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The procedural turn: artificial morphogenesis in urban design

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ABSTRACT

According to the seminal work *The Alphabet and the Algorithm* by Mario Carpo, we are in the very middle of a revolution in architectural and urban design. It seems that the declarative and allographic design methods developed in the early modern period are fading, and their 500-year-long use had been only an interlude in history. After understanding the underlying generative processes of cities, they become reproducible using the new generative and procedural methods. But, as Carpo emphasises, „similarity and resemblance, however, are not scientific notions, and are notoriously difficult to assess and measure" (Carpo 2011, p. 101). According to Karl Kropf, we co-evolve with the environment we create: the process is interdependent (Kropf 2017, p. 14). This interdependency and interconnectivity cannot be assessed, modelled, and designed in the usual declarative way. But methods of space syntax together with the integrated urban morphology method (Lovra (2019) provide tools to assess and measure the urban configuration, and to provide input for generative algorithms. The procedural, generative methods are suitable to understand and reproduce the nested and interconnected processes. Thus, the urban design will be a two-step process: at first, it has to be defined, what we would like to achieve (analysis), then generative algorithms have to be created to reproduce the quality of the desired type of urban fabric. This two-step method is the artificial morphogenesis.

KEYWORDS

Artificial morphogenesis, Generative design, Procedural design, Grasshopper, Gothic

1 INTRODUCTION: THE PROCEDURAL TURN

Discussing artificial intelligence, Douglas R. Hofstadter distinguishes two types of human knowledge in his seminal book *'Gödel, Escher, Bach'*: declarative and procedural. "A piece of knowledge is said to be *declarative* if it is stored explicitly, so that not only the programmer but also the program can »read« it as if it were in an encyclopedia or an almanac. […] By contrast, *procedural* knowledge is not encoded as facts–only as programs" (Hofstadter 1999, p. 363). In the first case the data itself is stored, in the second the process on how to create the data.

Similarly, architecture can be defined both as a thing (product) and as an activity (process) (Hillier 1996, p. 17). The rise of generative parametric software together with theories about space and architecture can shift the current declarative method of architectural (including urban) design towards a procedural practice. Although the algorithmic methods seem new, in fact they have their roots in pre-modern times. It is striking that two scholars who studied different eras from different points of view came to the same conclusion: it seems that the architectural practice of the last five hundred years had been only an intermezzo, moreover, in historic scale, a short one (Carpo 2011, Bork 2014). "Prior to the early-modern standardization of mechanically reproduced images, we lived for centuries in a world that was algorithmic and normative, not visual and repetitive" (Carpo 2004). The understanding of the pre-modern, pre-mechanic design processes together with the generative logic of organic cities "will help us to shape better things" (Carpo 2011, p. 128). The software of choice for the procedural modelling in this article is Grasshopper within Rhinoceros 3D, developed by Robert McNeel & Associates.

2 THEORY: PROCEDURAL AND DECLARATIVE THEN AND NOW

In his seminal 2011 book Mario Carpo argues, that the current architectural practice – which we take as granted – has its roots in the Renaissance age, mostly in the theoretical works of Leon Battista Alberti (Carpo 2011, esp. pp. 51–79). According to him, two major things changed then: architectural design has become allographic ("designed by one to be constructed by others" - Carpo 2011, p. 16.), and has lost its procedural nature.

In fact, the game-changer was not the appearance of allography, since autography (when the designer is part of the realisation process too) has survived in early modern and also in modern times: the supervision of the construction by the architect themself has been always inevitable for the success, especially in the case of great, remarkable pieces of architecture. Just one example: Le Corbusier personally supervised the construction of the Ronchamp chapel, and even made changes on the plan during construction (Cohen 2004, p. 65).

Detailed, orthogonal, consistent architectural drawings in a precise scale are also not the product of the Renaissance era. They existed already in the Gothic period, and thousands of them has survived, most of them from the 15th century. Although the scientific definition of the orthogonal projection didn't exist by that time, these drawings have all the essential elements of modern architectural drawings: "they display orthogonal projection, wall developments and scale, as well as concordance between ground plan and elevation drawing," and were intended for implementation (Böker 2005, p. 27).

The most important paradigm shift (the game-changer) was the end of the procedural nature of the architectural design. “Gothic design conventions governed the rules of the process more than the shape of the final product, which meant that the spatial relationships between building components varied far more widely in Gothic than in classical architecture” (Bork 2014, p. 2). Since then, the subject of the design has been the shape of the final product.

The idea of modern procedural design goes back to the 1964 book of Christopher Alexander (Alexander 1964). His main argument is that the intuitive factor of architectural design has to be eliminated, and the spatial arrangement has to emerge from the functional needs almost automatically, via a systematic procedure. As Bill Hillier points out, Alexander’s rigorous method fails at the first step: his starting point (the analysis) is based on intuitive assumptions. “Alexander still proceeds in the way he originally objected to: that is, by already ‘knowing’ the relations between form and function” (Hillier 1996, pp. 413–419).

This issue is crucial for the procedural method: what can be used as input for the generative algorithms? If we exactly know already at the beginning what to design, then the process will be declarative. To solve this problem, we have to turn back to the methods of the pre-mechanical word. According to Carpo, “pattern recognition: this is the operating principle that inspired Western visual culture from classical antiquity to the diffusion of printed images at the beginning of the early-modern age. […] In the algorithmic world the search for similarities or the recognition of hidden structures (pattern recognition) allows us to confer the same meaning onto different signs that have something in common” (Carpo 2004). “Similarity and resemblance, however, are not scientific notions, and are notoriously difficult to assess and measure” (Carpo 2011, p. 101).

Assessing and measuring architectural and urban quality is difficult. We co-evolve with the environment we create: the process is interdependent (Kropf 2017, p. 14). We are part of the system which we would like to shape. Philosophically speaking, “we are like the spider. We weave our life and then move along it. We are like dreamers who dreams and then lives in the dream” (Lynch 2007, p. 139).

Hillier makes a distinction between order and structure. The plan of an ‘ideal’ city of the Renaissance has a clear geometric order, while the organic towns don’t: they have not order but structure, “powerful spatial patterning”. This means that “structures cannot be seen all at once, nor are they imposed all at once by minds. They are asynchronous both in their genesis and in the way we experience them. They arise from a lived process, and are intelligible through the processes of living in the town, and, most especially, by the process of movement” (Hillier 1996, p. 235). As the aforementioned spider moves along its web. It is even more interesting, that “it is the ordered town that is usually confusing »on the ground«” (Hillier 1996, p. 235). An extreme value of the ordered town is the modern prefab housing estate with its high-rise, identical block of flats. Quoting Hillier and Hanson, “for the first time, we have the problem of a ‘designed’ environment that does not ‘work’ socially, or even one that generates social problems that in other circumstances might not exist” (Hillier and Hanson 1984, p. 28). Usually these prefab estates are seen as a product of the Modernism, but, in fact, they are the end product of the “mechanical universe of identical reproduction”, which begun in the Renaissance with the age of printing (Carpo 2004).

As the contrast between the “ordered” high-rise prefab housing estates and the organic towns suggest, the hidden structure is what has to be assessed. Again, the Gothic architecture can serve as an example. The architecture of the late Gothic era was considered by many art historians as decadent, chaotic, disobeying any rule or system (on the topic see Bork 2018 pp. 1–20). But its complexity, interconnectivity, and spatial virtuosity involves “conventions of procedure, governing the dynamic unfolding of successive geometrical steps” (Bork 2014, p. 1, in detail: Bork 2011), which can be even modelled in a generative way using algorithmic modelling software (Bereczki (2020). On Figure 1 the result of a recursive, fractal-like algorithm can be seen. One single algorithm code all of the parts (the pinnacles in various size and the entire tower itself), which is nested into itself on several recursive levels, and the complexity of the parts is the factor of their height, similarly how different parts of the DNA are activated in living organisms with the growth.

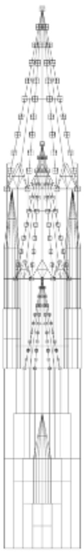

Figure 1: “Growing” a complex Gothic tower with a recursive definition. Author’s work. Source: https://zbereczki.github.io/generative-gothic/main/

To conclude, “in a sense, therefore, a Gothic design can be seen as an architectural topiary, in which geometry provides the quasi-random growth factor, while artistic judgment guides the pruning process. This dialog between growth and pruning helps to explain the organic quality characteristic of Gothic design” (Bork 2014, p. 5).

The duality of randomness and restrictions is the key for generative design, as Hillier and Hanson argue as well: “the system in effect requires both a spatio-temporal embodiment, and a randomly operating background process in order to produce its order” (Hillier and Hanson 1984, p. 34).

Interestingly, the Viennese architect Otto Wagner used an almost procedural approach in his 1911 book on urban design, entitled “Die Großstadt” (Wagner 1911). In this, he formulates rules (restrictions), and in this framework of rules random processes can generate the urban layout around any existing city, theoretically infinitely. As a proof of concept, his rules can be transformed into generative algorithms, then tested on different cities. The generative algorithm based on his rules consists of two main parts. The first one generates the boundaries of the new districts, and the second one populates these districts. The first one is a recursive aggregation process, where each ring of districts is created by the same algorithm, only their inputs vary. Then the blocks and buildings in each district are generated by another single algorithm (a subdivision-like process), where the input is the boundary of each district, and the variables can be defined according to the position of the district in the whole, and/or randomised (Bereczki 2021).

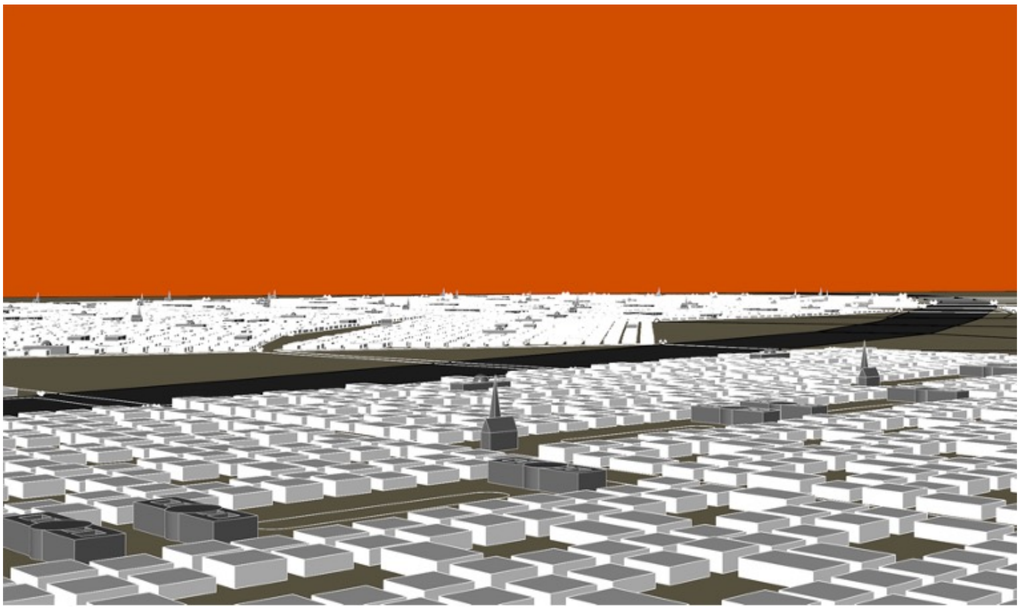

Figure 2: Otto Wagner’s Großstadt, generated by algorithm. Author’s work. Source: https://www.mdpi.com/2571-9408/4/3/59

The relationship between a single algorithm and the almost infinite number of geometries generated by it is similar to the relationship of genotype and phenotype in biology: a single genotype can result multiple phenotypes, all similar, but not the same. In the case of the example above Wagner’s rules served as a base for the genotype. In real towns such genotype doesn’t exist, but similarities can be observed between different towns or different neighbourhoods. Now we have arrived back to the hidden regularities. According to Hillier and Hanson, these regularities are ‘coded’ by the so called ‘inverted genotype’: “the programme does not generate reality. Reality generates a programme, one whose description is retrievable” (Hillier and Hanson 1984, p. 44). If this description is retrievable, then it can be used as an input for an artificial morphogenesis to generate a 'reality' which in key aspects is similar to the original one, but not the same (Bereczki and Lovra n.d.). "Two objects produced and formed by the same algorithm resemble each other in some way that the trained eye can detect and mathematics can demonstrate – but the mathematical formula is not legible in the object nor does the object disclose it" (Carpo 2004).

Generative design isn't necessary procedural. The former is only a tool, a means for the latter. In the procedural workflow at first the internal logic, the configuration of the subject has to be understood. The generation of building layouts form justified graphs is a good example. The justified graphs descript the configuration of the space, and it is possible to turn them automatically into floor plans. This way the *logic* of the layout is designed (the j-graph), not the layout itself. A tool for that is called Spiderweb, and it is (or was) developed at the Technical University of Vienna (Schaffranek and Vasku 2013); and another is Syntactic, developed at the Technical University of Delft (Nourian, Rezvani and Sariyildiz 2013a, Nourian, Rezvani and Sariyildiz 2013b). There are also efforts to automatise the improvements of axial integration in a network (Schaffranek and Vasku 2013, p. 050:6–050:6; Beirão, Nourian and Walderveen 2011). All these endeavours are part of the procedural revolution.

3 DATASETS AND METHODS

The aim of this research is to find those hidden properties of settlements which can be used as direct input for generative algorithms: to find the aforementioned inverted genotype. These properties are referred to as 'extrinsic' properties of space: they "cannot be seen all at once, but must be pieced together through movement, inference, recollection and so on" (Hillier 1999, p. 56.1). As an experiment, an important measure used by space syntax, the axial connectivity will be used as an input. The axial connectivity map and the related axial integration map are very informative tools to represent the configuration of settlements layout (Hillier and Hanson 1984, p. 103, Hillier et al. 1993), especially to analyse the structure (not the order!) of organic settlements.

Using the values from the analysis of an existing settlement (or part of it), the generative process can be modelled. The level of axial connectivity of each axis will be an input variable, the restriction in the randomly operating random process. This way an infinite variety of street networks can be generated, and each of them will have the same configuration (the value of the axial connectivity for each axis will be the same). Moreover, since the value of axial connectivity is an input parameter, it can be adjusted, and the street network will regenerate itself. In this article part the axial connectivity map *G* (Gassin) is used from the book *The social logic of space* (Hillier and Hanson 1984, p. 103) to create a generative algorithm.

On the level of plots and buildings the integrated urban morphology method can be used to obtain the input data (Lovra 2016, Lovra 2019). In this method the towns are distilled to their base fabric, considering the most important forming elements: street networks, plot series, green spaces, and so on. Based on those and on their relationship the main dominant urban tissue types can be defined on diagrams with crisp definitions. Pattern recognition is inevitable for identifying and defining the different tissue types, since their real-life representations aren't identical. "Human intelligence recognizes an invisible generative structure shared by two visibly different forms" (Carpo 2004). The task is then to create the generative algorithm for the structure (and, again, not for the order). The different tissues generated by the algorithm will be non-standard series: "all products of a non-standard series are different but they are also in some way similar to each other. What do they have in common? Technically, a mathematical algorithm; perceptually, however, it is difficult to say." (Carpo 2004)

In this article the tissue type labelled *'Ac'* is used from the book *Towns in Austria-Hungary. Urban Tissue Typology and Urban Typology 1867–1918* (Lovra 2019, p. 199).

4 RESULTS

4.1 Generative axial maps

As it was mentioned above, one part of the axial connectivity map of the town *G* (Gassin) (Hillier and Hanson 1984, p. 103) served as a base of this algorithm (Figure 3).

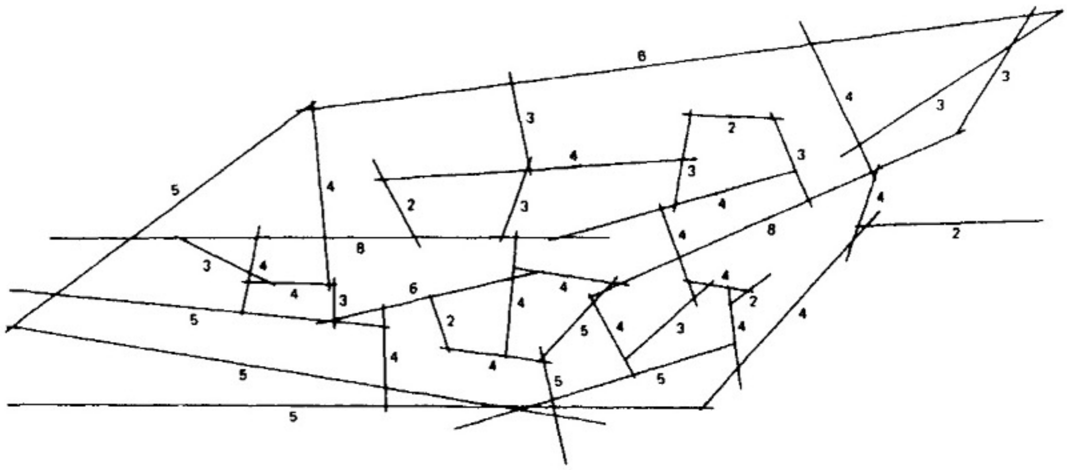

Figure 3: Axial connectivity map of the town G (Gassin) (Source: Hillier and Hanson 1984, p. 103)

The starting point is the axis with the greatest value (8). This means that this axis has eight intersections. At first a single line is created, referred to as axis*0*. The length of this line is 150 units (an arbitrary value without unit of measure, scale is irrelevant on these abstract – configurational – maps). The steps then are the following:

- Eight points are generated on axis*0*, at random distances, but at least 5 units away from each other (for the intersections). This number (8) is a variable, and can be changed.

- From each intersection lines are generated to both directions, at random angle and with random length. The extreme values (limits) for the random generators are set for the angles to 55 and 125 degrees, for the endpoints (lengths measured from axis*0*) of the new axes to 5 and 60 units. These values are approximated from the map on Figure 1, and can be easily changed. The resulting axes are the secondary axes, labelled as axis*1*–axis*8*. Their connectivity values, based on Figure 1, are the following:
  - axis*1*: 5
  - axis*2*: 3
  - axis*3*: 4
  - axis*4*: 4
  - axis*5*: 2
  - axis*6*: 3
  - axis*7*: 4
  - axis*8*: 4

These numbers already contain the intersections with axis*0*, so one less tertiary axis has to be generated for each secondary axis. The generation of the tertiary axes is a recursive process: the same definition (sub-algorithm) is reused (as cluster in Grasshopper terminology), but with different inputs. At first the tertiary axes connected to axis*1* are generated, in the required number, at random positions, random angles, and with random lengths. It is possible that a tertiary axis intersects the axis*0*. This has to be avoided, because this would change the connectivity value of the axis*0*. So, it is tested if a segment of a tertiary axis intersects the axis*0*, and if yes, that segment is eliminated. Then the tertiary axes connected to axis*2* are generated. At first the algorithm calculates the number of the already present intersections, then subtracts it from the number of the required intersections. Only the remaining number of new axes will be generated. Then it is tested if any segments of new tertiary axes intersect either the axis*0* or the axis *1*, and, if yes, that segment is eliminated. Then the tertiary axes for the axis*3* are generated in the same way, and so on.

For any set of tertiary axes connected to a secondary axis labelled *n* the inputs are the following:

- the secondary axis*n*
- the needed number of new intersections (can be used as a variable)
- the primary axis*0* (to test if a segment of a new tertiary axis intersects it)
- the secondary axis*n-1* (to test if a segment of a new tertiary axis intersects it)
- the tertiary axes connected to axis*n-1* (to calculate the number of the already present intersections).

In each case the seed number for the random generators can be set with a slider, to generate new geometry. (In Grasshopper the random number generator generates a set of new values when the seed number is changed, like a throw of the dice.) The following values are randomised in the algorithm which generates the tertiary axes:

- position of intersections
- length of tertiary axes from the intersection, in both side (limits: 5…40, can be modified as a variable)
- angles of tertiary axes (limits: 55…125°, can be modified as a variable).

Some examples (from the infinitely many possible) can be seen on Figure 4. The connectivity values of the axes are represented by colours, from blue (low value) to red (high value). In general, the configuration pattern is similar to the needed one. In some cases although, when the network becomes too dense (the randomly generated intersections get close to each other) and the randomly generated length of the axes is long, it can happen that the connectivity value of a secondary axis is larger then the required (especially on the last map of Figure 4). These situations are difficult to omit with this type of algorithm (where the tertiary axes are generated subsequently, step by step) because it would cause infinite loops.

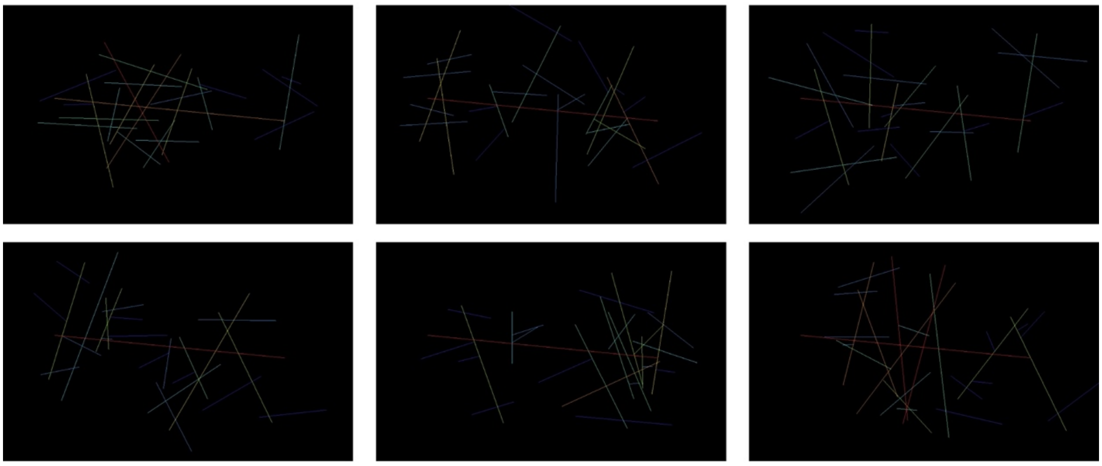

Figure 4: Randomly generated configurations with pre-set connectivity values for the primary axis and secondary axes. Source: author's work, using Grasshopper and DepthMapX

On Figure 5 only one value is changed, compared to the last map of the Figure 4: the connectivity value of axis*3*, from the original 4 to 5, 6, 7. It can be seen how the network and the configuration is changing.

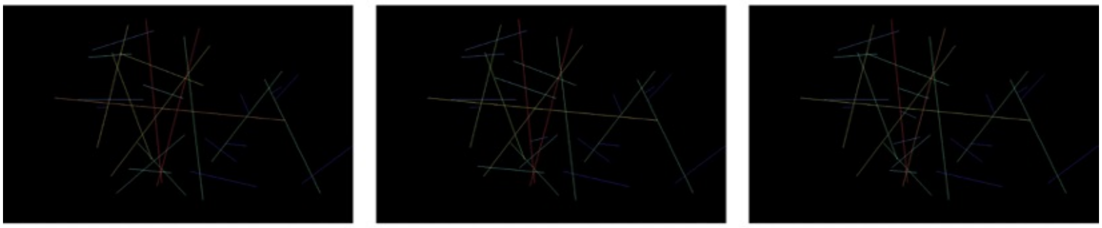

Figure 5: Same configuration as on the last map on Figure 4, but the integration value (as input) of axis*3* is increased from the original 4 to 5, 6, 7, subsequently. Source: author's work, using Grasshopper and DepthMapX

These networks are more like abstractions than street networks, but the algorithm illustrates on a basic level that it is possible to use connectivity values as direct input parameters for generating networks.

4.2 Generative urban tissues

In this case study (experiment) the base of the algorithm is an organic urban tissue type, which is characteristic for the pre-1867 parts of the towns in the Kingdom of Hungary. It is one of the identified and described 22 different pre-1867 urban tissue type in Éva Lovra's book (Lovra 2019, p. 199–201). The chosen type has the label *Ac*, and its description is the following (see Figure 6 too):

"Elongated rectangular plots with regular geometry, dynamics of the plot series are rhythmical/regular: width of the plots and the placement of the buildings are almost identical. The property consists of the main building and some additional buildings (outbuildings), that partially surround the inner courtyard. The buildings are adjusted to the line of the street, coherent free space is between the street line and the development in unbroken rows. The unbroken row of building is disrupted by open courtyards. Yards could be divided into two parts depending on the location (front and back yards): the two sections are separated by buildings and fence" (Lovra 2016, p. 210).

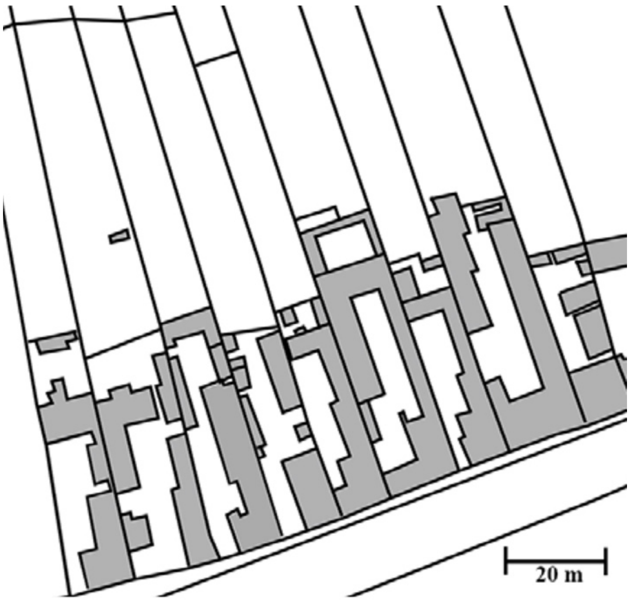

Figure 6: Diagram of the urban tissue type Ac. Source: (Lovra 2019, p. 199).

According to the above, the following data are used as input:

- for plots:
  - an irregular quadrilateral, marking the boundary of the urban block surrounded by streets
  - width of plots: between 12 and 18 metres

    - length of the front part of the plots: between 25 and 40 metres
    - front garden: 0 m
    - height of fences: 1.4 m
- for buildings:
    - main (front) wing:
        - width: on 80% of the plots the same as the width of the plot, on the rest 80% of it
        - deepness: between 8 and 12 metres
        - height: between 5 and 10 metres (either one- or two-storey)
        - height of the ridge of the gable roof: between 3 and 6 metres above the main cornice
    - side wing:
        - length: between 6 and 16 metres
        - width: between 5 and 8 metres
        - height: 80% of the main wing
        - height of the ridge of the monopitch roof: between 1.5 and 3 metres above the cornice
    - flat-roof outbuilding on the side (present only on max. 80% of the plots)
        - length: between 5 and 12 metres
        - width: 80% of the width of the side wing
        - height: 80% of the side wing
    - flat-roof rear outbuilding (they are present only on max. 10% of the plots)
        - width: 6/8 of the width of the plot
        - deepness: between 3.1 and 5 metres
        - height: 3 metres
        -

In the algorithm all of the from-to values above are randomised individually.

For generating the plot structure, at first the shortest side and the opposite one of the input quadrilaterals are halved, then the division points connected. This way the block is divided into two parts, and the same algorithm generates the two halves (of course with different values, so the result will be different). Both the front and the back widths of the plots are randomly generated, so the plots are slightly irregular. The L-shaped main building is present on each plot, but with different measurements. For the side outbuildings, at first a set of values is generated for the lengths, then it is compared to the still available place, and the building is generated only in those cases, if there is enough place left. Then 20% of the generated buildings is randomly deleted to achieve the required density. Same is true for the outbuildings at the end of the front part of the plots, for the same reason: they are generated only if there is enough room, and 90% of them are deleted. Some examples of the generated variations can be seen on Figure 7, and can be compared to the original tissue on Figure 6.

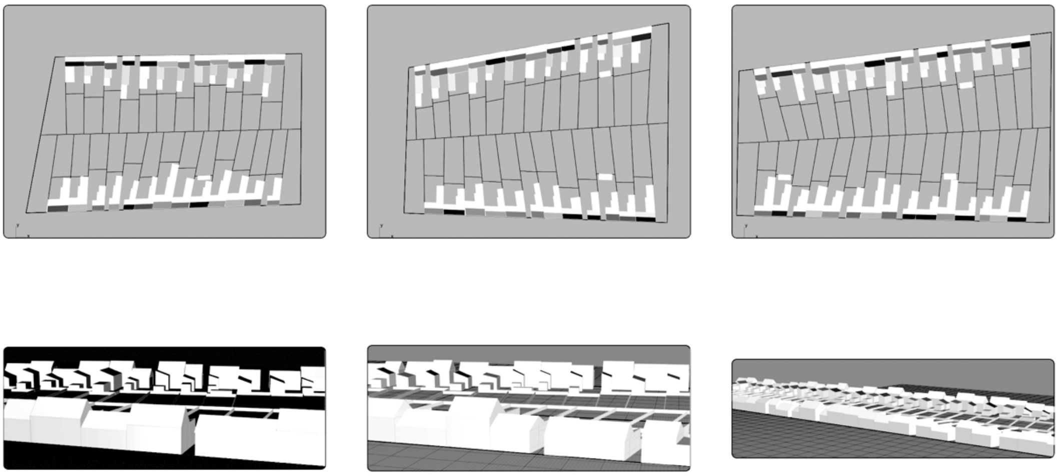

Figure 7: Generated tissues based on the tissue type *Ac*. Source: author's work, using Grasshopper

5 DISCUSSION

A possible application for the artificial morphogenesis is the healing of urban tissue damages. The events of the 20th century caused severe damages in the cities of Europe. The historical, organic urban tissues were erased in large areas, sometimes right next to or directly in the city centre. The majority of these areas – especially in the eastern part of Central Europe – is either urban void even today, or slum with rundown prefab housing. Usually even the original plots are eliminated. Reconstructing the entire original tissue is impossible and undesirable at the same time, but re-establishing the continuity of the urban tissue is desirable. (Bereczki and Lovra n.d.) The original (or the directly adjacent) tissue can serve as a model for the designed one, its analysis can provide the input data.

To illustrate how the above discussed algorithms can be used, a new street network and urban tissue was generated in place of the Vörösmarty housing estate in Miskolc, Hungary. It was originally a dense urban area (named Gordon) directly next to the city centre, with organic, archaic urban tissue, dating back to the 18th century. The entire area was demolished in the 1970s, to give place to a large prefab housing estate with 11-storey blocks. The whole street and plot structure was eliminated without any strategic planning, resulting negative consequences in urban life (Bereczki and Lovra 2022).

On an aerial photograph from 1975 the original tissue can be observed on the right, and at the same time the extent of the demolition with the first new prefab houses in the middle and partly on the left (Figure 8). The connectivity map of the original network can be seen on the Figure 9. This was used to provide the input values for the algorithm discussed in the subchapter 4.1 of this article. The connectivity values of the generated axes are the following:

- axis0: 17

- axis1: 5
- axis2: 2
- axis3: 2
- axis4: 7
- axis5: 2
- axis6: 1
- axis7: 2
- axis8: 2
- axis9: 10
- axis10: 8
- axis11: 2
- axis12: 1
- axis13: 4
- axis14: 7
- axis15: 5
- axis16: 4
- axis17: 8

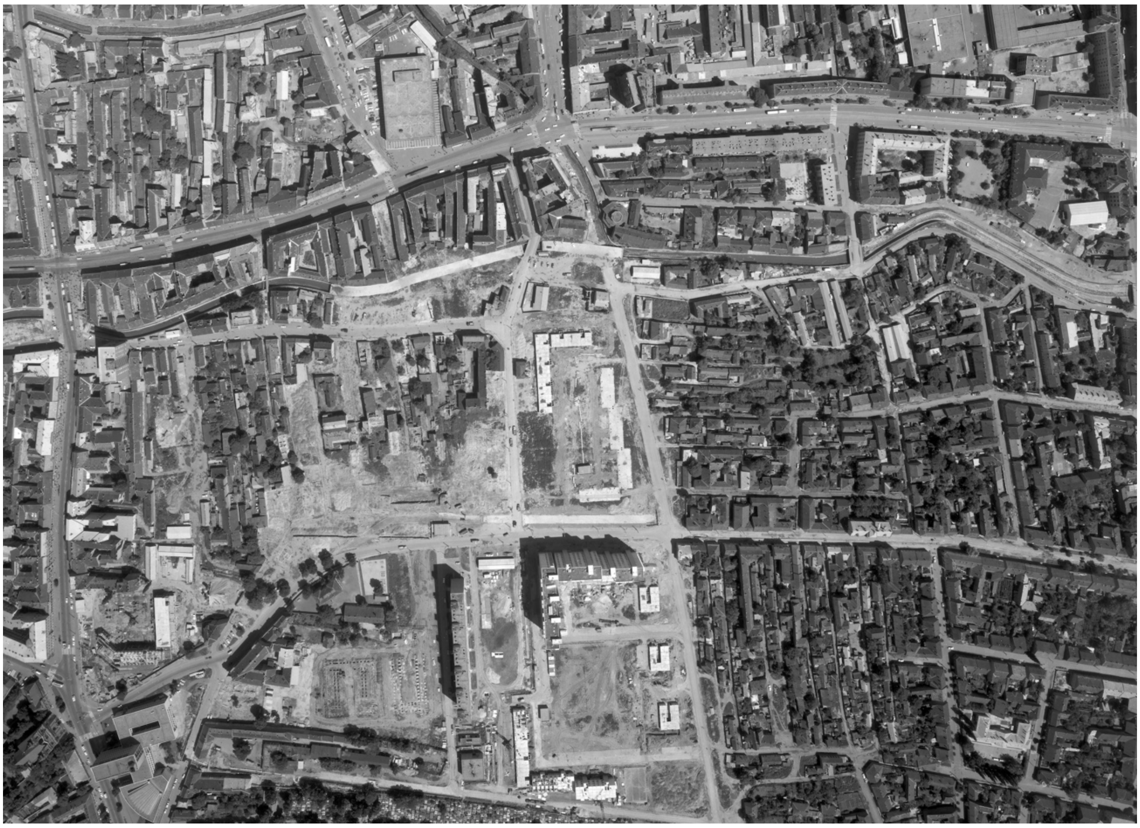

Figure 8: Aerial photograph of the demolition of the Gordon area in Miskolc, Hungary. Source: fentrol.hu, Lechner Nonprofit Kft.

Figure 9: Connectivity map of the Gordon neighbourhood in Miskolc, Hungary. Source: author's work, using DepthMapX.

The type of the original tissue was the above discussed Lovra-*Ac.* The newly generated street network has defined the shape of the blocks, and the blocks were divided into plots and populated by buildings using the algorithm discussed in the subchapter 4.2. The generated neighbourhood can be seen on the Figure 10. On the top view the generated tissue can be compared to the adjacent ones (displayed with pink lines), which are (more or less) preserved original organic ones. The generated street network can be compared to the original one, displayed on Figure 9. It is clearly visible, that the algorithmically generated new neighbourhood maintains the continuity of the organic city, unlike the prefab housing estate in the middle of Figure 10.

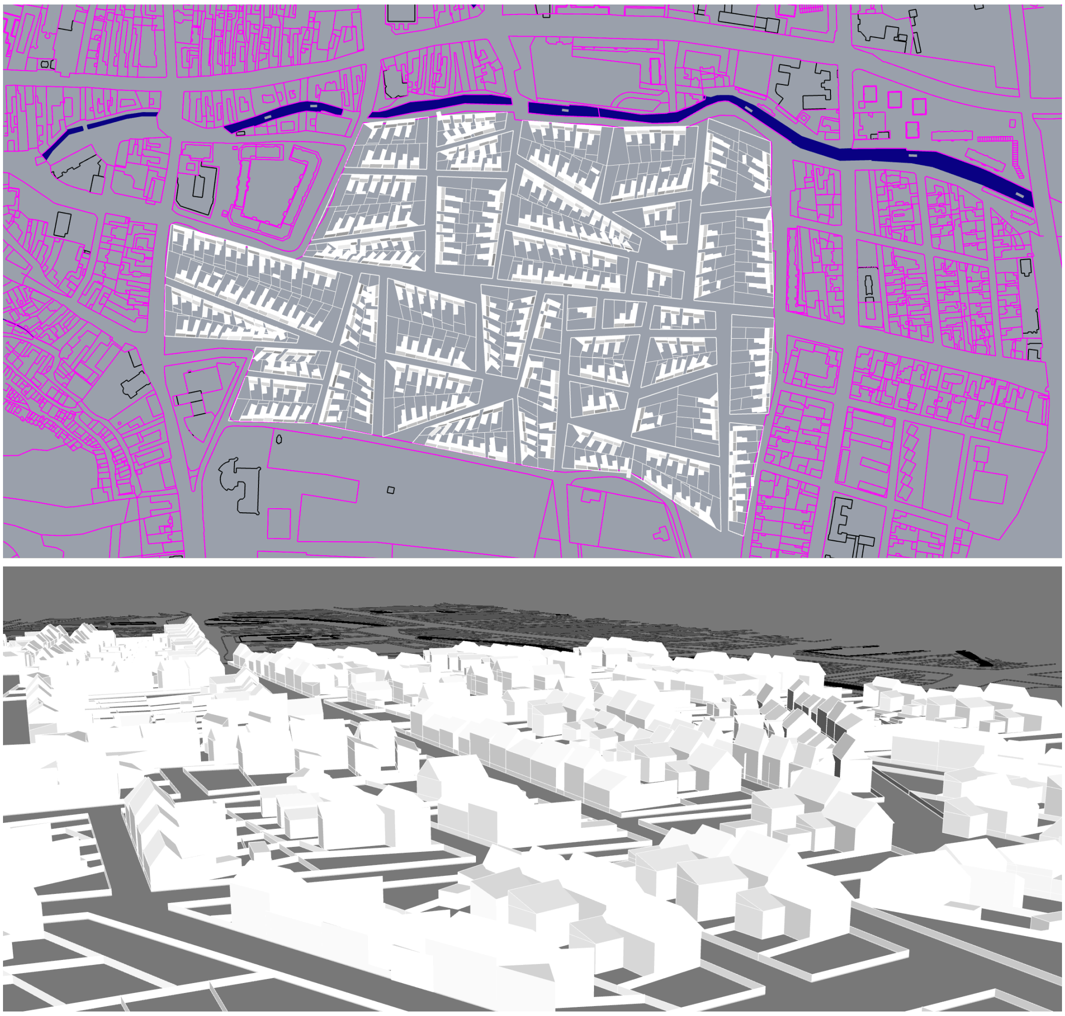

Figure 10: Newly generated urban tissue on the place of the Vörösmarty housing estate in Miskolc, Hungary. Source: author's work, using Grasshopper.

6 CONCLUSIONS

The algorithms have shown that the hidden qualities of settlements, the inverted genotype can be hard-linked to generative algorithms as input parameters. Infinite variety can be created using limited number of elements, not by reconstruction (declarative way), but simulating the original generative processes (procedural way). The organic historical districts of the cities are considered as valuable, liveable, human-scale neighbourhoods, and their density is sustainable. Tears in the fabric of the cities can be healed using the inverted genotype of the historical districts, moreover, industrial sites can be recultivated and integrated to the network of the cities, and even new districts can be designed this way.

The algorithms discussed here are experiments, their main goal is to test the possibilities. On the level of street networks not only the connectivity, but the integration and choice could be also implemented. Besides the one used here, the other Lovra-tissues can also be algorithmized, then combined (the author defines and describes more than sixty types, and using her methods new ones can also be described).

Besides the two analytical methods discussed here (connectivity maps, one single urban tissue type), there are several other quantification methods assessing the urban environment (see for example Batty 2013, D'Acci 2019). They can also provide results which can be used as input for generative algorithms. The abundance of available data in urban sciences paired with the advanced analytical methods cannot be a one-way-practice. Nowadays we know more about our cities than any time in the history, and this knowledge can fuel the procedural turn in urban design.

Not even space is the machine, but the generative process – the algorithm – that creates it.

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REFERENCES

Alexander, C. (1964) *Notes on the Synthesis of Form.* Cambridge, Massachusetts: Harvard University Press.

Batty, M. (2013) *The New Science of Cities.* Cambridge, Massachusetts; London, England: MIT Press.

Beirão, J. N., Nourian, P. and Walderveen, B. (2011) ' {Parametric 'Route Structure' Generation and Analysis. An Interactive Design System Application for Urban Design', in *Diversity and Unity: Proceedings of IASDR 2011,* Delft, pp. 1–11.

Bereczki, Z. (2021) 'Patterns of the Expanding City: An Algorithmic Interpretation of Otto Wagner's Work', *Heritage* 4(3), pp. 1062–1079. doi: https://doi.org/10.3390/heritage4030059

Bereczki, Z. (2020) 'Generative Interpretations of Late Gothic Architectural Forms.' *Symmetry: Culture and Science* 31(3), pp. 279–295. doi: https://doi.org/10.26830/symmetry_2020_3_279

Bereczki, Z. and Lovra, É. (2020) ' Tears in the Fabric of Cities in the Socialist Successor States of Austria-Hungary after World War II', *Central European Horizons* 2(2), pp. 42–90.

Bereczki, Z. and Lovra, É. (n.d.) 'Healing urban tissue damages using artificial morphogenesis', in *Proceedings of the XXVIII International Seminar on Urban Form.* Accepted for publication.

Bork, R. (2018) *Late Gothic Architecture. Its Evolution, Extinction, and Reception*. Architectura medii aevi. Turnhout: Brepols

Bork, R. (2014) 'Dynamic Unfolding and the Conventions of Procedure: Geometric Proportioning Strategies in Gothic Architectural Design', *Architectural Histories* 2(1), pp. 1–20. doi: http://dx.doi.org/10.5334/ah.bq

Bork, R. (2011) *The Geometry of Creation: Architectural Drawing and the Dynamics of Gothic Design.* Farnham: Ashgate.

Böker, J.J. (2005) *Architektur der Gotik. Bestandskatalog der weltgrößten Sammlung an gotischen Baurissen (Legat Franz Jäger) im Kupferstichkabinett der Akademie der Bildenden Künste Wien.* Salzburg: Pustet.

Carpo, M. (2011) *The Alphabet and the Algorithm.* Cambridge, Massachusetts; London, England: MIT Press.

Carpo, M. (2004) 'Pattern Recognition', in Forster, K.W. (ed.) *Metamorph. Catalogue of the 9th International Biennale d'Architettura.* Venice; New York: Marsilio; Rizzoli International, pp. 44–58. Online version: http://architettura.it/extended/20060305/index_en.htm

Cohen, J.-L. (2004) *Le Corbusier. 1887–1965. Die Lyrik der Architektur im Maschinenzeitalter.* Köln London Los Angeles Madrid Paris Tokyo: Taschen.

D'Acci, L. ed. (2019) *The Mathematics of Urban Morphology.* Cham: Springer.

Hillier, B. (1999) 'Space as paradigm for understanding strongly relational systems', in *2nd International Space Syntax Symposium. Brasilia, Brazil, March/April 1999. Proceedings.* pp. 56.1–56.16.

Hillier, B. (1996) *Space is the machine: A configurational theory of architecture.* Cambridge: Cambridge University Press.

Hillier, B. and Hanson, J. (1984) *The social logic of space.* Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo: Cambridge University Press.

Hillier, B. *et al.* (1993) 'Natural Movement: Or, Configuration and Attraction in Urban Pedestrian Movement', *Environment and Planning B: Planning and Design* 20, pp. 29–66.

Hofstadter, D.R. (1999) *Gödel, Escher, Bach - An Eternal Golden Braid*, Twentieth-anniversary. ed. New York: Basic Books.

Kropf, K. (2017) *The Handbook of Urban Morphology.* Chichester: Wiley.

Lovra, É. (2019) *Városok az Osztrák-Magyar Monarchiában. Városszövet- és várostipológia 1867–1918.* Budapest: Terc.

Lovra, É. (2016) 'Urban Tissue Typology and Urban Typology (1868-1918). Special Cases: Zagreb and Rijeka.' *Prostor* 24(2), pp. 202–215.

Lynch, D. (2007) *Catching the Big Fish. Meditation, Consciousness, and Creativity.* 10th Anniversary Edition. New York: Tarcher Perigee.

Nourian, P., Rezvani, S. and Sariyildiz, S. (2013a) 'A Syntactic Architectural Design Methodology: Integrating Real-Time Space Syntax Analysis in a Configurative Architectural Design Process', in Kim, Y. O. and Park, H. T. and Seo, K. W. (ed.) *Proceedings of the Ninth International Space Syntax Symposium,* Seoul: Sejong University Press, pp. 048:1–048:15.

Nourian, P., Rezvani, S. and Sariyildiz, S. (2013b) 'Designing with Space Syntax. A configurative approach to architectural layout, proposing a computational methodology', in *Computation & Performance: Proceedings of the 31st International Conference on Education and research in Computer Aided Architectural Design in Europe,* Delft: eCAADe, pp. 1–10.

Schaffranek, R. and Vasku, M. (2013) 'Space Syntax for generative design: On the application of a new tool', in Kim, Y. O. and Park, H. T. and Seo, K. W. (ed.) *Proceedings of the Ninth International Space Syntax Symposium,* Seoul: Sejong University Press, pp. 050:1–050:12.

Wagner, O. (1911) *Die Groszstadt. Eine Studie über diese von Otto Wagner.* Wien: Verlag von Anton Schroll u. Komp.