

# COMPACT SINGLE-FAMILY HOUSING GENERATED BY PARAMETRIC DESIGN – SEARCH FOR OPTIMAL, SUSTAINABLE OR SMART DENSITIES

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## Abstract

**Single-family housing – the form of residential buildings expected by the society is often inconsistent with the theoretical optimum form of housing that is recommended in urban theories and ideas. Research indicates that most Poles want single-family housing, while its density is low in comparison with multi-family housing which provides a more compact city. The paper identifies the thesis to what degree it is possible to develop a compact city with single-family housing. The authors verify how parametric design may be useful in urban design and spatial planning. The purpose of the article is to discuss the possibility to generate single-family housing estates' projects using the parametric tool of the Grasshopper program. The authors demonstrate how parameter tool-supported designing may be useful for better effectiveness of using space. The research used a script by Dawid Kańny, developed for the purposes of his diploma thesis, in which he attempted parametric variants and optimization. The paper describes the issue of "density vs quality of life" in quantitative terms. Quantitative density variants can be used in analysis for future smart and intelligent cities' development.**

**Keywords:** Parametric designing; Intense single-family housing; Numerical parameters of single-family housing; Smart cities; Compact city.

## 1. INTRODUCTION

The discussion on the optimum form of housing seems endless, but still the idea of compact city seems nowadays to be presumed as most sustainable. The concept of a compact city was first invented in 1973 by George Dantzig and Thomas L. Saaty [17], two mathematicians whose idea was directed towards a better use of resources. This concept can be combined with the book *The Death and Life of Great American Cities* (1961) published by Jane Jacobs [18], who criticized modernist planning policies that were considered destructive to the local communities. Jacobs also pointed several important conditions for the implementation of urban regeneration: mixed of use, small walking distance urban blocks, mixing of ages and types of buildings, and dense concentration of people (ap.100 apartments per acre 247 apartments per hectare). The idea of compact city exist in many varia-

tions in many theories including the idea of smart city, but all of them lead to discussion about the urban form of housing. Most people (and also Poles) prefer low rise single-family to multi-family housing [1]. However, it is clear that more effective use of compact area is evaluated as better and more future-oriented in terms of sustainable development [2]. In order to provide an optimum residential environment, what counts is the quality of space including, among others, local facilities for citizens (access to services, green areas and others). What is also important is the quantitative approach related to land use ratios, including the number of apartments and citizens on the given area. So far, the planning of housing complexes has been taking place in stages or comprehensively with the use of typical tools of spatial planning and urban design: dedication of the area to the given type of housing and specification of the borderline values of ratios [3]. The values of ratios are assumed based on typical recom-

mentations, standards or experience. Nowadays, such an approach may be supplemented by creating housing scenarios using parametric tools.

Parametric specification originates from mathematics, where certain parameters, i.e. variables, may be edited to manipulate the final result of an equation or system of equations. An example of such a parametric equation is presented in the study by professor Leszek Mieszkalski who developed the formula for mathematical modeling of potato tubers [4]. Patrik Schumacher, who cooperated with ZahaHadid, claims that parametric designing is not only the method of creating complex geometries, but also the next big step in architecture. In his opinion, it would be justified to introduce a new, global style, both in architecture and urban planning: parametricism [5]. A critical opinion on that movement and the possibilities to use it, were presented, among others, by Michał Stangel who considered it promising, but also bearing certain drawbacks [6]. Its application in designing cities is quite beneficial, as it allows to create a flexible structure that may be changed quickly and effectively, depending on designer's preferences or various conditions, which allows one to arrive at different results while starting from the same original idea. Also, this allows to adapt the project to new problems that appear over time during development of the urban fabric [5]. Other designers also emphasize the significance of parametric techniques in designing the so-called smart cities. They are characterized by much greater efficiency at lower consumption of resources. For that purpose, a gigantic number of factors has to be considered, analyzed, and then transformed into an urban form. The best way of resolving that problem is parametric designing [8].

Based on the broadly understood urban theory, a convenient area for the purposes of a theoretical project for a residential complex is ca. 100 ha, i.e. an area similar to a circle or square of the diameter or side equal to 1000 meters. That way of thinking was first introduced by Clarence Perry, with his theory of a neighborhood unit, which is currently disseminated and updated, among others, by Douglas Farr and Richard MacCormac. In his "Sustainable Urbanism", Douglass Farr proposed minimum values of density to make new housing areas sustainable – he suggested that minimum rational densities should not fall below 40 apartments per hectare [7]. In turn, Richard MacCormac claims that what is rational in terms of public transport economy, is placement of 10 thousands citizens in an area of ca. 100 ha [11]. It may be assumed that the center of such an area would be

equipped with a public transport stop as well as the basic facilities: a school, a preschool, a large food store, as well as a local park with a community center (cultural center or after school club). Such composition allows, in theory, to reach the center on foot (ca. 5–10 minutes) and so it is consistent with the broadly understood sustainable development movement, because it limits local trips. Among others, this is confirmed by Krystyna Solarek who stated that, *despite the fast and chaotic development of cities, certain rules can be found: the main transportation routes of urban units points towards certain local center, and plot parcelling led to an octagonal mesh* [9]. The following question may be asked based on the above-mentioned assumptions: In our times, is it possible to develop a properly compact single-family housing complex which, on the one hand, addresses the community needs of high quality of life and, on the other, meets the premises of properly dense housing? In order to answer that question, the authors decided to use the parametric method for simulation of housing variants.

## 2. METHOD

The research was based on the Grasshopper 3d program which is a visual programming language [12] used, among others, in structural engineering designs, parametric architecture, or parametric spatial structures. Grasshopper is considered one of the most user-friendly tools of that type [10]. That program was used for developing the script which allows to generate quickly single-family housing geometry prototypes in a large area on the basis of the parameters defined by the designer. The possibility to generate designs for a large area quickly (in ca. 1 minute) was considered an advantage for experimentation and multiple variants of various scenarios. In theory, it is possible to use the script in the area of even inconceivably large areas of several hundreds of hectares. An example of such an application is the virtual mega-district "GLANhatan" generated as an April Fools' Day joke by the authors, in the area of 190 ha, with multi- and single-family housing [14]. Due to the linear functioning of Grasshopper, it was necessary to determine one specific urban structure to be developed in each case. For the purposes of the experiment, the orthogonal system was abandoned. That method of designing proved very monotonous and failed to use the whole potential of the script. Therefore, the selected fundamental composition scheme for the whole experiment was the monocentric system – with the assumed area, a greater number

of centers would not be justified. Furthermore, the concentric arrangement seems attractive in terms of composition and functionality taking into account the easy (and obvious) connection to the center.

The division of the script into quarters is made using roads radiating from the center towards the margins and roads making up circles around the center. This results in cohesion, possibility to easily compare the respective arrangements and in clarity of composition. It was assumed that the script would generate diverse housing for an area of any shape. Specific, existing plots can be taken into account, but it was assumed that only theoretical lands with assumed surface area will be considered. In order to better demonstration the operation of the script, it was necessary to determine an irregular, but not exceedingly complicated, shape. For a single-family housing project, the above assumption seems to be natural and attractive in terms of composition. The script accounted for the following steps (Fig. 1):

1. Development of the whole shape.
2. Division of quarters in the center.
3. Division of the remaining quarters.
4. Assignment of quarters to types of housing.
5. Development of quarters with additional services and parks.
6. Parameters for single-family housing.
7. Additional division of quarters with articulated roads.
8. Additional division of quarters with straight roads.
9. Division and assignment of plots to types of single-family housing.
- 10.1. Generation of detached housing.
- 10.2. Generation of detached housing on triangular plots.
- 11.1. Generation of semi-detached housing.
- 11.2. Generation of two-apartment semi-detached housing.
12. Generation of terraced housing.
13. Generation of trees
14. Generation of preliminary visualization.
15. Calculation and export of urban ratios.

The implementation into the script looked as follows: First, it was measured whether at least two single-family plots of the minimum dimensions specified in the previous paragraph, would fit at the shorter sides. Then, in the resulting lots, the middles of the sides located at the street are connected to the opposing sides. Thus, the average plot situation direction develops, for which the North-South deviation angle is measured, and then it is verified whether terraced housing can be located there based on the maximum deviation angle. If it cannot, the same test is performed for semi-detached housing. The remaining plots are assigned to detached houses.

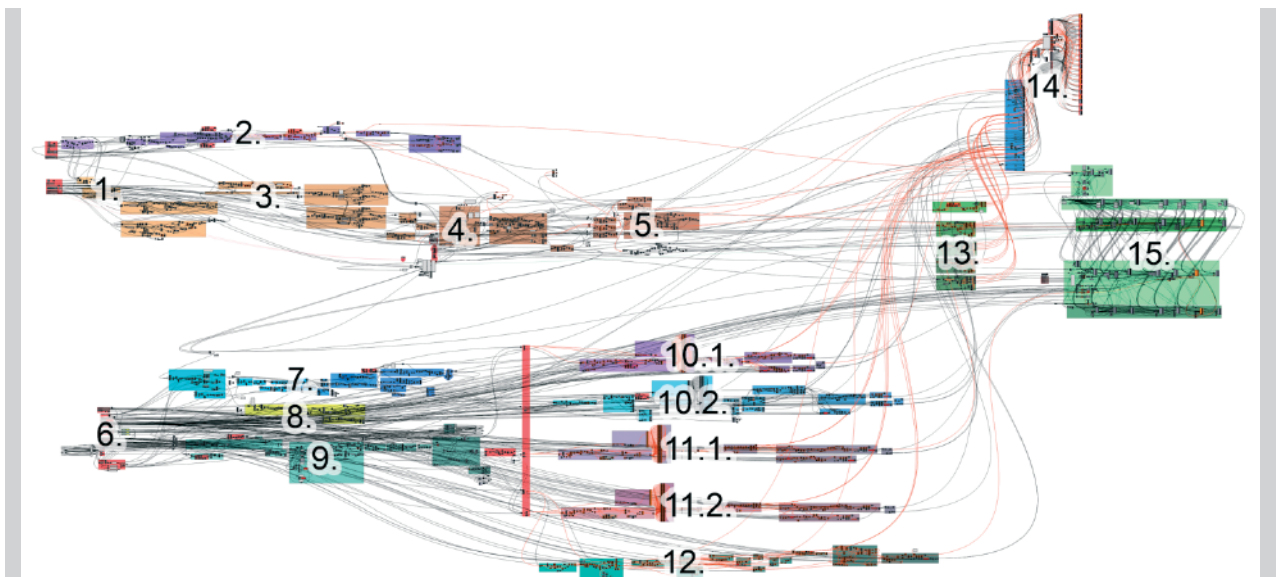


Figure 1.  
Entire script responsible for developing the single-family housing – print screen of the Grasshopper script

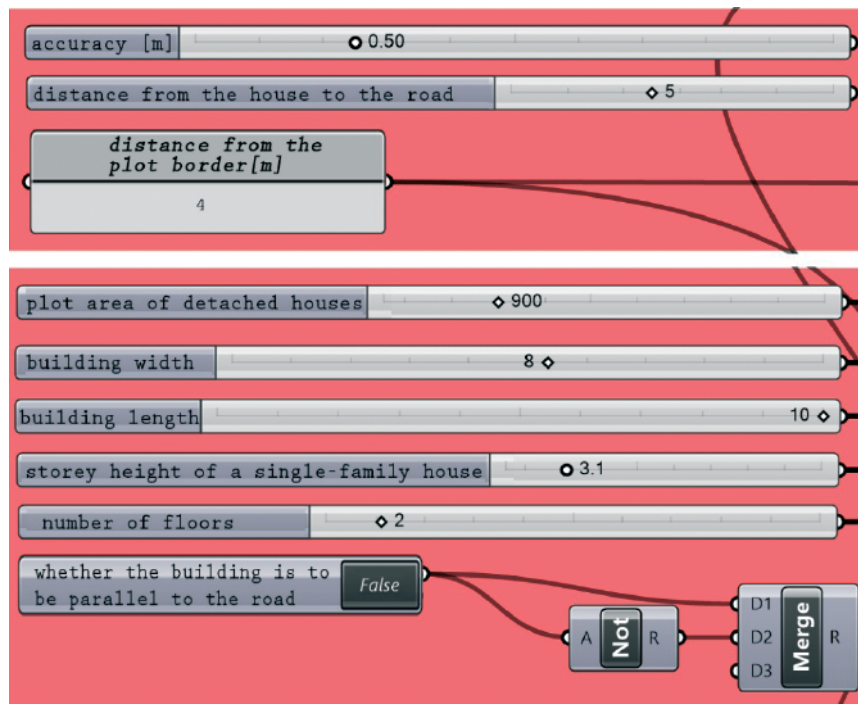


Figure 2.  
Parameters affecting terraced single-family housing

### Single-family detached housing

These divisions no longer take into account the minimum and maximum dimensions of single-family plots, because those conditions have already been met in the previous steps. The main parameter is the surface area that should be demonstrated by each lot according to the designer. Apart from the distance from the plot border, there are no Polish standards that would define that quantity. Typical area of a plot for single-family housing, specified in the local zoning plan, is between 500 and 1000 m<sup>2</sup>.

The remaining ones determine the dimensions of the building and its location with regard to the road. First, the area of the whole plot is calculated that is to be divided, thus arriving at how many single-family plots are possible. The areas of the final plots may be up to ~20% smaller or greater, which results from approximation of the division result ( $4500/700 = 6.42 \rightarrow 6$  single-family plots;  $6000/700 = 8.57 \rightarrow 9$  single-family plots). At the end, buildings are located on the plot at a specified distance from the plot border, parallel to the road or to the side borders of the plot (Fig. 62). In the first variant, there is the risk that, with a long plot facing the road at a sharp angle, a house turned towards it with the frontal wall would not meet the condition for minimum distance from the plot border. In most cases, that problem does not

exist, and the buildings situated in that manner make up a smoother sequence of housing. Both variants may be determined, and the designer can make the decision for which one to apply. A circle of the radius of 4 m is drawn on each corner as control for distance between the building and the border of the plot.

Semi-detached two-apartment housing is generated by analogy to detached housing. Lots may be larger or smaller by up to 30%. It is more than in the previous paragraph, because the whole plot is first divided into double plots, and only then into two halves for each semi-detached house.

For terraced housing, the area of the plot is not specified, just the width of the building and the minimum depth of the backyard. The maximum depth is the extreme measurement determined at division of quarters. In order to reduce housing monotonicity, it has been decided that rows of housing would be divided with a row of greenery into smaller groups every  $n$  segments. A separate row was created behind all the plots, the citizens have free access to their backyards on the other side. The border plots are broader by ~4m than others. The first stage is separation of a strip at the back of the plot. Then, the whole plot is divided into smaller groups. The optimum number of buildings shall be  $7 \pm 3$  in one row. At greater numbers, the housing rows are very long,



**Table 1.****List of different variants of housing types taken into consideration in the experiment, together with the resulting values of urban ratios**

Housing type	J	B	B2	S	A1	A2	A3	A4	A5
Single-family	100%				50%	40%	30%	20%	10%
Semi-detached		100%			20%	15%	15%	10%	20%
Semi-detached with two apartments in each half			100%		10%	15%	15%	20%	10%
Terraced				100%	20%	30%	40%	50%	60%
Number of apartments [units]	1,012	1,128	1,236	2,037	1,308	1,409	1,516	1,543	1,671
Gross land use ratio [apartments/ha]	10.12	11.28	12.36	20.37	13.08	14.09	15.16	15.43	16.71
Gross land net land use [apartments/ha]	16.36	17.95	19.66	32.65	20.98	22.44	24.21	24.68	26.68
Housing Density [m <sup>2</sup> /ha]	1,667	1,455	1,495	2,923	1,930	2,055	2,185	2,217	2,378
Housing area [%]	8.58	7.52	7.72	14.86	9.89	10.52	11.17	11.33	12.13
Biologically active area [%]	53.26	55.33	55.14	47.53	52.45	52.26	51.45	51.19	50.49
Transportation area [%]	38.16	37.15	37.14	37.61	37.66	37.22	37.38	37.48	37.38

and in smaller numbers – there are sets of 3 houses, sometimes even semi-detached houses which, in turn, would not be consistent with the objective of developing that type of housing. The direction of separating the entire plot into the respective parts is determined based on its lateral borders. The extreme divisions are properly larger. Figure 2 presents an example of the possibility to change parameters for terraced housing. Introduction of changes, i.e. definition of a different character of housing, takes place by changing the value of a parameter using the given slide – the program then generates a new variant of the housing complex design.

### 3. A VIRTUAL SINGLE-FAMILY COMPLEX GENERATED BASED ON PARAMETERS

For the purposes of a case study, about a dozen variants of single-family housing were tested, with different shares of single-family detached, semi-detached, terraced and two-apartment semi-detached housing. The type of two-apartment semi-detached buildings is often described from the point of view of architecture by Jan Pallado [13], while for the purposes of the experiment it was assumed that these are semi-detached houses of slightly greater dimensions, where each building contains 2 independent residential apartments (which results in significantly higher building density). The objective of that exercise was to verify whether it is possible to obtain high density by only using various types of single-family housing, including for services. The secondary objective was to demonstrate how an estate of over 100 hectares, which might be equipped with community infrastruc-

ture – several miniparks, a school, a preschool, a large food store/general store would look like. Although we can imagine an endless single-family housing complex (by analogy to American suburban estates criticized for urbansprawl), the visualization of such a complex in European conditions may stimulate one's imagination.

For the purposes of the experiment, the combinations specified by designers were assumed. Variants J, B, B2 and S were treated as references so as to demonstrate the effect of developing purely single-family housing of the same character. What is mainly significant here is the values of ratios that were obtained. The housing variants in different proportions were compared in 5 cases, from A1 to A5. All the cases were listed in Table 1.

A set of fixed input parameters was assumed for all the variants: open-access green areas take up 7% of the total area. The areas dedicated to community infrastructure constitute 7% of the whole area: four central quarters with a square in the middle which, together with four roads adjacent to it, are for pedestrians only. The following were assumed for the respective types of single-family housing:

- detached housing – 8×10 m buildings – plot area: 500 m<sup>2</sup>
- semi-detached housing – 12 (2×6)×10 m buildings – plot area: 500 m<sup>2</sup> per one half
- two-apartment semi-detached housing – 16 (2×8)×14 m buildings – plot area: 800 m<sup>2</sup> per two apartments
- terraced housing – 7×10m buildings, at least 9 m of backyard



Figure 3.  
Variant J – perspective and top view



Figure 4.  
Variant A1 – perspective and top view

In terms of variety and high values of the ratio of the number of apartments per hectares, the most promising variants are A3, A4 and A5. It turns out that, the best results were obtained by increasing the amount of terraced housing and two-apartment semi-detached housing, thus decreasing the number of detached houses. In the area of 100 ha, this results in the difference of over 300 apartments between variants A1 and A5, i.e. the number of apartments per hectare increased from 21 apartments/ha to almost 27 apartments/ha. The negative aspect of increase in the amount of terraced and semi-detached housing of both types was the relatively disadvantageous location of some buildings in terms of cardinal directions.

The research into the above-mentioned cases in quantitative terms may be conducted from the point of view of the highest degree of using land or in quantitative terms from the point of view of quality of residential environment, taking into account the amount of biologically active area. The research results seem surprising: it occurs that the differences between the respective variants are just 2% regardless of the type of housing, and so the degree of investment – share of the biologically active area is between 45% and 47%, which constitutes quite a significant share. This means that single-family housing intensification makes perfect sense and does not take place at the cost of green areas. At the same time, the ratios of



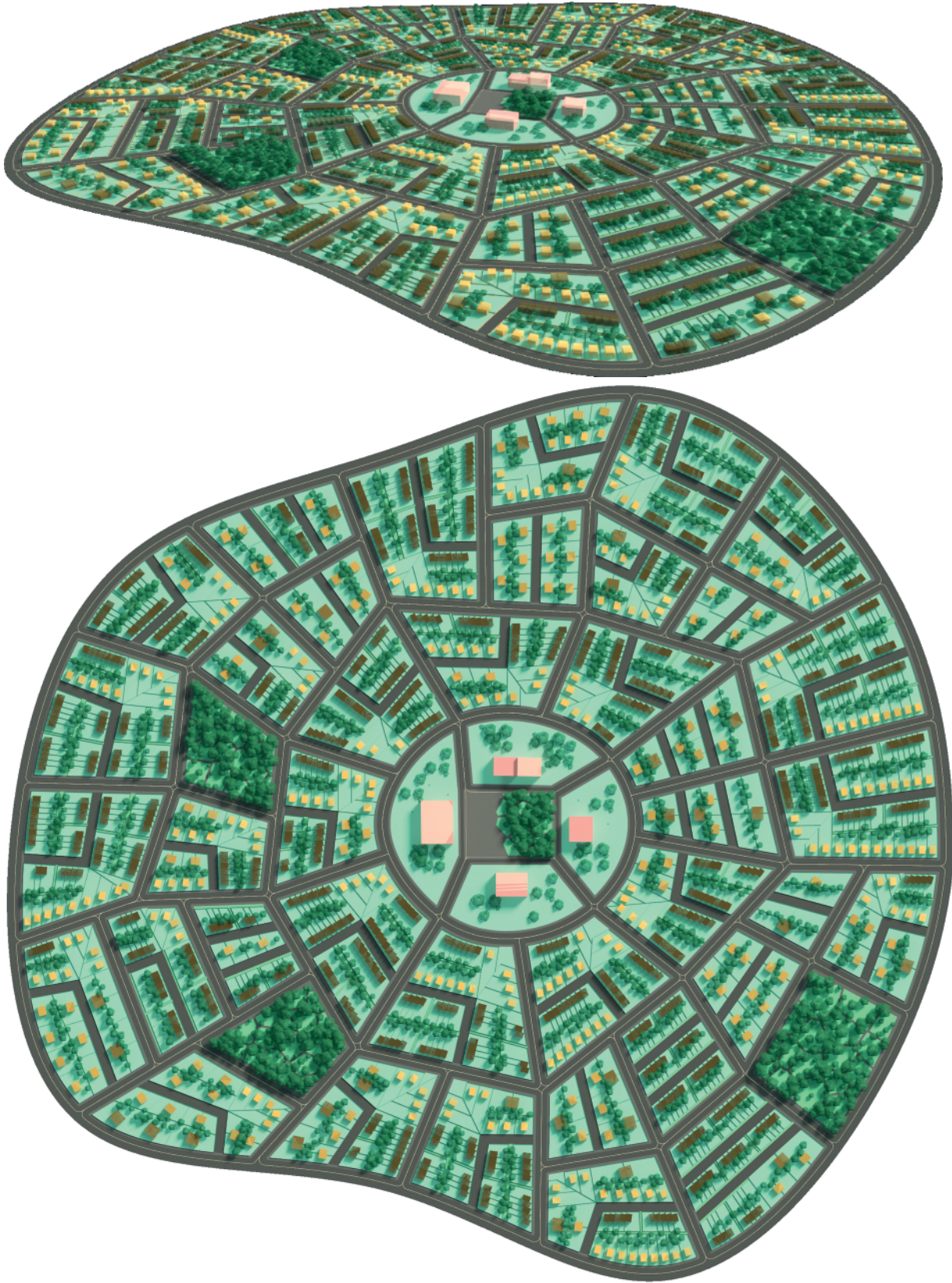


Figure 5.  
Variant A5 – perspective view

areas dedicated to transportation are between 37% and 38% respectively, which means that, on the one hand, the amount of transportation area is almost identical in each form of land investment, while on the other, it is a very significant share in the whole area. The chart below summarizes the collected data (Fig. 6).

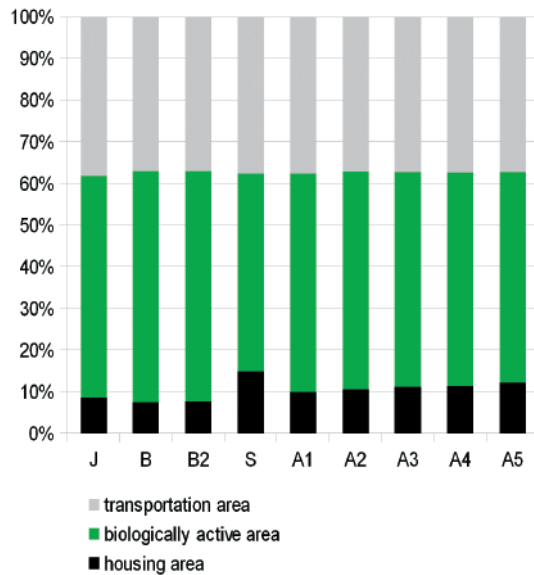


Figure 6.  
Land use specification for the respective cases tested in the experiment

## 4. SUMMARY

The discussion conducted results in the following conclusions. Some of the studied variants allowed to obtain relatively high housing densities through a proportion of terraced single-family housing and two-apartment housing in greater numbers. The maximum density values were 16 apartments per hectare gross, while the net densities were between 17 and 33 units per hectare. Such values may be considered high, similar to low multi-family housing accompanied by parking spaces on the surface. The test results provided a better ratio of land use with the application of the Galapagos script – the results were between 1% and 3% higher as a result optimization of street arrangement and quarter size parameters.

However, the questions remains of whether the resulting effect is an actually good environment to live in in all respects? Single-family housing left to its own devices may not make up a city, which is usually associated with multi-family housing. Can we imagine a small town or estate of several thousand citizens liv-

ing only in single-family housing? Let's assume the answer is yes, because it is possible to achieve high densities, but we certainly do not know whether we would like to live in such a housing environment. The quantitative and ratio advantages of the given place of residence does not reflect the quality of space even if that type of space is characterized by correct ratio values. The presented experiment also shows that the strive for the highest possible density (case of only terraced buildings) results in the need to develop homogenous buildings which are certainly monotonous.

The presented method, effects and results of its application demonstrate that parametric design methods may be useful in contemporary urban design and spatial planning. Their particular advantage is the multi-variant possibility to prototype various designs with 3d models illustrating the character of housing as well as all the ratios. The advantage is the very short time of generation of a single variant, ease of experimentation with mixing various types of housing and with simultaneous visualization, which is tantamount to visual assessment of the generated space. The additional advantage is the possibility to use transportation and plot geometry optimization as well as other parameters for the given variant (the average time for multi-variant testing in a cycle is ca. 30 minutes). Quantitative density variants can be used in analysis for future smart and intelligent cities development. The authors perceive special potential in development of the script and of the method itself, to use it for simultaneous preparation of variants of multi-family housing and single-family housing. Such types of methods allow to presume that, in the future, parametric design processes, in a broader scope, i.e. also taking into account other aspects (connected to transportation, infrastructure or community), may be useful for better spatial management. The authors are convinced that parametric design is a currently developed and future method that can be used as efficiently in urban design as BIM technology in architectural and structural design.

## AFTERWORD

A part of the following MA thesis was used in this paper: Kałny Dawid "ATTEMPT TO DEVELOP A PARAMETRIC METHOD OF RESIDENTIAL HOUSING DESIGN USING THE GRASSHOPPER PROGRAM AS AN EXAMPLE OF A MULTI-VARIANT DESIGN FOR A HOUSING COMPLEX ON PLOT X", advisor: Tomasz



Bradecki, Silesian University of Technology, Faculty of Architecture, 2019.06. The article itself was prepared jointly at the request of the adviser and services to promote the possibilities of parametric designing. Short brief on the Thesis have been published in Architektura&Biznes online magazine [19]

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