Generation and evaluation of alternative urban densification scenarios

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Abstract

This paper discusses a research aiming toward the development of a computational environment for the generation and evaluation of alternative urban densification scenarios. The envisioned densification scenarios include measures such as new buildings on yet empty building lots as well as horizontal and vertical extension of existing buildings. The respective potential future developments are framed here in part by a set of spatial constraints defined in building regulations and guidelines (such as, property boundaries, permitted building heights, daylight access). The generated alternative urban densification solutions can thus be subjected to comparative assessment and ranked with regard to multiple evaluative indicators pertaining to energy and environmental performance.

Introduction

The world population is rapidly increasing, especially in metropolitan areas (WHO 2016). Recent projections foresee a vast expansion of urban population by 2050, with an increase from 60% in 2030 to 66% by 2050 (UN 2014, 2015). This development has been accompanied by growing urban sprawl and its corollaries in terms of environmental degradation, including waste heat and CO2 emissions, deforestation, as well as social segregation and negative economic implications (Wilson and Chakraborty 2013, Zhao 2013). In this context, densification of existing urban structures has been suggested as a promising strategy with important sustainability implications (Nabielek 2011, Fatone et al. 2012, Schmidt-Thomé et al. 2013). In general, urban densification entails a more compact city aimed at reducing the carbon footprint, resulting from optimized energy use and traffic flows. Whereas the importance of urban densification has been recognised, it has not been consistently included in urban planning. Consequently, there is a paucity of relevant computational environments for the efficient analysis of the existing urban fabric and its potential for increased density.

In this context, the present contribution investigates the potential and implications of urban densification of existing urban domains. Specifically, we describe the essential features of a computational environment for the automated generation of large-scale schemes for urban densification. Such schemes typically include measures such as new buildings on yet empty building lots, horizontal and/or vertical extension of the already existing buildings, and reallocation of lots with non-building destinations to building sites. The respective developmental work requires the collaboration of experts in urban planning, building informatics, and performance simulation. To obtain the necessary empirical data for development and validation purposes, we rely on an ongoing case study involving a specific urban district in the city of Graz, Austria, as a potential candidate for densification measures.

Note that the main purpose of the proposed computational environment is to support an iterative generation and evaluation approach in urban densification planning. As more detailed descriptions of the research regarding the evaluative component of the environment can be found in a number of previous publications, we focus, in the present contribution, primarily on the generative aspects of this environment.

Approach

Sources of constraints

To investigate the potential and implications of urban densification of existing urban areas, a number of schemes for urban densification can be envisioned. As mentioned before, such schemes include measures such as new buildings on yet empty building lots, horizontal and/or vertical extension of the already existing buildings, and reallocation of lots with non-building destinations to building sites. As with many similar situations, the respective potential future developments in view of densification are constrained by various spatially relevant boundary conditions. Instances of such constraints are expressed, for example, in building regulations and zoning guidelines.

In the present contribution, a specific class of constraints are informed by corresponding local urban development concepts, as well as land use and building regulations as per well-established national (Austrian) and local (i.e., relating to the city of Graz) standards and legislations. These pertain to land use allocation and zoning (FLÄWI 2016, BBPL 2016) regarding green areas, building areas, traffic areas, maximum permitted building density, and land use type (e.g., residential, commercial, mix-use). Moreover, more specific regulations (e.g., OIB 2016) spell out a set of spatial and design guidelines applicable to the buildable areas (e.g., building lots, position of built structures, boundaries of buildable areas).

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The spatial potential for densification and the required features of proposed additional built spaces are furthermore constrained by guidelines issuing essential technical requirements and regulations in the building sector, such as energy requirements, daylight access, fire safety, and noise control. Altogether, these documents and guidelines establish a distinct set of spatial and regulatory constraints pertaining to variables such as horizontal and vertical limits of spatial growth (e.g., property boundaries, building footprints, maximum permitted building height, building density, daylight access). Table 1 provides an overview of a number of key spatial constraints and corresponding definitions.

Rules and algorithms

To explore the district-level densification potential, we adopted an approach that couples rule-based reasoning and generative algorithms. Figure 1 illustrates the schematic representation of the generative components of the envisioned modelling framework. The incorporated process involves the following steps:

First, the urban domain is represented in terms of "positive" (built volumes) and "negative" (i.e., void) spaces. Secondly, within the negative space, irreclaimable parts – such as those allocated to streets, urban parks, plazas – are identified. Thirdly, the building potential of the remaining volume is examined with regard to the aforementioned contextual (spatial, legal, functional) constrains. Thereby, different spatial arrangements are generated, including vertical extensions (additional floors, given structural feasibility) and/or horizontal extension of existing buildings, given accessibility, insolation, and daylight feasibility. (A more detailed illustration of this process is provided in the following section of the paper.)

Finally, the generated solutions may be compared, evaluated, and ranked based on a diverse matrix of evaluative indicators, including net built volume gain as well as estimations of energy efficiency, environmental impact, and cost factors.

Table 1: List of constraints

Constraint	Definition
Property line	The lot boundary beyond which a building cannot be built
Setback line	The distance from the lot boundary beyond which a building cannot be built
Building height	The permitted height of the buildings within a specific urban zone
Building distance	The minimum required distance between a building and a neighbouring lot
Floor area ratio	The ratio of a building's total floor area (gross floor area) to the lot area
Visual connection to	The minimum distance from a building window to the outside obstacle (e.g., tree,
Daylight access	Access to the visible sky shall not be obstructed beyond a 45°sloped plane originating from the facades' lowermost windows and extended toward neighbouring buildings

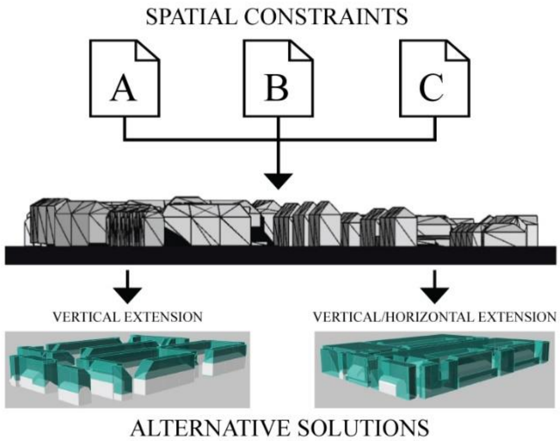

Figure 1: Proposed framework for urban densification (information extracted from multiple sources of constraint are successively applied to the existing substance of an urban district, resulting in multiple spatial densification schemes).

Note that the entire process is not meant to result in a unique optimal solution. Rather, it is intended to enable users and stakeholders to iteratively generate, compare, and evaluate multiple intervention scenarios.

Implementation process and features

In the current implementation, the initial district model is generated in the CAD-based modelling environment Rhinoceros 3D (2016). Toward this end, we utilised digital information provided by the city of Graz, including multi-layered CAD representations of geometry, cadastral lots, and street network. Thereby, urban geometries are provided as a collection of closed polygons (such as, street segments, building footprints, green areas, cadastral lots, and urban blocks) and as a 3-dimensional mesh building model. The multi-layered structure of the representation allows for the differentiation between buildable and non-buildable areas.

The imported district geometry model was further enhanced with the aid of parametric modelling and visual programming plug-in Grasshopper (see Rhino3D 2016). For this purpose, we used a number of built-in algorithms provided in Grasshopper (GH) to visualise the 3D geometry (such as, Delaunay triangulation). Once the initial district model is generated, custom GH C# add-ons are developed for the inclusion and coherent application of spatial constraints within the buildable areas. The respective GH C# add-ons were developed within the Microsoft Visual Studio Integrated Development Environment (Visual Studio IDE 2016). Visual Studio IDE was selected due to its capabilities toward a seamless integration with third-party applications via a number of specifically crafted extensions. Furthermore, Visual Studio IDE allows for testing, debugging, and analysing the quality and computational performance of an engineered code.

To facilitate the respective developmental work, we used the Grasshopper Assembly Wizard extension for Visual Studio that provides a ready-made template for creating GH components (Grasshopper Assembly 2016). The template is structured into five essential parts of a GH component: basic information (i.e., component name, nickname, description, category and subcategory), input of the component (defines the required input data parameters, such as lines, points, or polygons), output of the component, envisioned procedure referred to as the SolveInstance (defines the targeted spatial concepts and generative algorithms), and Component Icon (optional). Once all template aspects are specified, a custom Grasshopper assembly project file (.GHA) is created, which is then imported into the GH environment for further application.

The illustrative case of daylight access

To further illustrate the above implementation process, consider the case of daylight access computation. The respective operations are informed by rules meant to ensure that natural light is properly provided to all the buildings on the lot. The respective calculation methods and building code requirements are formulated in OIB Guidelines, document number 3 (OIB 2016). Put in simple terms, the method ensures that building facades' access to the visible sky shall not be obstructed beyond a 45° sloped plane originating from the facades' lowermost windows and extend toward neighbouring buildings (see Figure 2). Hence, vertical extensions of the neighbouring buildings above these planes would not be permissible. The required input data for the respective functionality developed in GH includes building footprints provided in the form of closed polygons (Figure 3). The algorithm then recognizes each polygon edge and computes a 45° plane in Z-direction from the corresponding edge.

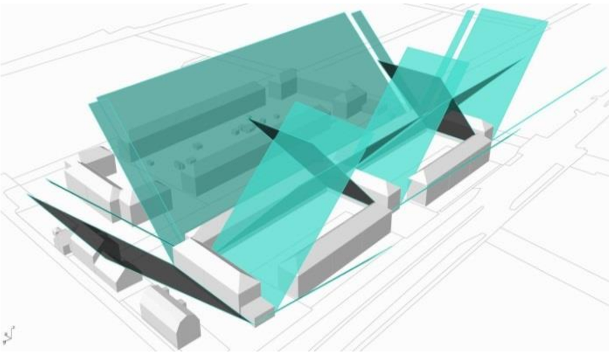

Figure 2: The 3D representation of obstruction planes for daylight access computation.

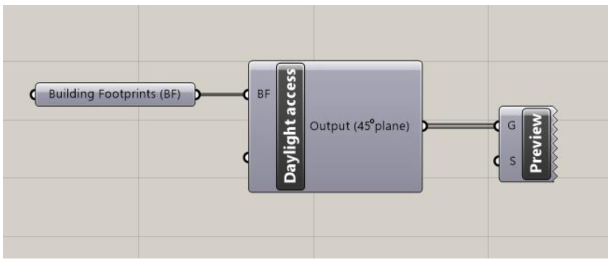

Figure 3: The application of developed GH component for daylight access computation.

Application scenario

The urban context

The proposed approach and related tools are currently being tested based on a data set for a specific urban area within the city of Graz, Austria (see Figures 4 and 5). The domain is representative of a low-density urban typology in this city. The permitted Floor Area Ratio (FAR) of the area is in the range of 0.4 to 0.8. However, for 2/3 of the area, around 70% of the density potential is currently used. The remaining 1/3 uses only around 32% of the density potential. The area is predominantly residential (social housing), with a number of local retail facilities (e.g., grocery stores, cafés). The buildings were mainly constructed in the period between 1940 and 1950. The building envelopes are of poor thermal quality. Buildings are typically of 2 to 4 stories high, with pitched roofs. The general position of the buildings on the lot allows for front gardens due to large setbacks. The area is also characterized by relatively large distances between buildings. Green spaces (mostly private gardens) take more than 50% of the area. Both wide and narrow streets with medium to high traffic rates intersect the area. The area is very well served by public transport. The terrain is slightly sloped.

Figure 4: Map of the study area.

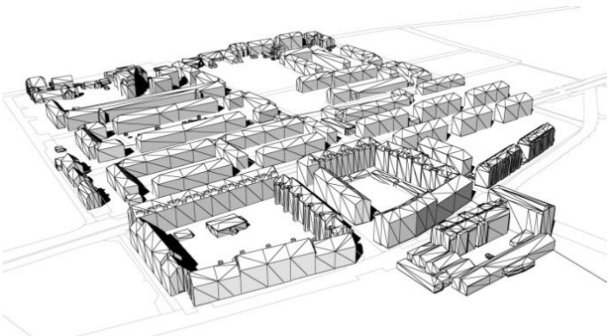

Figure 5: 3D model of the study area.

Illustration of constraint-based generative sequences

As such, the developed routines for constraint-based spatial operations can be arranged and executed in terms of different sequences. For the purposes of present treatment, consider the status quo representation of the relevant urban area as depicted in Figure 6. Starting from this state, two illustrative alternative densification sequences are described in the following.

The first sequence (S1) explores the generation of the theoretical maximum buildable potential by combining vertical and horizontal extensions (see Figure 7). Table 2 includes the operative steps involved in this sequence.

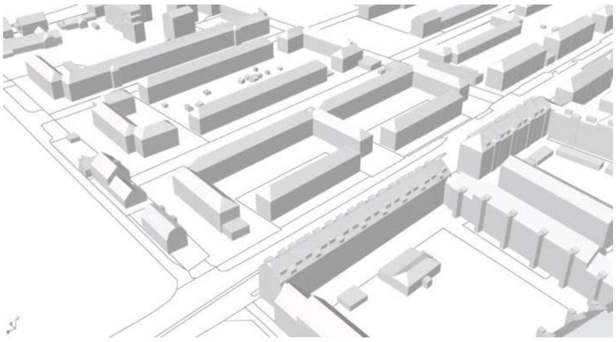

Figure 6: The initial model representing the status quo of the selected urban area in the city of Graz.

Table 2: Illustrative densification scenario S1

Sequence	Operation
S1_a (see Figure 7a)	All theoretically buildable areas are vertically extended until the permitted building height is reached. This step constitutes the theoretical maximum spatial extension potential.
S1_b (see Figure 7b, c, d)	From the volume associated with the above maximum potential, additional volumes are carved out via successive execution of further constraint-based operations. For this purpose, the following constraints are considered and successively applied: building distance, visual connection to the outside, and daylight access.
S1_e	Once the resulting spatial solution is generated, users can appraise it in terms of the potential volumetric gain, energy demand, environmental impact, and cost factors.

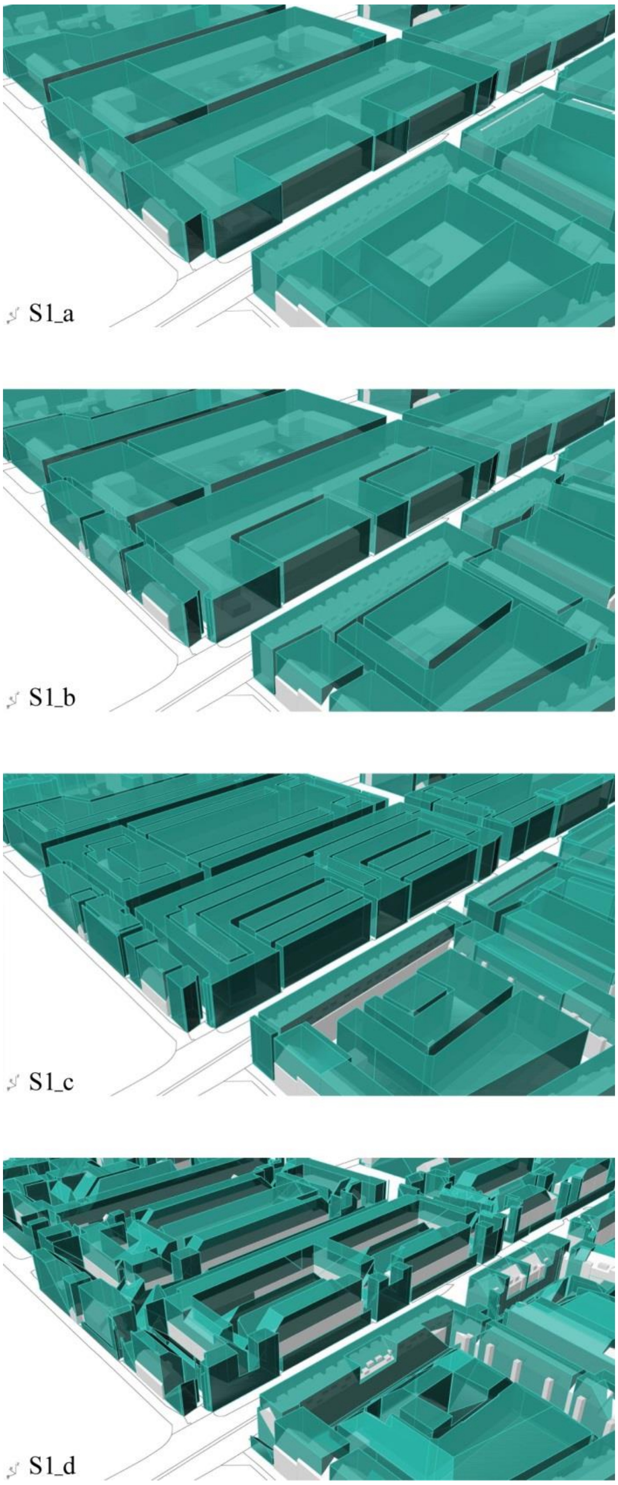

Figure 7: The illustrative sequence for the generation of theoretical maximum buildable potential: S1_a) The application of building height constraint, S1_b) The application of building distance, S1_c) The application of visual access to the outside, S1_d) The application of daylight access.

The second sequence (S2) explores the generation of vertical extension potential of existing buildings (see Figure 8). Table 3 includes the operative steps involved in this sequence.

Table 3: Illustrative densification scenario S2

Sequence	Operation
S2_a (see Figure 8a)	All theoretically buildable existing buildings are vertically extended until the permitted building height is reached.
S2_b (see Figure 8b)	From the volume associated with the above vertical potential, additional volumes are carved out via execution of the constraint-based operation related to the daylight access.
S2_c	Again, to evaluate the generated solutions, net built volume gain as well as indicators pertaining to energy, environment, and costs are taken into consideration.

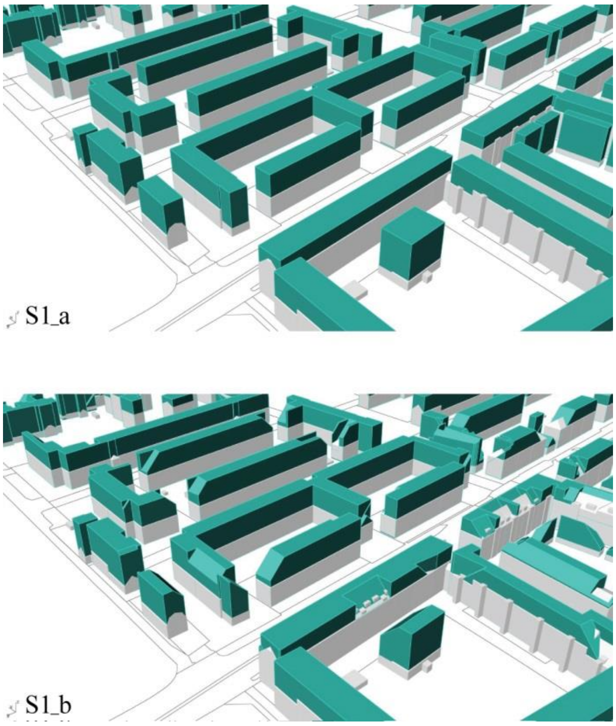

Figure 8: The illustrative sequence for the generation of vertical extension densification potential: S2_a) The application of building height constraint, S2_b) The application of daylight access constraint.

Evaluation of potential future developments

As mentioned above, once the respective potential future developments are generated, they may be appraised based on a flexible matrix of evaluative indicators. Toward this end, a set of related indicators for the inclusion in the framework are considered, such as, the net built volume gain, factors related to the energy use, and cost factors.

As such, the net building volume gain may be assessed by means of a volume component readily available within the GH environment. In case of the illustrative instances described above, the theoretical potential volume gain potential by means of combined horizontal and vertical extension is 250%, whereas vertical extension alone displayed a volumetric gain ration of around 60%.

Ongoing work

As alluded to before, generated urban densification scenarios need to be evaluated in the light of multiple performance indicators. Thereby, one class of essential evaluative processes pertains to energy performance. Toward this end, we have adapted a specific approach that incorporates full dynamic numeric simulation capability in the urban energy computing environment.

Toward this end, first a reductive bottom up urban stock energy use model is constructed. In order to enable the large scale adoption of transient building performance simulation tools, a two-step method (i. sampling-based reduction and ii. re-diversification) is adopted (Ghiassi et al. 2015, Ghiassi and Mahdavi 2016a, 2016b, 2016c). The resulting urban energy computing environment can facilitate the generation of dynamic and realistic energy use patterns via incorporation of stochastic occupancy models, as well as pertinent (locally-adjusted) representation of external boundary (microclimatic) conditions. This environment can thus enable users to assess the energy and environmental implications of large-scale design and renovation proposals to support, amongst other things, policy making at the urban level.

A further ongoing activity involves the organization of workshops with potential users of the environment. Thereby, feedback from pertinent stakeholders are documented, providing the basis for adjustments and improvements. A recent related workshop suggested that the spectrum of potential applications of envisioned environment is rather wide. Municipalities are interested in the environmental, economic, and social impact assessments of different urban densification strategies over time. Private entities such as construction companies are interested in an efficient and rational investigation of the possibilities for development and improvement of building stock, and estimation of its baseline energy demand. As such, the proposed research and development effort has the potential to contribute to the provision of timely and detailed information regarding urban development and environmental sustainability to a diverse set of stakeholders including, but not limited to, the community of architects, urban planners, municipalities, environmental agencies, and energy utilities.

Conclusion

In this paper we introduced a computational environment, which is intended to support the generation, visualisation, and evaluation of alternative urban densification schemes. The implementation process demonstrated the capability of proposed tool to generate potential densification schemes, such as horizontal and vertical extension of the already existing buildings, while accommodating the consideration of spatial constraints defined, for instance, in building regulations and guidelines.

The outcome of such parametric analyses of urban densification scenarios is expected to provide valuable feedback to the decision makers toward more sustainable urban environment design and practices. The work conducted so far offers a promising starting point toward comprehensive analysis of the existing urban fabric and its potential for increased density.

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References

BBPL (2016). Available online: http://www.graz.at/cms/ziel/1277375/DE/ (Last acessed: 24.11.2016.)

Ghiassi, N., Hammerberg, K., Taheri, M., Pont, U., Sunanta, O., Mahdavi, A. (2015). An enhanced sampling-based approach to urban energy modelling. Proceedings of the 14th IBPSA Conference, Hyderabad, India, 7-9 December.

Ghiassi, N. and A. Mahdavi. (2016a). A GIS-based framework for semi-automated urban-scale energy simulation, Proceedings of the CESB Conference, Prague Czech, 22-24 June.

Ghiassi, N. and A. Mahdavi. (2016b). Utilization of GIS data for urban-scale energy inquiries: A sampling approach, ECPPM 2016 eWork and eBusiness in Architecture, Engineering and Construction, Limassol, Cyprus, 7-9 September.

Ghiassi, N. and A. Mahdavi. (2016c). Urban Energy Modeling Using Multivariate Cluster Analysis, Proceedings of the CESBP Central European Symposium on Building Physics AND BauSIM 2016, Dresden, Germany, 14-16 September.

Fatone, S., Conticelli, E., Tondelli, S. (2012). Environmental sustainability and urban densification. *WIT Transactions on Ecology and the Environment 155*, 217-228.

FLÄWI (2016). Available online: http://www.graz.at/cms/beitrag/10084441/1604085/ (Last acessed: 24.11.2016.)

Grasshopper Assembly (2016). Available online: https://visualstudiogallery.msdn.microsoft.com/9e389515-0719-47b4-a466-04436b491cd6 (Last acessed: 24.11.2016.)

Nabielek, K. (2011). Urban densification in the Netherlands: National spatial policy and empirical research of recent developments. 5th International Conference of the International Forum on Urbanism (IFoU), Global Visions: Risks and Opportunities for the Urban Planet, Singapore, Malaysia, 24-26 February.

OIB (2016). Available online: https://www.oib.or.at/en/oib-guidelines (Last acessed: 24.11.2016).

Rhino3D (2016). Available online: www.rhino3d.com/ (Last acessed: 24.11.2016.)

Schmidt-Thomé, K., Haybatollahi, M., Kyttä, M., Korpi, J. (2013). The prospects for urban densification: a place-based study. *Environmental Research Letters 8*, pp. 11.

UN (2014). United Nations, Department of Economic and Social Affairs. World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352).

UN (2015). United Nations, Department of Economic and Social Affairs. Working Paper No. ESA/P/WP.241.

Visual Studio IDE (2016). Available online: https://www.visualstudio.com/ (Last acessed: 24.11.2016.)

Wilson, B. and A. Chakraborty (2013). The Environmental Impacts of Sprawl. *Sustainability 5*, 3302-3327.

WHO (2016). Global report on urban health: equitable, healthier cities for sustainable development. World Health Organization, Geneva, pp. 239.

Zhao, P. (2013). The Impact of Urban Sprawl on Social Segregation in Beijing. *Tijdschrift voor economische en sociale geografie 104 (5)*, 571–587.