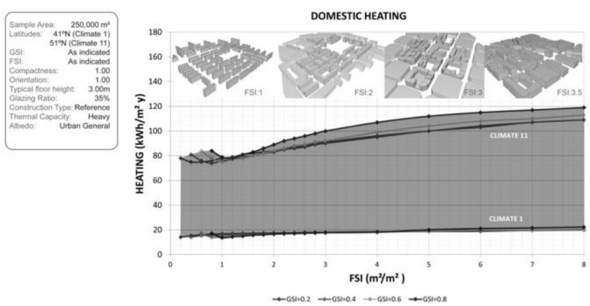

Figure 6: Parametric analysis. Domestic Heating versus FSI and GSI

Parametric analysis performed in the spreadsheet model is useful to identify trends between urban form and energy demand. However, further formats have been devised to increase the flexibility and applicability of the model:

- **Diagram.** It consists on climate and building type specific diagrams, which only require knowledge on FSI and either Compactness or GSI to obtain the energy demand for that specific use, building type and climate (fig.7)

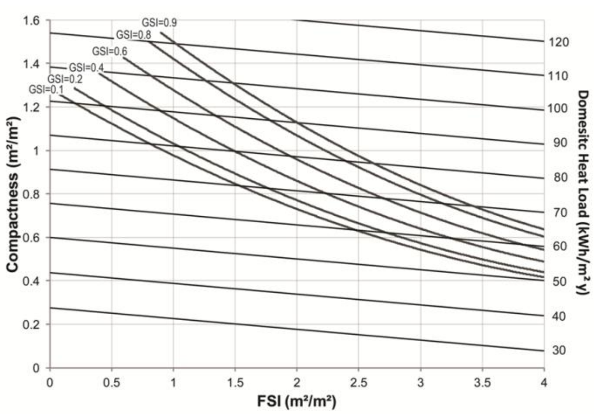

Figure 7: Diagram for domestic heating in Climate 11

- **GIS**. The integration of the model in GIS aims to extend the capacity of the tool to handle big datasets and, eventually, to perform energy assessments of larger urban areas, from neighborhood scale up to the whole city. Algorithms are embedded in the system so that inputs are automatically obtained from cartographic datasets and results are deployed as density maps (fig. 8).

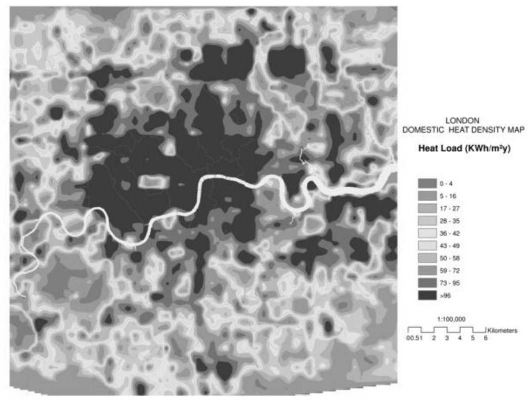

Figure 8: London heat density map performed using the model in ArcGIS

CONCLUSIONS

This paper has explained the development and validation of a tool to take account of urban morphological parameters such as urban intensity (GSI and FSI), compactness (Comp) and Orientation Ratio together with location and climate, to estimate energy demand associated to urban form

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