Chapter 9

Urban Morphology and Energy Consumption:

Simplified Tools for the Estimation of Energy Needs and Solar Income at the Urban and District Level

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ABSTRACT

Urban form matters in assessing the energy consumption of buildings. This chapter introduces three useful tools to assess the environmental impact of the urban form and to define possible energy scenarios. These outcomes can be used to inform the redevelopment or the new design of urban districts, or simply to evaluate the overall energy performance of different urban fabrics. The tools presented comprise: (a) simplified indicators of energy-dependent variables based on morphological information of the urban form; (b) algorithms for the estimation of the heating energy needs of the urban fabric, based on the implementation of European Standards; (c) algorithms for the assessment of the solar potential of the urban form, computing the solar irradiance impacting on different sloped urban surfaces. The techniques introduced are based on an innovative approach that makes use of Digital Urban Surface Models (DUSMs) and Digital Image Processing (DIP) techniques.

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PART 1: ESSENTIAL CONCEPTS AND KNOWLEDGE

1. Introduction

We argue that site layout planning and the arrangement of buildings are crucial in assessing the energy consumption of the urban form. For instance, both the relationship between buildings (e.g., solar access and reciprocal overshadowing) and the geometry of the single buildings (e.g., compactness and heat loss) affect the overall energy performance of the urban fabric. The energy performance of buildings – and consequently its computation – is directly related to manifold factors that cannot disregard from the morphological and climatic context where the building is located. If correctly considered in the design phase, an energy-conscious morphological layout can lead to huge savings, thus anticipating the benefits of implementing eco-technologies at the building level.

In recent years, most of the research on energy efficiency has been devoted to building technology, aiming at increasing the performance of buildings through a series of technical solutions derived from the dictates of passive architecture (e.g., improving thermal insulation, thermal inertia, orientation of facades, natural ventilation).

"Learning from the past" is a common paradigm in architecture and urbanism, and it refers to pre-modern times when the city was not dependent on mechanical facilities. In fact, during the centuries, buildings had been skilfully adapted to places by using different materials and typological solutions depending on the locations. As a matter of fact, traditional northern Europe constructions – where the climate is very cold and rigid for the major part of the year – are characterized by materials (such as wood, straw, stone) with a good thermal inertia and high insulation properties. Furthermore, numerous solutions capable to capture and store solar gains were developed. In addition, buildings are generally box-shaped to minimize heat losses (i.e. low surface-to-volume ratio). Conversely, places where the climate is very hot and dry are traditionally characterized by solutions that favour internal heat losses. Buildings' plaster and wall paint are very bright and the materials used (such as wattles, terracotta bricks) tend to delay the thermal wave. The openings are tiny and oriented such to create internal air flows or to tap the natural ones that are already present. Not only building design but also traditional city design relied upon the optimization of local natural resources, and the form of the city as a whole was the major clue of a wise understanding of modalities for rational use and energy saving, through a series of rules derived from "passive urbanism" principles. Street orientation on coastal areas allowed to invite pleasant breezes to penetrate or to stop cold winds; the tight disposal of buildings made it possible for heat and mass transfer control, as opposed to porous environments with detached housing that enabled to cool down building surfaces and interiors. In short, sun, wind and soil (geothermic energy) assumed the role of urban-form generators.

The majority of traditional knowledge has been abandoned during the 20th century. Modern technologies have enabled to overcome local hurdles due to the specific climatic context, thus contributing to the wide spread of the International Style architecture, which could be replicated everywhere in the world. During the second half of the last century, the necessity of a rapid reconstruction after World War II and the increasing availability of standardized technologies lead to the diffusion of new building typologies, obviously divergent from the traditional ones. That trend was justified by the necessity of providing affordable housing for everyone, speeding up the building process and containing the expenditure, frequently at the expense of quality (i.e. rapid obsolescence, scarce thermal performance). In fact, starting from the Fifties, the new building technologies tended more and more to decrease the thermal inertia properties of the building envelope, by reducing the amount of insulating materials and the overall wall thickness. An improper and immoderate use of the heating plant-system was concurrently used to cope with the problems caused by the deficiency of thermal insulation. Still today, the globalization and "spectacularization" of architecture tends to prioritise the aesthetical value of building design, independently from its location and climatic context (the numerous buildings signed by renown architects are a clear demonstration for this trend). The oil crisis in the Seventies and the recent concerns due to climate change led to a new awareness about the implications of design choices in architectural and urban planning. In the last decades numerous improvements have been carried on, and nowadays carbon-neutral housing is a reality. Although the design of new constructions have been inspired by energy efficiency principles, the same has not happened yet for refurbishment of existing urban fabric, especially the constructions from the Fifties to the Eighties. For instance, two main research gaps remain: firstly, the improvement of the energy performance of the existing urban fabric by means of technological solutions (i.e. insulation, eco-friendly equipment) and secondly, a morpho-typological redesign of urban districts. This latter investigation is the motivation for the work presented here. Restarting from the quantification of urban morphology indicators of past – and also more sustainable – environments represents a useful modality for posing the discipline of urban morphology back at the centre of planning and decision making. Evaluating the performance of the urban layout in respect to solar accessibility, wind exposure and thermal and mass balance can be carried on based on morphological investigations. As a matter of fact, we argue that both the reshaping of the urban form and the assessment of the proper eco-technologies, depending on the typo-morphological characteristics of the buildings' layout, can happen if well-grounded on a series of tools and indicators for the prediction of the energy consumption. Three tools are presented: (a) simplified indicators of energy-dependent variables based on morphological information of the urban form; (b) algorithms for the estimation of the heating energy needs of the urban fabric, based on the implementation of European Standards; (c) algorithms for the assessment of the solar potential of the urban form, in order to define possible energy scenarios for local production of renewable energies.

2. Research Context

The literature on the analysis and quantification of morphological features of the urban form represents a useful reference for this work. Urban morphometrics represents an emerging concept; hence literature on this topic is quite recent. Already applied in other disciplines such as biology, zoology and medicine, morphometrics investigates the variation and change in the form of objects. In the urban context, the analysis concerns the shape of the city itself (as a whole or subdivided into a regular grid of cells), the urban block, the plot or the street. Those latter elements compose the image and structure of the urban form which is the result of local identity and historical processes, and has continuously changed through time by adapting to the evolution of technologies, such as building technologies and transport means. For this reason, we cannot ignore the tradition of urban morphology studies, which represent a great and inspirational resource for better understanding the mutual relations among the basic urban elements and types. Introducing urban morphology literature goes beyond the scope of this work, but see for instance Conzen (1988) and Whitehand (2007).

The increasing interest on urban measurements is not only relevant to urban historians and analysts, but also to designers, since the introduction of evaluation criteria and certification systems in the urban planning discipline more and more push to anticipate the performance of the design choices, thus changing the overall approach to urban design. Thanks to its adaptability, urban geometry plays a crucial role in assessing the energy and environmental performance of cities. For instance, extracting data from urban shapes, solely from geometry and urban materials (building technologies) already enables a series of considerations in terms of environmental and energy performance.

Urban morphology studies investigating the relation of the urban form to energy and environmental aspects are not a novelty. UK had a leading role in this type of scientific studies. Starting in the Sixties, the Martin Centre at Cambridge University founded by Leslie Martin and Lionel March represents the pioneer centre for the analysis of the energy and environmental performance of the urban form. For instance, Martin and March (1972) started systematic studies about the physical structure of the city by modelling existing relations and extracting rules for a good environmental urban design. Topics such as density and typology in relation to environmental variables, comparative analysis of solar irradiation and illuminance conditions, prediction models about energy consumption at the urban scale deal explicitly with the topic energy and the urban form.

About ten years later, the Centre for Configurational Studies in Milton Keynes, directed by Philip Steadman, started a series of studies about the energy performance of a group of buildings by applying thermal dispersion and insolation models (Owens, 1986). An important contribution of that period is the book “Energy and Urban Built Form” (Hawkes *et al.*, 1987), which collects all the studies previously conducted on this topic.

Finally, at the end of the Nineties, tools for the environmental prediction of the urban texture were implemented at the University of Cambridge by Nick Baker, Carlo Ratti, Paul Richens and Koen Steemers and further developed at the Senseable City Laboratory at the Massachusetts Institute of Technology (Baker & Steemers, 1992; Baker & Steemers, 2000; Ratti & Richens, 2004; Morello & Ratti, 2007). The approach is based on a novel technique of image processing for the analysis of simple raster images representing the urban form. For instance, it is possible to map and analyse the environmental and energy performance of the urban texture, focusing on several selected indicators. This technique is promising thanks to the increasing availability of 3-D information of the urban fabric (CAD models or remote sensing imagery), and is presented more in detail in the next section.

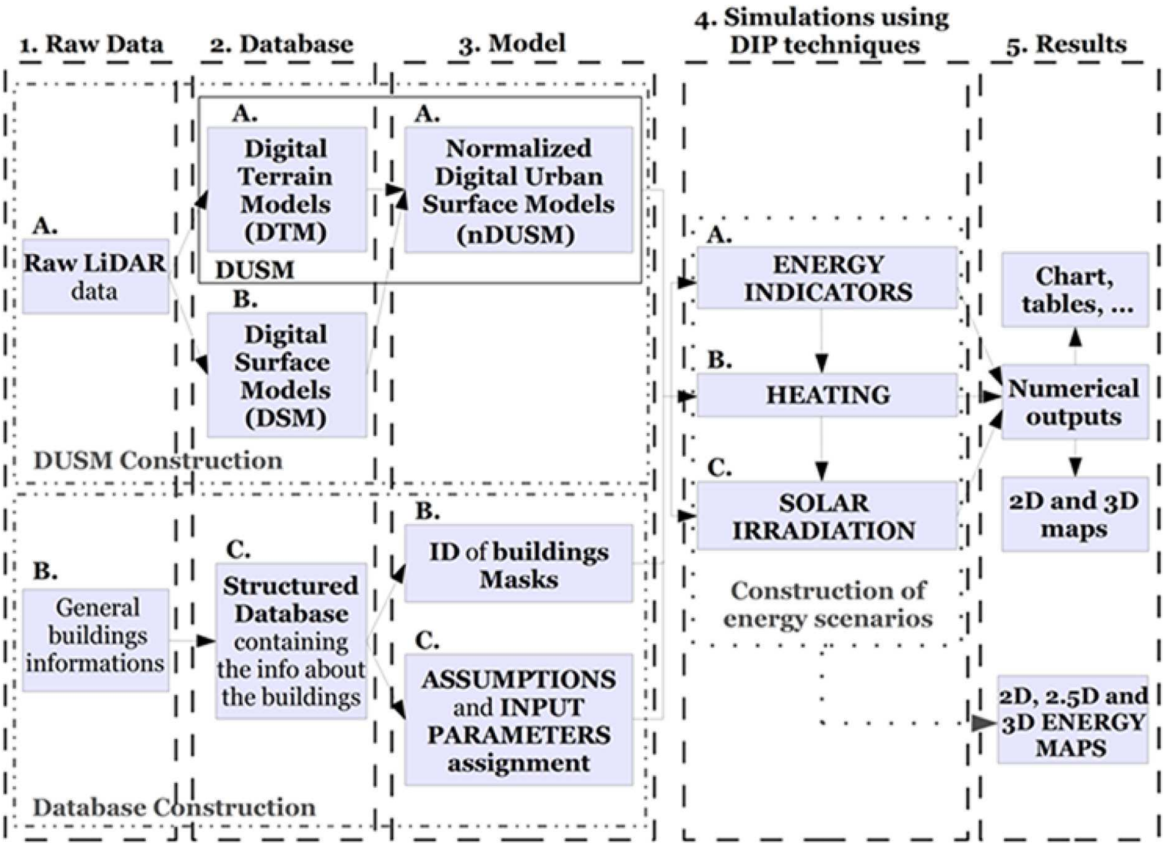
In particular, the use of remote sensing imagery and Light Detection and Ranging (LiDAR) data in urban studies, already gave some relevant feedback to urban planners. The extraction of morphological properties of city blocks using an urban landscape model, constructed from a large LiDAR dataset, was introduced by Yoshida and Omae (2005). Moreover, Koomen and Bação (2005) proposed a new methodology for the calculation of urban volumes and density properties of an entire urban system. More recently, a hybrid approach that uses urban model construction from LiDAR and 2-D/3-D vector data was proposed to compute (based on Digital Image Processing (DIP) techniques) the morphological properties of buildings (Carneiro et al., 2009; Carneiro et al., 2010).

PART 2: METHODOLOGY DESIGN AND IMPLEMENTATION

3. The Technique: Processing Digital Urban Models

The method of analysis presented here is based on the use of urban models constructed from LiDAR and 2-D/3-D vector data stored in common Geographic Information Systems (GIS), combined with other databases containing specific information about the urban fabric (for example an energy cadastre with building information) (Figure 1). These models have to be constructed in order to be applied for the environmental analysis of cit-

Figure 1. Block diagram of the steps necessary to assess the energy performance of the urban form, starting from LiDAR data and geo-referenced databases



ies. Outputs are both visual (maps) and numerical (charts and tables) and can be used to inform the delivery of urban or district energy plans.

The use of raster images of the urban form is the prerequisite for this work. The technique presented here refers to the use of Digital Surface Models (DSMs) – in this study defined as Digital Urban Surface Models (DUSMs) - as the main source of information. DUSMs are raster images representing the distribution of the elevations of a 3-D surface such as a landscape. The area under study is sampled using an equal-spaced grid where the side of each cell is small enough that the elevations within each cell can be considered constant. Then, the digital image is obtained by creating a numerical matrix where each element $Z_{i,j}$ is proportional to the elevation value inside the cell (i, j) of the grid. This way, it is possible to store 3-D information in a 2-D support: as a matter of fact, a DUSM is a top view of the area analysed.

In order to be applied for environmental analysis, DUSMs have to be carefully prepared. The first step consists in the model construction, where a model with specific characteristics has to be prepared in order to permit the second step, which is the analysis based on DIP techniques.

3.1. Model Construction

Two types of DUSMs are used in this study: (1) – the normalized DUSM of buildings (without vegetation), also called Digital Height Model (DHM), and (2) – the DUSM of buildings with vegetation. Those are constructed on a step-by-step basis: LiDAR points corresponding to terrain, buildings and vegetation are independently analysed and interpolated. A hybrid approach, combining LiDAR data and 2-D cadastral vector data of building outlines, is applied to improve the final quality and reliability of the constructed urban models (Hofmann, 2004; Schwalbe et al., 2005).

Firstly, a Digital Terrain Model (DTM) is interpolated by classifying the LiDAR points according to the following sequential operations:

- Using GIS software, LiDAR points contained within the 1 meter buffer generated from building outlines are eliminated.
- Using the algorithms initially presented by Axelsson (1999):
    - LiDAR points for which the elevation value varies significantly from surrounding points are considered artefacts and are therefore removed. Examples of artefacts include: aerial points (e.g., if the laser beam touches a bird) and vehicles;
    - LiDAR points classified as vegetation are also removed.

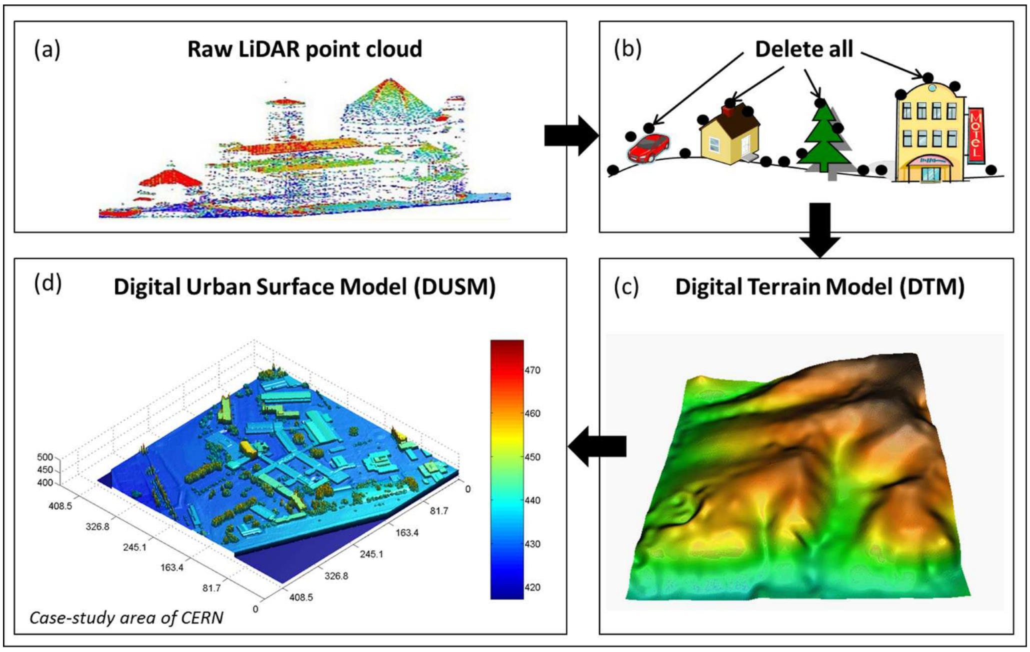
Following the elimination of artefacts and vegetation, a DTM can be interpolated only from ground points. Indeed, there is no significant difference among some of the existing gridding interpolation methods, such as the nearest neighbour binning, inverse distance weighting, triangulation with linear interpolation, minimum curvature, kriging and radial basis functions, which can be employed (using LiDAR data with a density of at least 1 point per m2, such as in the two case-study areas highlighted in this investigation) to generate this type of models (Gonçalves, 2006). All these interpolation methods are accessible in common GIS software available on the market. Due to its generalised use by the scientific community for DTM interpolation, the triangular interpolation was chosen.

Afterwards, a value for each pixel corresponding to a building value is interpolated (using only LiDAR points classified as being contained within building outlines). Thus, a triangulation with linear interpolation is also applied to each building. For each building and more specifically for each pixel contained within, its height is taken to be the value of subtraction of the terrain elevation (calculated in the DTM interpolated) from the building elevation. Hence, a normalized DUSM of buildings (without vegetation) with height information is constructed. It allows, for instance, the calculation of two main morphological properties of the urban fabric: volume and area of external facades of buildings.

Subsequently, each building is added to the DTM as a column (the borders are defined from the building outlines), using the building height found previously for each pixel contained within. As a result, DUSM of buildings is built, which is composed only of information on terrain and roof altitudes. Finally, the incorporation of LiDAR points classified as vegetation (mostly trees) allows to construct a DSM of vegetation with elevation information. For each pixel, the height is taken to be the value of subtraction of the terrain elevation (calculated in the DTM interpolated) from the DSM of vegetation with elevation information. Thus, the height of vegetation is added to the DUSM of buildings previously built. The final result allows the construction of a DUSM of buildings with vegetation, which is composed of information on terrain, roof and vegetation altitudes. It allows, for instance, to compute the solar irradiance impacting on the urban surfaces.

A synoptic outlook of the process of construction of both Digital Urban Surface Models (DUSMs) used in this study is shown in Figure 2.

Figure 2. General overview of the process of construction of both Digital Urban Surface Models (DUSMs) used in this study. From above: (a) the original LiDAR survey data; (b) the removal of LiDAR points corresponding to buildings, trees, cars and other minor details, and the selection of LiDAR points corresponding to the terrain; (c) the construction (based on a TIN interpolation) of the DTM; (d) the construction of the normalized DUSM of buildings (without vegetation) and the DUSM of buildings with vegetation (image highlighted in this figure), where: (1) – the detection of building is based on a hybrid approach using both LiDAR data and 2-D vector data, and (2) – the detection of trees is based on the classification of LiDAR points proposed by Axelsson (1999).



3.2. Digital Image Processing of Urban Models

Once the digital image is constructed from LiDAR data, the models can be analysed with Digital Image Processing (DIP) techniques, using the Matlab® environment in this case. For instance, the models are processed as mathematical arrays, whereby each number (i.e. the intensity value of the matrix) corresponds to the height of the model in that point. For further description of the technique see Ratti and Richens (2004). The three applications presented in the next chapter are all based on routines that were implemented in Matlab®, and are based on the analysis of the pure geometry of the urban form.

By importing the models into the Matlab® environment, a series of calibration instructions have to be performed in order to create a direct correspondence between the real dimensions of the case-study site and those of the raster image. In this sense, it is necessary to define the image resolution and the vertical calibration. Considering input LiDAR data (density of points per square meter), the image resolution (the length of the pixel side) for the representation of urban areas varies in the range from 2 to 0.5 meters. Higher resolutions are only possible with very high quality raster images, but this affects the computational time of the analysis.

4. Three Applications: Assessing the Energy Performance of the Urban Form

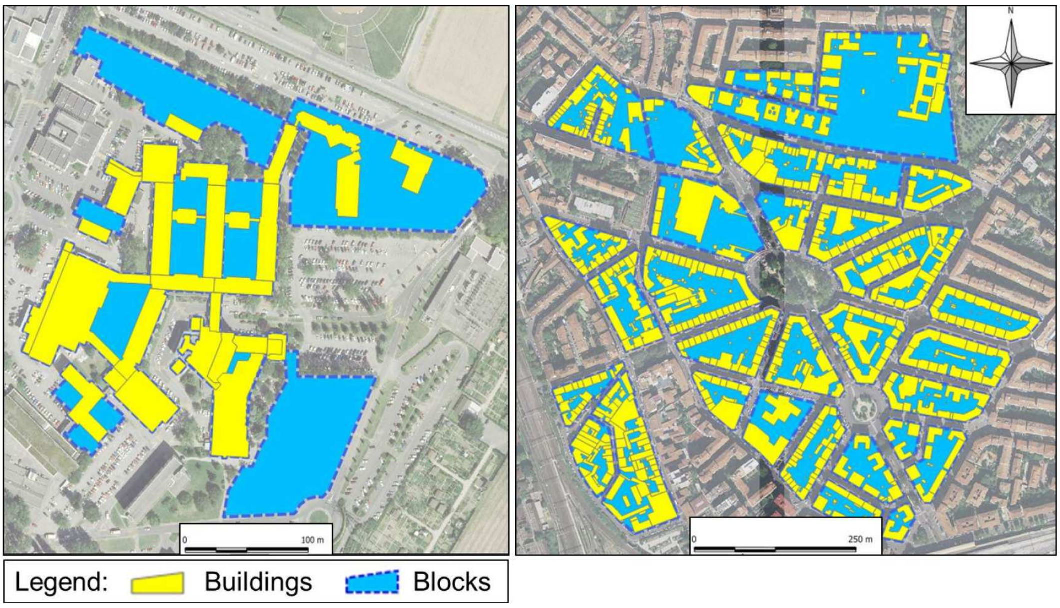
Three tools are presented here to approach the relationship existing between energy consumption and urban form. A first investigation aims at defining simplified indicators of energy-dependent variables based on morphological information of the urban form. These indicators are useful for the recognition of different behaviours among urban patterns, thus helping in the definition of alternative energy scenarios at the city level. A second tool, with a higher level of detail, estimates the heating needs of the urban fabric, on the basis of European Standards on energy performance of buildings. This tool represents a simplified and accurate way to estimate the overall performance of the urban fabric. A third tool assesses the solar potential of the urban form by computing the solar irradiance impacting on the urban surfaces (such as roofs and open spaces in general).

Two case-study areas were chosen for this investigation. The first one corresponds to a part of the CERN campus in Geneva, while the second one is a 19th century district in the city of Florence (Figure 3). As the aim of this work is to show the applicability of the proposed technique on very different datasets and environments, the two samples chosen are very different each other in terms of size, block layout, building typologies, etc.

4.1. Energy-Related Urban Form Indicators

The first and computationally inexpensive tool involves the calculation of morphological indicators that have direct or indirect implications for energy performance, or can help in defining a general energy demand of the urban form, by identifying a general set of involved quantities.

Figure 3. The two case-study areas: The CERN campus in Geneva (left) and the Piazza Leopoldo area in Florence (right)



The analysis can be conducted at different levels of detail depending on the scope of the investigation. For instance, at the city level, an investigation of the urban patterns is appropriate in order to get an overall picture of the general performance of different urban fabrics. In particular, a first investigation could be conducted on urban tiles to be derived from the subdivision of the city into a regular grid (for example a mosaic with 800 m2 wide tiles); otherwise, the "perimetration" of identified homogeneous urban districts characterized by similar morpho-typological features represents another possibility. Anyway, this latter modality requires a supplementary work of reading and clustering the territory into sub-areas, a task which is often time-consuming and open to subjective interpretation (e.g., the way to identify clusters, or the number of urban morphology classes to take into account).

Another level of analysis can be computed at the scale of the urban block. The same set of indicators can be applied on blocks, as far as those can be easily identified on an urban map. For instance, the traditional pre-modern city block was clearly defined by a regular grid-like street network. Conversely, in modern urban patterns based on a car-dependent city design and characterized by "cul-de-sac" street design, often the boundaries of the city block dissolve. In fact, the two case-study areas already show significant differences in this sense.

We selected a number of indicators that are relevant for two main reasons. Firstly, they enable to get a rapid picture of the quantities involved in the estimation of energy needs (e.g., from the calculation of the volumes and urban densities we can assume the theoretical number of inhabitants and average consumptions); secondly, morphological indicators can be related to passive architecture principles (e.g., solar exposure, compactness). In particular, we organized the indicators in three categories, namely morphological properties, density indicators and energy-related indicators. The complete list of the indicators selected and a short definition is reported in Table 1.

The calculation of simple morphological indicators is carried out by using the normalized DUSM of buildings (without vegetation) and the mask with the identification of each building (i.e. raster information interpolated directly from 2-D GIS vector data where each building is considered a single polygon with a unique identifier). These indicators provide a first picture of the urbanization typology, and help in deriving the other sets of indicators.

Aside from traditional measurements that do not require specific insights, we chose to compute six energy-related indicators that are usually applied to buildings but can be easily transferred to the urban form as listed below:

- **The Surface to Volume Ratio (S/V) [1/m]:** This is a typical measure of morphological compactness – widely used in biology – which refers to the capacity of a body to conserve or disperse heat: the lower the ratio the higher the energy saving performance in extreme climates; for instance, buildings located in cold climates do not disperse internal heat, whereas buildings in hot climates do not expose too many surfaces to solar irradiation.
- **The Passive to Non-Passive Zones Ratio [0-1]:** This is a measure initially proposed by Baker and Steemers (1992). It is a more suitable indicator for temperate climates as opposed to the S/V ratio, since it takes into account the quantification of potential building spaces that can make use of passive architecture principles such as the use

Table 1. List of energy-related urban form indicators for the Florence case-study

		Totals on the sample area	**Results block by block (6 sample blocks chosen among 28 in total)**					
	ID of the block	-	1	2	3	4	5	6
morphological properties	width of the site [m]	800	800	800	800	800	800	800
	area of the site [m2]	640,000	4,084	15,587	8,875	5,932	12,600	6,906
	covered areas [m2]	238,720	2,704	11,489	5,791	3,942	6,266	4,105
	uncovered areas [m2]	401,280	1,380	4,098	3,084	1,990	6,334	2,801
	% of covered (built) areas [%]	37.30	66.21	73.71	65.25	66.45	49.73	59.44
	% of unbuilt areas [%]	62.70	33.79	26.29	34.75	33.55	50.27	40.56
	total built volume [m3]	3,641,200	37,696	135,280	87,453	47,771	67,911	60,585
	mean height of the buildings [m]	15.25	13.94	11.78	15.10	12.12	10.84	14.76
	maximum height measured on the site [m]	53.74	24.55	34.23	26.55	25.50	19.02	24.57
	built perimeter [m]	63,395	988	2,640	1,699	1,315	2,106	1,352
	total floor area [m2]	1,137,900	11,780	42,275	27,329	14,928	21,222	18,933
	areas of the vertical surfaces [m2]	870,280	11,975	28,106	22,650	14,200	20,546	18,103
density indicators	built volume / total area of the site [m3/m2]	5.69	9.23	8.68	9.85	8.05	5.39	8.77
	covered area / total area of the site [m2/m2]	0.37	0.66	0.74	0.65	0.66	0.50	0.59
	total floor area / total area of the site [m2/m2]	1.78	2.88	2.71	3.08	2.52	1.68	2.74
	total floor area / built area (FAR) [m2/m2]	4.77	4.36	3.68	4.72	3.79	3.39	4.61
energy related urban form indicators	surface to volume ratio (S/V) [1/m]	0.30	0.39	0.29	0.33	0.38	0.39	0.37
	ratio of south oriented vertical surfaces [0-1]	0.16	0.19	0.15	0.11	0.07	0.14	0.04
	ratio of south east to south west oriented vertical surfaces [0-1]	0.37	0.46	0.33	0.28	0.34	0.40	0.37
	passive zones / non passive zones ratio [0-1]	0.86	0.96	0.77	0.91	0.93	0.93	0.95
	porosity [0-1]	0.91	0.73	0.80	0.73	0.77	0.81	0.75
	roughness length [m]	0.54	0.00	0.01	0.00	0.00	0.00	0.00

of natural light and ventilation. The higher the ratio the higher the overall energy performance of a building.

- **The Ratio of South Oriented Vertical Surfaces [0-1]:** This indicator represents another passive architecture rule, aiming at quantifying the amount of south oriented surfaces on the total. In fact, indoor energy consumption, both in summer and winter, highly depends on the orientation of the building facades.
- **The Ratio of Southeast to Southwest Oriented Vertical Surfaces [0-1]:** The sense of this indicator is similar to the previous one, but it considers a less restrictive condition by including a wider spectrum of facades orientations, ranging from southwest to southeast.
- **The Porosity Ratio [0-1]:** Calculating porosity is crucial in addressing the behaviour of the urban form towards natural ventilation and consequently thermal comfort (or discomfort). The porosity factor (p) (Balocco & Grazzini, 2000) is here expressed by the control volume (Vr) and the effective volume of the considered urban portion, such as the entire urban sample or the urban block (Vbm):

$$p = 1 - \left(\frac{V_{bm}}{V_r} \right)$$

whereby the control volume is the maximum volume considered on site, i.e. the reference area multiplied by the reference maximum height on site plus 10 meters. This last value is the standard height for measuring wind speed in urban areas and is usually quantified by a "roughness profile," which depends on the height of the frontal area divided by roughness height z0 (BRE, 1985).

- **The Roughness Length [m]:** It is an expression of the resistance of the urban skyline against natural ventilation, and can provide a global indication of the different canopy layers in the built-up area studied. The computation of the roughness length used in this work refers to the concept introduced by Macdonald *et al.* (1998) and is a function of the plan area ratio, the frontal area ratio and the average height of the buildings. Another way of calculating the urban roughness refers to the standard deviation of building volumes of an urban portion from the average volume of the reference area (Balocco & Grazzini, 2000).

Computation of Energy-Related Indicators

In order to tile the urban samples tessellation, we make use of GIS methods to create new maps of the existing urban blocks, which are based on 2-D vector street network. Shaping vector information individually by urban block (single polygon with a unique identifier) allows to interpolate a mask. This last one and the normalized DUSM of buildings (without vegetation) represent the sole input data needed for the calculation of the principal indicators for each urban area under study. Afterwards, we apply DIP routines to compute the indicators in the Matlab® environment.

Firstly, the analysis on the entire urban sample (the tile) is conducted. Secondly, the indicators are computed for the urban blocks. In this latter case we have to take into account the edge effect. In fact, blocks on the boundary of the urban tile are discarded because they are cut and can falsify the outcomes of the analysis.

Considerations on the Outcomes

The analysis of morphological indicators is useful as a preliminary step in order to map urban diversity and identify different urban types and potential energy performance at the city level. For instance, different urban patterns correspond to different energy patterns and thus site specific guidelines can be proposed, depending on the local potential. In particular, different technologies for energy production (e.g., solar thermal, photovoltaic, geothermal) and different urbanization strategies (infilling or re-naturalization) can be applied according to the analysis presented in the following sections.

In particular, from the numerical outputs (Table 1) and the corresponding visualizations (Figure 4), different energy performances of blocks emerge at first glance. For instance, elongated south-oriented urban blocks with higher compactness show higher potentials in terms of energy savings, since they could eventually integrate passive architecture solutions together with solar energy production on site. In general, from these sample investigations we cannot derive significant conclusions

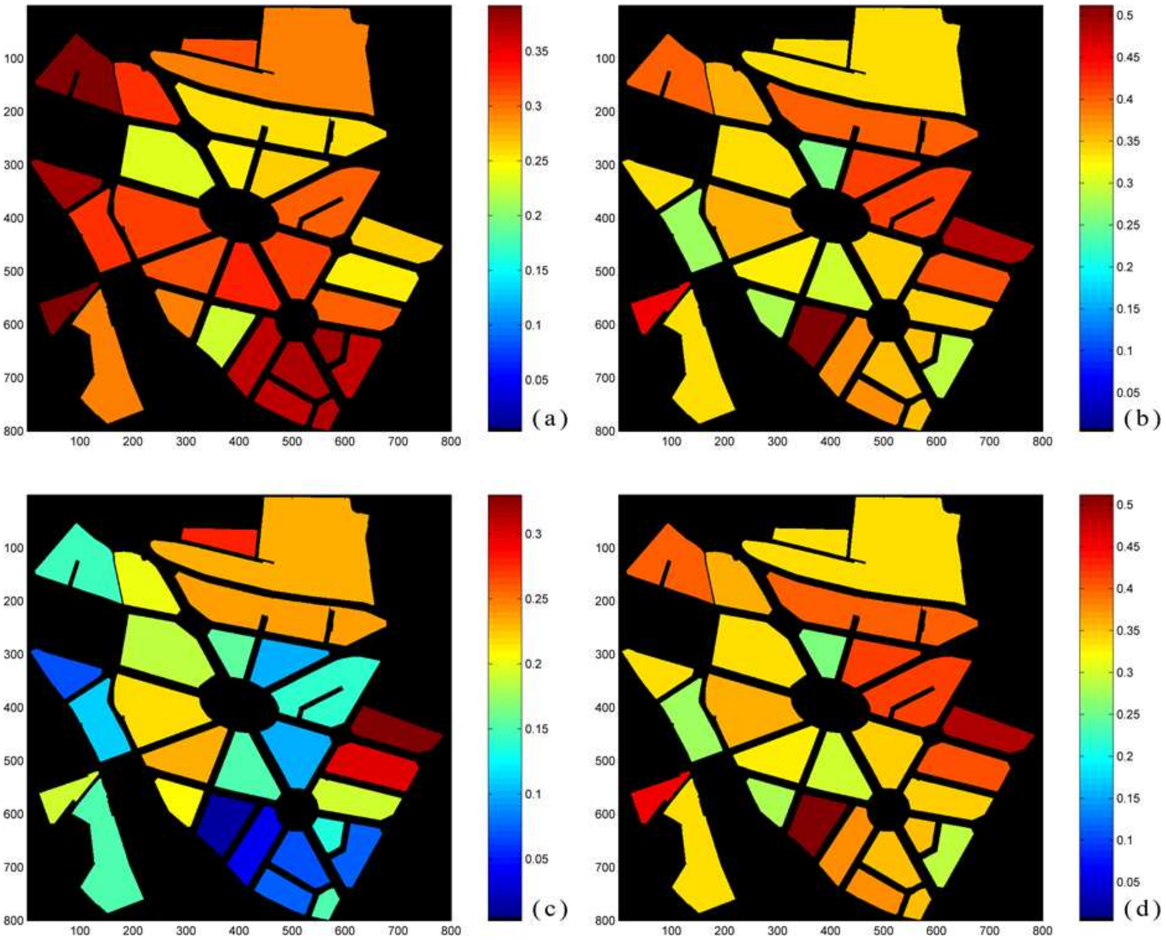


Figure 4. Energy related morphological indicators computed on a block basis for the Florence case-study: (a) The Surface to Volume Ratio [1/m], (b) the passive zones to non-passive zones ratio [0-1], (c) the ratio of south oriented vertical surfaces [0-1], (d) the ratio of southeast to southwest oriented vertical surfaces [0-1].

at the city level, and urban strategies should be derived from a larger investigation able to define the peculiarities of each urban pattern.

4.2. Estimation of the Heating Demand of the Urban Texture

The goal of this section is to present a tool for the estimation of the heating energy needs at the district level, highlighting the weight that each single component has on the final result. Such tool is of particular importance because it enables designers to control and choose – since the first steps of planning – which one of the proposed solutions is also the most energy efficient. In addition, the tool could also be used by policy makers to adopt strategies that make the best use of public financing committed to building rehabilitation or installation of renewable energy plants.

The aim of this project is obtained by developing some software algorithms (in Matlab®) that, starting from both Digital Urban Surface Models (DUSMs) of the urban area under study, implement the current European Standard for the evaluation of the energy performance of buildings (UNI EN ISO 13790:2008 and its Italian version UNI/TS 11300-1:2008) taking into account the effects of mutual shadowing by the surrounding urban fabric.

The seasonal heating energy need of the whole area analysed is obtained by summing up the monthly energy requirements for each building belonging to the area under study. For this purpose, the urban fabric is sliced at constant intervals in order to simulate the building storeys (Gori, 2010; Gori *et al.*, 2011). In particular, in this work the height of each slice was considered 3 meters high. This subdivision is useful to take into account possible gradual restrictions of the building shape or to assign different uses to the spaces (in this study, only the residential use was considered in both case studies). The heating period is determined referring to the climatic data of the location analysed.

According to the procedure suggested by the Standard, we impose the energy balance between the heat gains and the heat losses through the building envelope (both opaque and glazed surfaces) of each thermal zone corresponding to each storey of each building. Then the monthly thermal needs are computed taking into account the intermittency and the efficiency of the heating system and the utilization factor of total heat gains.

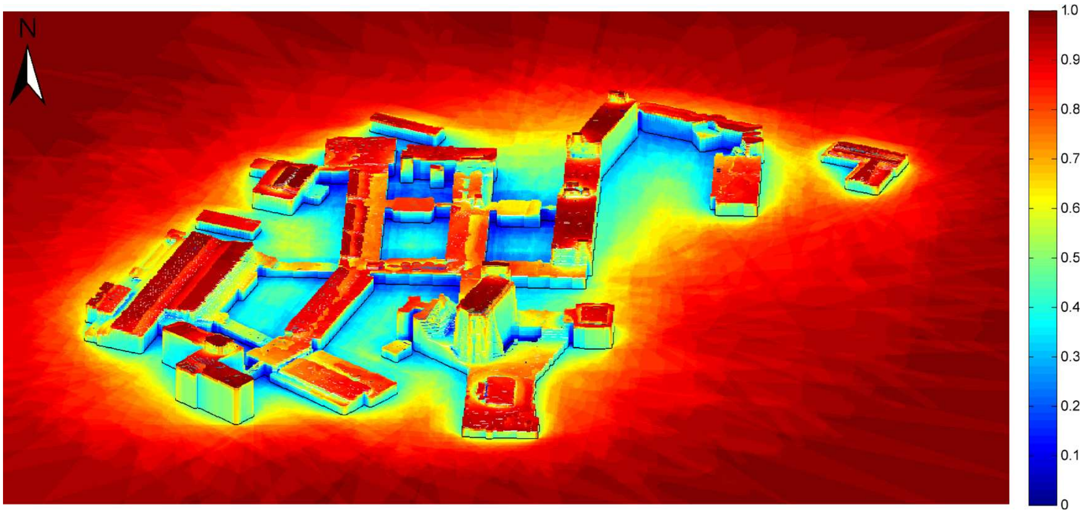
The heat losses are represented by the heat exchanges for ventilation and transmission through the building components and the extra-flux due to the infrared radiation toward the sky vault. The thermal gains are represented by the internal gains – due to the presence of people and equipment inside the thermal zone considered – and the solar radiation intercepted by the external building envelope, according to the surfaces orientation and inclination and the presence of surrounding buildings and vegetation. Results can be visualized for the whole area under study, for each building or for each storey of each building.

The effects of surrounding buildings and vegetation are accounted for by the computation of two shadowing factors: (1) - the shadow cast by the sun at different times of the day; (2) - the Sky View Factor (SVF), which represents the visibility of the sky vault from each pixel belonging to the built envelope and the streets (Ratti & Richens, 2004) (Figure 5). More details about the computation and use of these two elements for the assessment of the solar potential in the urban form are given in section 4.3.

Besides both DUSM of the urban area investigated, the input parameters necessary to perform the simulations include:

- Climatic and geographical data of the analysed site, e.g., the latitude, the monthly global and diffuse solar irradiation on horizontal surfaces (from which the direct or beam component can be deduced), the direct solar irradiation on vertical sur-

Figure 5. Sky View Factor (SVF) for the CERN case-study. Unobstructed horizontal surfaces have a SVF equal to 1, while unobstructed vertical surfaces have a SVF equal to 0.5. Partially obstructed surfaces have a SVF smaller than the above values.



faces (normal beam) for North, South, West and East orientations, and the mean hourly external temperature (please refer to section 4.3 for more details about these parameters);

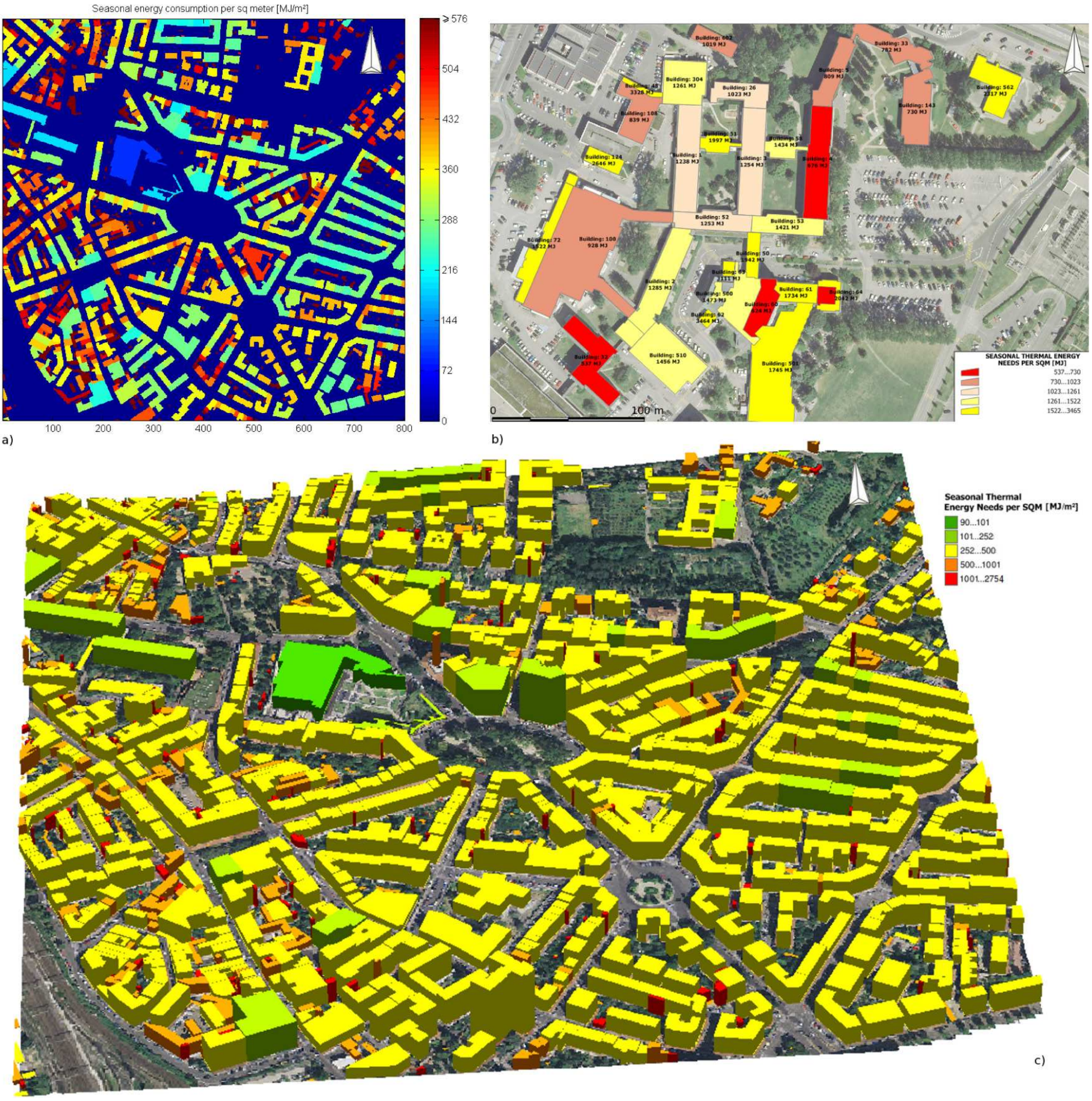
- Thermal parameters of the building elements, e.g., the thermal capacity of the walls, the thermal transmittance of the opaque and glazed surfaces, the solar transfer coefficients of the windows;
- Constructive characteristics of the buildings, e.g., the glazing ratio (i.e. the ratio between the opaque and the glazed surface on each orientation), the external wall thickness.

It is worth noticing that these parameters are very simple to retrieve and they are generally known since the very first steps of the design process. For this reason, such a tool can be very useful for urban policy makers. A number of boundary conditions are imposed to simulate the intermittent regime of the heater and take into account the different use of the thermal zone depending on the time of the day. In our setting, three time spans (7 AM – 7 PM; 7 PM – 11 PM; 11 PM – 7 AM) were introduced and two indoor climatic conditions were imposed. A temperature of 20°C and 50% of relative humidity was assumed between 7 AM and 11 PM, while during the rest of the night it was imposed a temperature of 18.5°C and 50% of relative humidity. These conditions were chosen according to the CEN Standards for indoor air quality.

At first, the method was tested on simplified urban configurations based on archetypal building forms. Afterwards, it was tested on two real case studies, corresponding to the Piazza Leopoldo area in Florence and the CERN campus in Geneva. In this second phase, additional geo-referenced information about buildings (e.g., the Florence Municipality Environmental Energy Programming: PEAC) was also used: for instance, the year of construction of each building allowed to set the thermal parameters of the building elements and its constructive characteristics. The seasonal heating energy needs for both case studies are shown in Figure 6, by using different visualization techniques.

In the last years, the increasing availability of 3-D data of cities has opened up the possibility of using this kind of information for urban and architectural planning. However, the transition from a traditional urban planning approach to another that makes use of these new technologies is still in an incipient stage.

Figure 6. The seasonal thermal energy needs per square meters [MJ/m2]. (a) The area of Piazza Leopoldo in Florence, represented by using a 2-D visualization as obtained from Matlab; (b) the CERN campus in Geneva, represented by using a 2-D vectorial data visualization, obtained by superimposing the results obtained over an aerial view of the site; (c) the area of Piazza Leopoldo in Florence, represented by a 3-D visualization that makes it simpler to read and easier to understand for lay people.



4.3. The Assessment of the Solar Potential of the Urban Form

The third tool proposed concerns the assessment of the solar potential of the roofs in the urban area under study. The solar geometry formula (given below) allows deriving *hourly* global irradiation on an inclined surface (Ig *h*) from the beam (Ib *h*), diffuse (Id *h*) and ground reflected (Ir *h*) components of hourly radiations for every orientation and inclination of surfaces.

$$Ig\ h = Ib\ h{*}Sb\ h + Id\ h{*}Sd + Ir\ h$$

As meteorological input of radiation on horizontal surface, we used the Meteonorm® database that generates statistical data for the period 1980-2000 for many cities in the world, and thus for Geneva and Florence. However, calculating irradiation for each hour and for each pixel of a high resolution DUSM models would result of several days of computer time simulation. Consequently, we reduced our solar irradiation dataset by averaging hourly values for each month. We compared the irradiation results from applying strictly and average hourly values in Geneva: the relative error is statistically very few significant particularly for the south oriented surfaces. The model of diffuse component on inclined surface should be selected very carefully so as to take into account the anisotropy of the phenomenon. Among the numerous anisotropic models, those of Perez (1990) and Hay (1979) are the most common. The model of Hay was chosen as it is particularly addressed to the use of average hourly values as explained above.

Both of the main components of the global irradiation (direct Ib *h* and diffuse Id *h*) are multiplied by a shadowing factor:

- **Shadowing on Direct Component (Sb h) at a Given Hour [0, 1]:** A shadow cast by the sun at different times of the day routine is applied to each pixel of the DUSM of buildings with vegetation;
- **Shadowing on Diffuse Component (Sd) [0, 1]:** The calculation of the Sky View Factor (SVF) of each pixel of the DUSM of buildings with vegetation evaluates the reduction of the sky visibility due to obstacles (buildings and vegetation) in the surrounding environment. It is thus not time-dependent.

After determining the shadowing condition, the SVF, the orientation and the inclination of each pixel of the DUSM of buildings with vegetation, we can assign the global incident solar radiation calculated in W or J/m2 for various time scales (i.e. hour, aggregation to month and aggregation to year).

User requirements concerning the utility and usability of 3-D urban models for communication and visualization purposes are very important to consider. Therefore, through GIS post-processing on raster irradiation outputs, it is possible to derive useful indicators for different purposes.

The yearly percentage of shadowing is calculated as the ratio between the annual irradiation taking into account shadowing and the irradiation without shadowing. It allows the clearly differentiation of which parts of the solar radiation concerns the direct or diffusing components. This indicator is considered to be very useful for the analysis of shadowing along roofs. In fact, Photovoltaic (PV) technology is very sensitive to diffuse radiation, while PV mono-crystalline is very sensitive to direct radiation.

The potential user of this tool would be interested in assessing which roofs' sections would be suitable or not for solar panels installation. Grid pixel representation is not really appropriate for this purpose. Therefore, the transfer of irradiation values of pixels to roof sections vector layer enables to compute statistics like minimum, maximum, average, median irradiation pixels values on each roof section, as well as the standard deviation. The average value of irradiation enables to evaluate if the roof is globally suitable for energy use. Visual results

(3-D representation) of the average radiation on roofs for the case-study area of CERN are shown in Figure 7.

Additional statistics enable to consider how far the irradiation is heterogeneous on roofs due to local shadowing effects and to the accuracy of LiDAR data, which involves heights variations up to 20 centimetres.

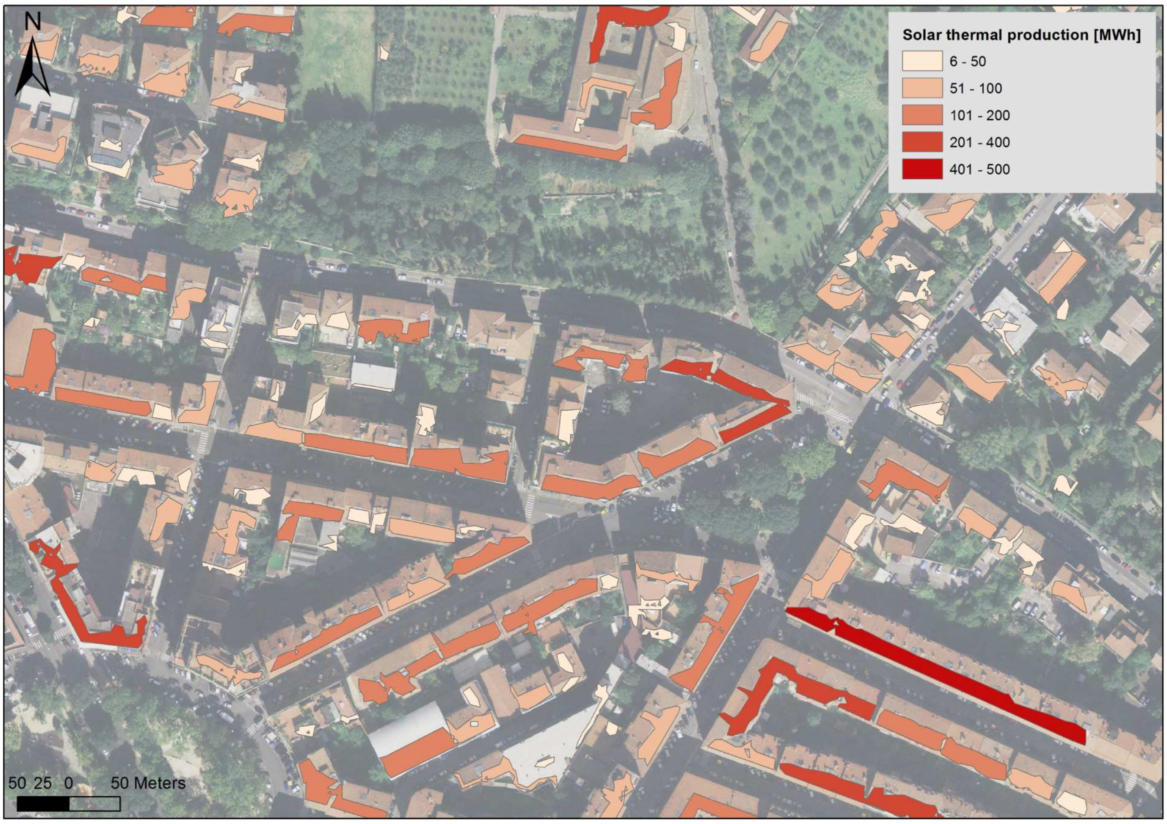
A more detailed analysis can be also applied concerning the most suitable roofs' areas, for the installation of solar PV panels. According to Morello and Ratti (2009), appropriate roofs for the installation of PV must present a yearly irradiation higher than 1000 kWh/m2. Moreover, by integrating the information derived from the morphological analysis of the areas of roofs (slope), it is also possible to derive the real area of each of the selected parts of roofs. The method applied is based on a mix approach combining raster and vector formats: roof cells having an irradiation greater than 1000 kWh/m2 and a favourable orientation between 95° and 265° are selected and then agglomerated as vector eligible pieces of roof.

Once identified the most suitable part of roofs and calculated their real area, it is then possible to estimate the solar energy production through PV and thermal panels. The solar PV panels will particularly address buildings that offer large roof area and thus significant electric production power (generally minimum 10 kWc that corresponds to about 200 m2 of flat roof). For most of the common technologies of poly-crystalline and mono-crystalline, an electrical production equivalent to about 10% of the global irradiation is considered. However, the thermal production generally corresponds to 40% of the global irradiation (with glazed collectors).

Visual results (2-D representation) of the potential thermal energy production on the suitable roof sections for the Florence case-study are shown in Figure 8. The thermal energy potential on a given building is compared to the energy needs of this building for Domestic Hot Water (DHW) and heating in order to evaluate how far needs can be satisfied by this technology. PV and thermal panels can be combined on a given roof area of building that require heating needs (PV

Figure 7. Average yearly irradiation on building roofs for the CERN case-study

Figure 8. Suitable parts of roofs with annual thermal energy production for the Florence case-study



panels are installed in the remaining part of the roof after deduction from the thermal needs, if the area of this part is enough in terms of significant electric power).

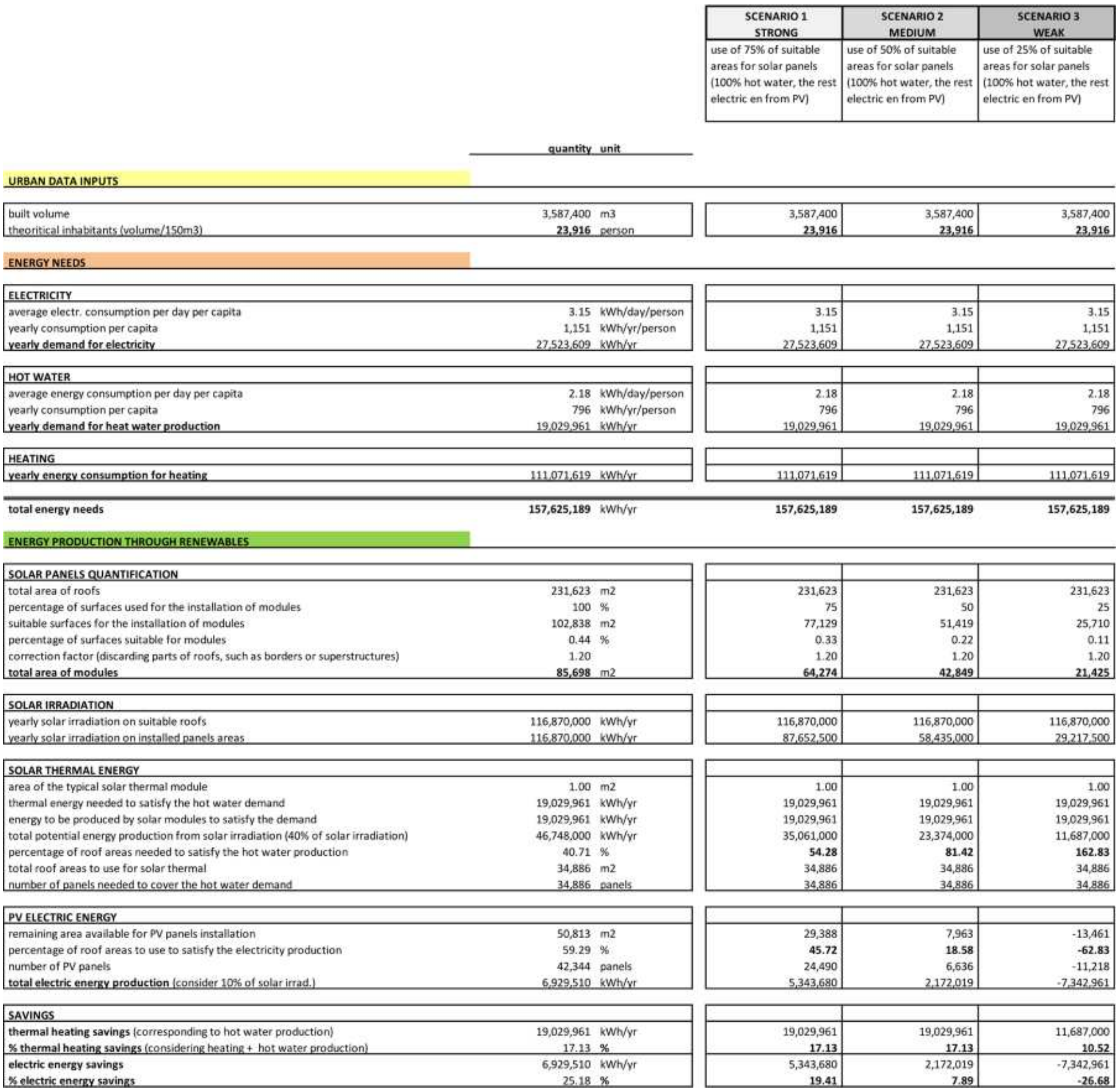
5. Implementing Urban Energy Scenarios

The proposed tools provide useful information to attempt urban energy scenarios. The first tool enable to derive simple quantities (morphological indicators) involved at the district level; the second tool computes the heating needs of the urban fabric, whereas the third one provides the potential energy production through solar energy.

A series of energy scenarios can be derived by assuming different levels of policy implementation, from strongly environmental-friendly policies to less ambitious urban targets. The scenarios shown in Table 2 are only a very preliminary attempt based on the case-study area of the urban district in Florence. Of course, if implemented over the whole city, this method could lead to site specific policies and incentives.

Energy scenarios are built upon the quantification of the urban volume which is derived from the morphological analysis. Hence, the number of inhabitants can be derived considering the average volume per capita (in this case we chose 150 m3 per capita in Florence). Starting from this

Table 2. Three energy scenarios considering energy needs and energy production from renewables for the Florence case-study



	quantity	unit	SCENARIO 1 STRONG	SCENARIO 2 MEDIUM	SCENARIO 3 WEAK
			use of 75% of suitable areas for solar panels (100% hot water, the rest electric en from PV)	use of 50% of suitable areas for solar panels (100% hot water, the rest electric en from PV)	use of 25% of suitable areas for solar panels (100% hot water, the rest electric en from PV)
URBAN DATA INPUTS					
built volume	3,587,400	m3	3,587,400	3,587,400	3,587,400
theoritical inhabitants (volume/150m3)	**23,916**	person	**23,916**	**23,916**	**23,916**
ENERGY NEEDS					
ELECTRICITY					
average electr. consumption per day per capita	3.15	kWh/day/person	3.15	3.15	3.15
yearly consumption per capita	1,151	kWh/yr/person	1,151	1,151	1,151
yearly demand for electricity	27,523,609	kWh/yr	27,523,609	27,523,609	27,523,609
HOT WATER					
average energy consumption per day per capita	2.18	kWh/day/person	2.18	2.18	2.18
yearly consumption per capita	796	kWh/yr/person	796	796	796
yearly demand for heat water production	19,029,961	kWh/yr	19,029,961	19,029,961	19,029,961
HEATING					
yearly energy consumption for heating	111,071,619	kWh/yr	111,071,619	111,071,619	111,071,619
total energy needs	**157,625,189**	kWh/yr	**157,625,189**	**157,625,189**	**157,625,189**
ENERGY PRODUCTION THROUGH RENEWABLES					
SOLAR PANELS QUANTIFICATION					
total area of roofs	231,623	m2	231,623	231,623	231,623
percentage of surfaces used for the installation of modules	100	%	75	50	25
suitable surfaces for the installation of modules	102,838	m2	77,129	51,419	25,710
percentage of surfaces suitable for modules	0.44	%	0.33	0.22	0.11
correction factor (discarding parts of roofs, such as borders or superstructures)	1.20		1.20	1.20	1.20
total area of modules	**85,698**	m2	**64,274**	**42,849**	**21,425**
SOLAR IRRADIATION					
yearly solar irradiation on suitable roofs	116,870,000	kWh/yr	116,870,000	116,870,000	116,870,000
yearly solar irradiation on installed panels areas	116,870,000	kWh/yr	87,652,500	58,435,000	29,217,500
SOLAR THERMAL ENERGY					
area of the typical solar thermal module	1.00	m2	1.00	1.00	1.00
thermal energy needed to satisfy the hot water demand	19,029,961	kWh/yr	19,029,961	19,029,961	19,029,961
energy to be produced by solar modules to satisfy the demand	19,029,961	kWh/yr	19,029,961	19,029,961	19,029,961
total potential energy production from solar irradiation (40% of solar irradiation)	46,748,000	kWh/yr	35,061,000	23,374,000	11,687,000
percentage of roof areas needed to satisfy the hot water production	40.71	%	**54.28**	**81.42**	**162.83**
total roof areas to use for solar thermal	34,886	m2	34,886	34,886	34,886
number of panels needed to cover the hot water demand	34,886	panels	34,886	34,886	34,886
PV ELECTRIC ENERGY					
remaining area available for PV panels installation	50,813	m2	29,388	7,963	-13,461
percentage of roof areas to use to satisfy the electricity production	59.29	%	**45.72**	**18.58**	**-62.83**
number of PV panels	42,344	panels	24,490	6,636	-11,218
total electric energy production (consider 10% of solar irrad.)	6,929,510	kWh/yr	5,343,680	2,172,019	-7,342,961
SAVINGS					
thermal heating savings (corresponding to hot water production)	19,029,961	kWh/yr	19,029,961	19,029,961	11,687,000
% thermal heating savings (considering heating + hot water production)	17.13	%	**17.13**	**17.13**	**10.52**
electric energy savings	6,929,510	kWh/yr	5,343,680	2,172,019	-7,342,961
% electric energy savings	25.18	%	**19.41**	**7.89**	**-26.68**

input and the heating calculation introduced above, several assumptions are taken into account to define the overall yearly needs (namely electricity, hot water and heating) of the urban portion investigated.

In parallel, the production of electricity and hot water through renewables can be estimated referring to the solar analysis computed on the roofs. In particular, we propose three scenarios, from a weak to a very strong energy production depending on the surfaces available on urban roofs. For instance, we can assume that only a percentage of the surfaces available will be used for the installation of solar modules. Once the involved surfaces for panels are estimated, we firstly use it to cover the hot water demand with solar thermal panels; the remaining surfaces are employed for electricity production, thus satisfying a percentage of the overall demand.

A series of savings are finally computed on the three scenarios by distinguishing thermal energy for hot water production and electricity needs. Results show that only the first two scenarios can cover the total hot water production, whereas the third one is undersized. This type of evaluation really gives a clear sense of possible strategies to be implemented on urban districts, enabling to calibrate different energy productions according to local peculiarities.

6. Conclusion and Future Research Directions

Energy is a fundamental point when talking about socio-economic well-being that provides comfort, mobility and development. However, energy production, energy consumption and the different conversion processes place considerable pressure on the existing environment. These weighty day-to-day social behaviors have a direct impact on climate change, depletion of natural ecosystems and resources, and tarnishing of the built up environment. Furthermore, it also causes adverse effects on human health.

Urban planning often has a concern for the appearance of space. However, in many cases the application of wrong actions gives rise to disorganized land use practices and unsustainable urban sprawl. Consequently, it increases traffic congestion, air pollution, inefficient energy consumption, loss of open space and habitat, inequitable distribution of economic resources and the loss of a sense of community. Nowadays, planners cannot address spatial problems of cities without first understanding environmental and energetic issues as well as socio-economic dynamics. For this reason, they have to put effort into coordinating transportation, energy and land use planning to create more "sustainable" cities. A key-question for a sustainable and efficient energy use is the role of urban form and energy use. Thus, the shape, materials, and energy performance of buildings, the configuration of urban space, the use of green areas in different ways and the microclimatic conditions are all important topics that must be carefully studied. Moreover, they do have a direct impact in the outdoor and indoor thermal and visual comfort of people.

The analysis proposed here on the relationship between urban form and energy indicators represents just a first attempt to quantify the potential performance of cities. In this work we assume urban geometry alone as the crucial parameter for the investigation: for instance, assessing shape characteristic of urban patterns, like compactness, porosity, solar exposure and SVF, can give back clues about applicable energy strategies in order to optimize efficient actions for energy conservation and production in relation to the different layouts.

The public policies and strategies endorsed during the present energy crisis are also critical points when setting-up a more efficient and cost-effective energy plan at local, municipal and regional levels. The consequences of climate change and rapid urbanization along with possible energy crisis have once again brought energy issues forward for policy makers and researchers. Moreover, new technologies have redefined small-scale generation and distribution, and efficiency opportunities at different urban scales. Thus, different public administrations have responded with their own energy strategies and plans. Indeed, two issues are fundamental for any energy planning scenario: firstly, how are energy programs institutionally/programmatically organized and supported by local, municipal and regional governments; secondly, the effectiveness of local programs and strategies. Although research projects in this area may address both issues as part of the same investigation, it is important to consider their particular aspects separately. Indeed, effectiveness is a criterion used to evaluate the programs and determine what is and is not working properly.

The crucial part of the proposed methodology concerns an integrated urban energy use and supply, which is strongly based upon a sustainable development concept. The use of the policies proposed in this investigation allows the development of different approaches, which incorporate energy supply and infrastructure analysis into existing regional housing, land-use and transportation planning processes. Furthermore, according to the environmental demand for energy policy implementing institution, this novel approach is a useful tool that puts forward effective local energy procedure proposals.

The methodology presented is also particularly useful in order to get a general overview of energy issues at different urban scales. Outcomes are twofold: on one hand, the mapping of energy-related issues at city and district level with different level of detail (urban patterns, urban blocks, buildings and surfaces); on the other hand, the implementation of energy scenarios that consider the physical layout of urban patterns. In general, this method is suitable for both the analysis and the design of urban environmental strategies. Thus, if applied at the entire city level, the analysis could lead to *in-situ* specific policies and incentives.

Future work will focus on three main areas:

- The integration of building renovation strategies in the energy scenarios, which is relevant to get effective reduction of urban energy demand;
- The computation of air-conditioning demand during the summer season, which is crucial to get a realistic picture of the yearly energy consumptions;
- The implementation of a more integrated, comprehensive and user-friendly toolkit, which is fundamental if the objective is to diffuse the technique. Indeed, urban planners and policy makers have to be involved in the energy assessment in all the phases, from the analysis to the design.

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KEY TERMS AND DEFINITIONS

3-D Geospatial Data Analysis: The process of gathering, reviewing and analysing (mostly quantitatively) three dimensional geographical data to form some sort of outcome or conclusion when conducting a research experiment.

Digital Image Processing (DIP): Any technique that changes the digital values of an image, such as slope interpolation or low/high-pass filtering using DUSM.

Digital Urban Surface Model (DUSM): A digital map (pixel values) of the elevation of an urban area of the earth. DUSM are usually constructed using LiDAR mass point cloud datasets and are grey scale images wherein the pixel values are actually elevation real numbers. The pixels are also matched to world space (usually projected longitude and latitude coordinates), and each pixel represents some variable amount of that space (meter, kilometre, etc.) depending on the use of the DUSM and area involved.

LiDAR Data: Light Detection And Ranging (LiDAR) is an optical remote-sensing technique that uses laser light to measure highly accurate x,y,z points, thus allowing to model the surface of the earth.

Renewable Energy Potential: The assessment of possible energy production from renewable energy sources that can be obtained on the territory.

Urban Energy Performance: The energy performance of the urban form, in terms of energy conservation, efficiency and production.

Urban Morphology: The study of the urban form, including the process of formation and transformation of human settlements.