Energy efficiency in the urban scale. Case study: Prague, Czech Republic

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Abstract. *Cities are a complex mass of morphological properties of many city fragments, which play a major role in energy consumption. Urban form, urban patterns, or city fragments can also be seen as defined by algorithms or form generators. Cities are designed taking into account infrastructure, city standards and land use regulations. Energy efficiency of the urban form may be understood as the balance between gains and losses of energy, which may depend on a set of parameters mostly defined by the geometrical shape of the buildings and the distance between them. The study starts from the development and analysis of 60 hypothetical models in order to evaluate their energy efficiency potential. The Galapagos Evolutionary Solver is used as a tool in order to find the set of parameters, which brings to the morphological properties the optimal combination of density and surface-to-volume ratio. At the final stage morphological properties of 64 Prague's patterns were selected. Computer simulation and analysis is performed using the models extracted from the virtual Google Earth model of Prague. During the process of evaluation of the samples, the relationship between the urban form and such parameters as plot coverage, surface-to-volume ratio and the incident solar radiation was established and potentially higher energy efficient structures were indicated. As the result of analysis the interrelation between urban form and energy efficiency was established, which allowed to identify the urban patterns with the higher potential of energy efficiency.*

Keywords: Algorithmic modelling, digital city, parameters of energy efficiency, morphological properties, urban pattern, Prague

Introduction

Parametric urbanism can be interpreted in various ways, and for the study of the energy efficient cities the focus is on the display and interpretation of parameters influencing the possible energy gains and losses of the built structures. Centrally-planned urbanism addresses to a big-picture view, and misses all the local details that significantly affect the solution. This centralized approach invariably works through large-scale destruction of existing structures (either man-made or natural), followed by the construction of lifeless non-adaptive solutions (Salingaros, 2011). Parametric urbanism is about development of strategy and channeling of information, analyzing the data before drawing conclusions. It results as a city, where social, economic, environmental and spatial equations are resolved in favor of construction of the most sustainable and efficient urban morphology (Hindi, 2013). Application of algorithms could help city modeling adapt to different measures using algorithmic simulations (Leach, 2009). De Landa (2004) draws some connections between what he calls self-organizations and genetic algorithms of applied scripting patterns.

Fortier states, that the urbanist nowadays deals with management, logic on the things, reflect on the harmony of the space, dissonance and difference, doing things more comprehensible. The objectives of the profession are different from the 16th century Palladio or 19th Century Urbanism (Fortier, 2003). Owens (1986) explains, that spatial configurations of the city for evaluation are selected with varying degrees of subjectivity and most them is ruled out by non-energy considerations. Salat emphasizes the importance of city density, which is a major contributor to energy efficiency, especially in relationship to transportation (Salat et al., 2012). High density cities increase the social networks development and community interactions (Doherty et al., 2009). Lower density structures demonstrate the lower level of energy efficiency (Rode et al., 2014). There is a common agreement among researchers about the efficiency of compact cities (Große et al., 2016), there are other important issues, such as passive solar radiation and the ventilation factor. With the increase of compactness, the possibility to use natural resources like passive solar energy is decreasing since the tall building may cast shadows and block the natural light and solar heat and reduce the efficiency of passive cooling (Littlefair, 1998).

Buildings are the major agents of energy consumption. Energy efficiency of housing is very difficult to tackle because of its very complex properties related to lighting requirements, construction, privacy requirements and urban regulations. The energy efficient properties should meet at the same time social, physical and economic criteria. Research on surface-to-volume ratio is addressed to find the building typology with the minimal surface area and consequently the minimal potential energy losses, and the maximal built volume. March (1971) suggested, that the most efficient building would be "a half Cube or half sphere". This statement is based on surface-to-volume ratio, where a more energy efficient structure is actually less exposed to the outer environment. Compact, cube-like building actually has the minimum of heat gains and losses, but the large part of the central floor area is not accessible for natural daylight (Behsh, 2002). Outer surface is a major medium of temperature

exchange that follows a linear law by which for the same volume the more surface means more energy spent for keeping the same temperature. A low surface-area-to-volume ratio is optimal for a passive, low-carbon building (Thorpe, 2014). Curdes compares the index of surface to volume of different typologies where very obviously modernist high-rise buildings seem to have a good ratio. Poor performance is evident in individual housing, medieval and traditional European urban block structures are identified as energy efficient (Curdes, 2010). Increase of building compacity, which is higher for the structures with the simple footprint and clear undivided volume, reduces the heating and cooling loads of the building (Adolphe, 2001).

Solar radiation has a tremendous effect on energy efficiency, especially through passive solar gains, which is in fact the amount of solar energy that is absorbed by the thermal mass of the building. Exposure of the building or south facing orientation is one of the most fundamental principles which increase solar energy gains. The total gain from solar radiation is defined as the incident solar radiation during the selected period on the facades of a building (Rode et al., 2014).

Wind pressure has a major effect on temperature exchange. The relationship is linear: the more pressure, the higher the rate of temperature exchanges. In winter, the wind movement in the outdoor environment affects heat loss of the building, while in summer the change of wind direction and speed in the outdoor environment affects the ventilation and indoor air circulation. (Huifen et al., 2014)

Methodology

This study aims to find the relationship of morphological properties of urban pattern, such as shape and dimensions of the built units, and its energy efficiency, testing the criteria of density, site coverage, available solar radiation, wind flow and surface-to-volume ratio.

The research is performed by the following steps:

Definition of the set of measurable parameters which influence the energy efficiency of the urban pattern

Generation of a variety of 3dimensional models, which could be used for computer analysis

Analysis of energy efficiency of the urban patterns according to the selected criteria

Optimization of the dimensions of the main six typologies with the use of genetic algorithms Analysis of energy efficiency of morphological properties of city fragments of Prague

In order to find the influence of the geometrical parameters of the urban patterns on its energy efficiency, the study starts by generating of a set of hypothetical models or archetypes of urban pattern which may create possibilities for further testing or computer simulations. 60 generated patterns vary from 1 to 10 stories and include Square house, Row house and Urban block typologies arranged with the use of rectangular and circular grid. The Grasshopper definitions (urban morphology algorithms) are designed in a way, that the number of the buildings and dimensions of the built units (the length and the width) are adjusted in the fixed site according to the building height. Samples of the generated models are presented in (Figure 1). At this stage, some other properties which work independently from urban geometry, such as occupant behavior, thermo-insulating materials or human feeling of the temperature are omitted. Energy efficiency of urban morphology is analyzed through comparison of its performance by different criteria such as density and site coverage, surface-to-volume

ratio, annual solar radiation, wind sheltering factor, building dimensions and geometry.

The second part of research is based on an investigation of possibilities to find the geometrical properties and the way of spatial arrangement of the most energy efficient urban morphology. The problem of finding the urban pattern with the optimal combination of the high building density and low surface-to-volume ratio was examined with the use of the Galapagos Evolutionary Solver. The Evolutionary Solver requires variables or genes (the height and the width of the generated building), which are allowed to change (Rutten, 2010). Evolutionary algorithms are applied to the pattern definitions in order to optimize the morphologic properties of building blocks in relationship to minimal surface-to-volume ratio and maximal density.

At the final stage, the performance of theoretical generated urban morphologies is compared with the behavior of the groups of buildings, which are extracted from the existing city. Prague is very rich in urban forms with different layers of urban patterns, starting from the European City Block to prefabricated row-houses of the communist era buildings, to postmodern typologies, thus it is an exemplary site for the experiment. The 3D model of Prague is available in Google Earth since 2009 (Mellen, 2009) and the selected parts of it were exported for the further analysis (Figure 2). Different urban morphologies in Prague, including urban patterns of different shapes and models from triangular patterns to hexagons, and from row housing to towers and urban blocks are compared through the tri-fold properties of energy efficiency – surface
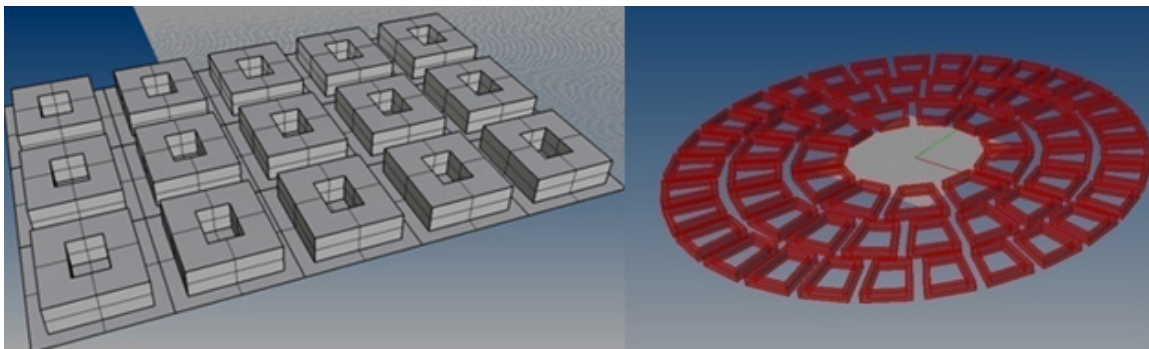

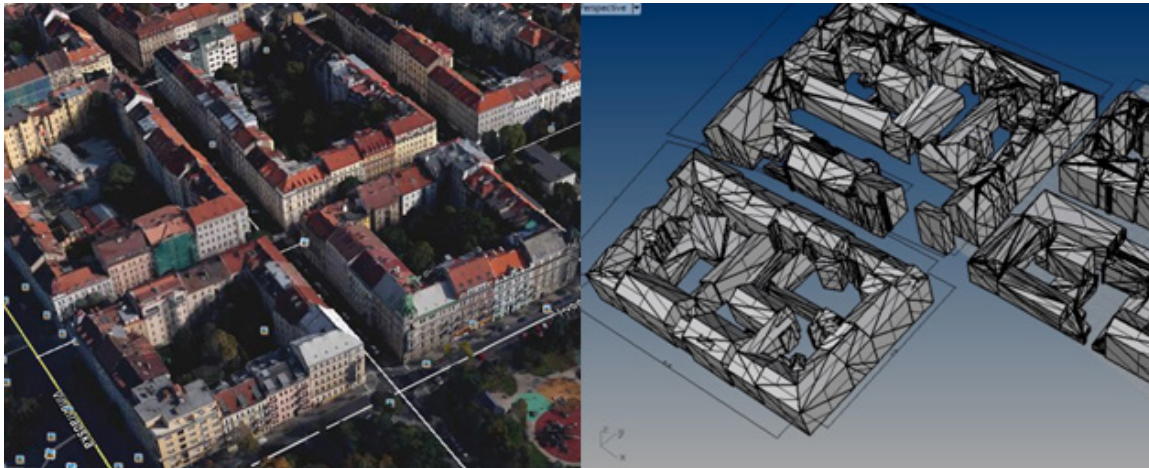**Figure 1. Sample screenshots of 3D models of urban patterns**

Figure 2. A screenshot of the GoogleEarth 3D model of Prague (left) and group of buildings exported from Google Earth to Rhino (right)

to volume ratio, incident solar radiation and building density.

Measurement and analysis: Density and Site Coverage

Density is one of the most important qualities of urban morphology, which is connected with its energy efficiency potential. The highest efficiency is usually associated with the highest density, which means at the same time reduction of the urban road network, the network of energy supply and rational organization of the urban space. There is no direct connection between the density and the height of the building. At it is seen after the comparison of 60 generated patterns from 1 to 10 floors, for the square- and rectangle-based building, density is increasing only up to 5 floors with the growth of the floor number. For rectangular and trapezoidal urban blocks density is growing proportionally with the increase of the building height. At this stage it is important to understand that the building height can not grow without limits. Tall buildings are negatively perceived by inhabitants. An increase in height requires the increase of the space between buildings and the existence of wide streets.

For every generated urban pattern site coverage ratio is decreasing with the increase of the height of the building. The highest values are noticed for the rectangular and trapezoidal urban blocks, and the lowest values characterize the patterns generated by square-based buildings. Site coverage is restricted by

the urban regulations, and for all the low-rise and especially single floor building patterns, it is at least 60%, which is not permitted by the urban regulations.

The task of finding the variety of urban patterns with the maximal density is investigated at the second stage of the research. The dimensions of the same six generated morphologies were set as flexible. With the application of genetic algorithm, the set of the most optimal solutions for the given site was found. The statement, that the highest density is typical for the rectangular and trapezoidal urban block patterns, is proven by the results of optimization. The optimal density is achieved by the application of the 6, 7 or 9 floor buildings; the width of the units may vary slightly. According to this statement, there is no need to use the buildings with maximal height in order to achieve maximal density.

For Prague models calculation of the density was complicated by the fact, that real buildings could have different heights of floors and floor plans configurations at different levels. Therefore, in this case the site coverage is a value, which is more objective. The average value of site coverage reaches the maximum for the bar or tower-shape buildings, since there are no closed or semi-closed courtyard available. It is at the same time an indicator of the lack of private space, which is associated with the specific building. For rectangular, triangular and trapezoidal urban blocks, site coverage ratio is the highest for the filled

structures and for the urban morphologies with narrow units. In this case it may be observed, that the inner courtyard of the built unit is filled by one or two floors of uninhabited structures, which reduce the private open space. The two groups of the medieval streets have the highest value of site coverage.

High level of density for the urban pattern is associated primarily with the economy of resources and energy. For the real urban situation the connection is not straight. The statement, that higher density may minimize energy losses, is valid only for the generated abstract models, where the distance between buildings is set to provide the minimal solar obstruction angle of 45 degrees. In this case the building receives the maximal solar radiation. In the real city the distances are smaller in many cases, and buildings may cast shadows one to another. The balance between energy gains and losses can be different.

Surface-to-volume ratio

Buildings with the higher surface exposure have more intensive temperature exchange and higher energy losses. High surface-to-volume ratio shows the potential heat losses though the external surfaces of the building. The more compact is the outer envelope of the building, the smaller is the surface-to-volume ratio and the better is its energy performance.

60 generated models of the six basic typologies are designed in a way that the built unit has a simple box-like shape, or in case of the urban block – the perimeter, trapezoidal or rectangular building with open courtyard. At this stage, it is easy to conclude, that the surface-to-volume ratio and, therefore, the potential energy losses of urban block are higher than the compact building due to the presence of void. The performance of the urban block pattern based on the use of rectangular grid is better than the one with the circular grid. For the tower and row house patterns the surface-to-volume ratio does not depend of the type of the spatial arrangement – rectangular or circular. The highest surface-to-volume ratio is found for the low-raised buildings, which makes this typology less energy efficient.

The ratio is decreasing with the growth of the physical dimensions of the buildings, which shows the bigger and taller buildings are more efficient. Pattern with tower built units has the maximal ratio, which shows the lowest efficiency of such type of urban development. Minimal surface-to-volume ratio was used as a parameter for the optimization of generated morphology with the use of a genetic algorithm. The lowest ratio, the lowest potential energy losses and consequently the better energy performance was demonstrated by the urban block patterns. The optimal dimensions of the urban block in application to the given site are relatively small: 70x70m for the rectangular unit and 64x69 for the trapezoid and the optimal height - 10 and 8 floors consequently. This correlates with the conclusion from the previous phase that it is not necessary to apply maximal dimensions to the buildings in order to achieve density and minimize the energy losses. For the units of tower and row house patterns dimensions tend to be maximal, but the use of the specific site provides multiple solutions with the best fitness value.

In the case of Prague, the minimal surface-to-volume ratio is registered for the simple-shaped contemporary structures. These buildings are characterized using the compact volume with a simple geometry, flat roof and lack of the building details. The parameters of the variations of urban blocks, such as square, rectangle, triangle and trapezoid are similar. Examining the variations between the geometries of urban block, the pentagon shape demonstrates higher surface-to-volume ratio, making it less efficient. The triangular urban block may be considered as the most compact structure with minimal energy losses. The specificities of the real morphologies, such as the distance between the two buildings which formed the courtyard, or the narrowness of the pattern and the level of courtyard infilling, slightly influenced the overall performance. The long medieval street has performance equal to the urban block groups, while the courtyard medieval street is closer to the contemporary structures.

It is important to note that the surface-to-volume ratio cannot be observed as the only parameter which affects the energy efficiency

of the urban patterns. It indicates the potential energy losses, but there are also potential energy gains of solar radiation. In this case it may be predicted that the perimeter urban block will always cast a shadow on to one of its walls, which will reduce the possible energy gains.

Annual Solar Radiation

Solar radiation indicates the energy which is received by all the walls and roofs of the built units of the urban pattern. The higher level of received solar radiation indicates the pattern with higher energy gains, which gives to it the potential to be more efficient. The computer simulation was conducted for the 60 generated urban patters and for the 64 samples from Prague.

At the first stage of research by results of simulation the urban block performs worse in comparison to the other generated patterns. Both circular and rectangular urban block patterns receive less solar radiation, which can be explained by the complex shape of the building with the courtyard, which causes an extra shading of the walls. Incident solar radiation increases with the decrease of the building height for all cases. The relation is not linear, which can be explained by the fact of adaptation of the distances between units according to the heights in the generated model. For the two morphologies based on the use of the square-based building and for the circular urban block pattern, there is a segment between 3 and 9 floors, where the difference in values is minimal.

In the case of the Prague examples, the solar energy which is received by different typologies of urban blocks is higher than the one of the contemporary simple buildings. The blocks with the irregular orientation of sides, such as triangular or trapezoidal are preferable than rectangular. The structures with an open courtyard gain more radiation than the ones with the filled one. The medieval street structures perform the worst. For the contemporary buildings, the simple bar or tower-like building is more efficient than the L-shape or U-shape.

Wind Sheltering Factor

Simulation of the virtual wind tunnel was conducted for an analysis of wind performance of 60 generated urban patterns. The acceleration of wind speed is connected with the decreasing of the air temperature and therefore with potential energy losses. The study was based on the presupposition that in conditions of central Europe it is preferable to create the wind shadow and therefore to prevent the cooling of building surface by the air flow.

In both rectangular and circular form, low storey buildings create a wind shadow for the whole examined area. Up to the 5-6 floors the wind speed is still lower than the average, but for the high-rise buildings, it is significantly higher, resulting in the appearance of wind tunnels between the buildings. The wind speed accelerates more than average along the perimeter of the morphologies, indicating the necessity of additional thermal insulation and wind protecting membranes of the building facades. In the circular pattern, this phenomenon is more evident.

Conclusion

The study is based on the search of the balance between the energy losses and energy gains of the morphological properties of urban patterns. In some cases, the requirement which may enforce one of the elements of this equation, will contradict the other. Nevertheless, it is possible to draw the general set of rules, which may be applicable for different urban solutions. Low energy losses are character for the compact urban structures with high density. For the simple-shaped box-like buildings, the highest reasonable level of density is achieved for the built units of 5 floors. The same height is the best solution for the wind sheltering. Simple-shaped buildings have low surface-to-volume ratio which decreases with the increase of height and perimeter of the building. In this case it is important to note that building dimensions cannot increase endlessly; building height is usually controlled by the urban

regulations and building width is accepted according to the necessity of direct lightening of the rooms. Potential energy gains of the simple-shaped buildings are higher. Incident solar radiation decreases with the increase of the building height, but it may be noticed that it remains stable from 5 to 7 floors.

The urban block demonstrates the increase of the density with the increase of the building height. Application of the genetic algorithm allowed to identify its optimal dimensions. In order to minimize the energy losses, the side of the urban block should be about 60-70m. Urban block demonstrated the best results in its ability to create a wind shelter. The courtyard remains protected with the use of the building of any height. Meanwhile, in order to create a comfortable flow through the streets, the height of the built unit should not be more than 6-7 floors. The energy gains of the urban block are smaller than of a similar pattern which is combined by the simple-shaped buildings.

The study had been developed based on the climate conditions of Central Europe with the condition of maximization of energy gains and minimization of energy losses. In order to apply the theory to a different place, the balance between these two factors should be changed according to actual climate conditions. Thus, in severe north conditions where the issue of minimal energy losses dominates, compact building shapes and creation of the wind shelter prevails over the potential gains of solar radiation, since the intensity of northern sun is very low. In moderate climates, the issue of wind protection may be less important, but in wet climates the natural ventilation should be encouraged. In hot climates, the situation is reversed and the built form should be designed in order to maximize the energy losses and maximize the shading. The building shape in this case becomes less compact and more porous.

Selection of the type of urban form depends in every case not only on the requirements of energy efficiency, but on the urban context, climate, tradition and other factors. Different typologies from the individual houses, row houses to the residential towers can be applied within the borders of one city, but the factor of selection of the morphology with the correct balance between the energy gains and losses can advance the urban planning towards more sustainable solutions.

The algorithms or form generators could be used in designing the cities of the future or scanning and analyzing existing cities. The concept further advances the ideas of parametric urbanism in an era where information technology could be used as a tool to improve cities and urban form based on the use of algorithms. The generated optimized city could be more energy efficient and socially and economically viable in the threshold between open space and built form.

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