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MODEL USE IN THE STUDY OF DYNAMIC URBAN PHENOMENA: STUDY OF A CITY GROWTH MODEL AND A TRANSPORTATION ACCESSIBILITY MODEL

ZASTOSOWANIE MODELI W BADANIU DYNAMICZNYCH ZJAWISK URBANISTYCZNYCH. STUDIUM MODELU HISTORYCZNEGO I MODELU DOSTĘPNOŚCI KOMUNIKACYJNEJ

ABSTRACT

The processes of founding, operation, and development of cities are difficult to describe using traditional representation methods. Breaking away from these constraints becomes possible with models that define interrelated objects, dynamically changing over time. This paper presents the authors' experiences regarding the use of digital models in the study of urban phenomena, along with the historical and methodological context of such models. The authors analysed two models of dynamic urban processes: the historical growth model of proto-town of Pultusk and the transportation accessibility model of Donostia / San Sebastián. Both examples are part of research conducted by the authors. Conclusions on the method implemented, and more general assumptions concerning simulation models' role in rational design were presented.

Keywords: design methodology, urban planning, dynamic model, simulation

STRESZCZENIE

Procesy tworzenia, funkcjonowania i rozwoju miast są trudne do opisania za pomocą tradycyjnych metod reprezentacji. Przełamanie tych ograniczeń staje się możliwe po zastosowaniu modeli definiujących obiekty powiązane relacjami, dynamicznie zmieniające się w czasie. W artykule przedstawiono doświadczenia własne dotyczące wykorzystania modeli cyfrowych w badaniu zjawisk urbanistycznych oraz kontekst historyczny i metodyczny modeli tego typu. Przeanalizowano dwa przypadki modeli zawierających informacje o dynamice procesów urbanistycznych: model historycznego wzrostu protomiasta Pułtusk i model dostępności komunikacyjnej Donostia / San Sebastián. Oba przykłady zaczerpnięto z badań prowadzonych przez autorów. Przedstawiono wnioski dotyczące doświadczeń w zakresie zastosowanej metody oraz szerzej — znaczenia parametrycznych modeli symulacyjnych dla racjonalnego projektowania.

Słowa kluczowe: metodyka projektowania, urbanistyka, model dynamiczny, symulacja

1. INTRODUCTION

Representing phenomena in the scope of urban planning requires the use of models with diverse characteristics. The spatial arrangement, morphology of urban spaces, landscape issues or silhouette studies can be analysed with tools that are familiar for architects, where the primary object of mapping is the geometric structure. In other layers of investigation, urban models depend on methods taken from the interdisciplinary space. These are both direct adoptions (e.g., the use of transport models to study transport circulation in the city) and indirect ones (e.g., the use of flow models to valorise the quality of urban space). This paper describes urban models created by architects with the purpose of solving problems beyond the representation of space.

The paper consists of two essential sections: 'Research background' and 'Multiple-case study'. They are followed by 'Discussion' and 'Conclusions' sections. The background was described using the method of critical analysis of sources. The case study implemented elements of prototype testing and an experimental approach. The prototype solutions developed for both models were evaluated based on their coherence with context data.

Goal of the study

The authors intended to present two models that differ in the subject of mapping (historical city fabric vs. transportation subsystem). What these representations have in common is that they both concern intangible phenomena that change over time and require the use of interdisciplinary data. Both were undertaken in cooperation with external stakeholders, with the intention of using them outside the academic sphere. The aim of the work was to understand the differences and similarities in models describing the dynamics of urban processes. The authors' intention was also to join the discourse on the methodology of dynamic urban models. The presentation of the results may be useful for assessing the effectiveness of the techniques presented and comparing them with alternative representation methods.

Various members of the same team participated in creating both models. Similar programming tools were used for implementation. It allowed for a mutual understanding of objectives and a constant exchange of experiences to improve modelling techniques in both fields.

2. RESEARCH BACKGROUND

Considerations relevant to this paper regarding the transformation of architecture in the era of the information revolution are included in the work of Antonino Saggio (2010). It must be seen as the result of more general studies on the civilizational breakthrough, having both an academic and literary dimension.

The specificity of urban models has been distinguished in the context of a systemic approach (Bettencourt, 2021). The theory of digital representations of city processes and the taxonomy of algorithmization methods (Batty, 2017) were brought as a reference for our observations. The socio-technical perspective of City-Scale Digital Twins (Nochta et al., 2021) has been considered during the construction of the models. Concerning the transfer of information and increasing the medium's efficiency and flexibility, the paper is based on conclusions grounded in the field of the humanities (Manovich, 2006). In the area of predictions, the authors relied on their studies and the works of William Mitchell as visionary images of future digital urban planning.

The presented study stays in relation to the latest research in the field of digital urban models. The reconstruction of Pułtusk uses a virtual environment to disseminate knowledge, similar to the reconstructions of German cities described by Deggim et al. (2017). It is an example of a digital twin system, where, as in the work of Psomadaki et al. (2018), the real twin is a set of relics expanded with knowledge and historical documentation. Representation of the dynamics of public transportation in the city is based on mathematical formalization, as in the work of Zhang et al. (2020). An important strand of discourse influencing the presented work concerns digital support for modelling urban intelligence. A broad discussion of trends in this area is provided by Atitallah et al. (2020).

Both models presented in the article were built on the assumption that they depict systemic phenomena as seen by classical Wiener's cybernetics and that we can distinguish algorithmically descriptive patterns (Alexander, Ishikawa and Silverstein, 1977) according to which mechanisms that automate the creation of models can be established.

Using Batty's taxonomy, the Pułtusk model should be included in the category of urban dynamics of building transformations in relation to their life cycle and community changes. It also contains elements specific to spatial interactions, where spatial phenomena result from occupying characteristic locations. The San Sebastián model corresponds to the Land Use Transport (LUT) category, which extends the category of mobility management urban digital twins (Ferré-Bigorra, Casals and Gangolells, 2022) as it includes additional information on the number of inhabitants, jobs and facilities.

The authors developed their models in accordance with the refinement methodology described by Batty. Validation was performed by examining the compliance of external data with the model (location of archaeological relics in Pułtusk; morphology and land use of San Sebastián). When constructing communication mechanisms and interfaces, they calibrated the models to present relevant data as faithfully as possible.

2.1. Formal concepts, systemic and algorithmic approach, digital medium

In the post-war period, urban model creation gained a new theoretical reference. Advanced solutions of the industrial era, new achievements in mathematics, and the appearance of computers contributed to the formation of the systems approach. Thanks to the work of Norbert Wiener, the dynamics of natural processes have been described as diagrams of feedback and conditional loops. The theoretical scheme matched the electromechanical and, later, digital experiments.

Systems theory was translated into architecture and urban planning in the following decades. The complete picture of a system analysing spatial conditions (including dynamic ones) and solving design tasks was proposed by Christopher Alexander. His formulas, described by a decision diagram, can be considered prototypes of models used to find optimal solutions in architecture.

Michael Batty's works are essential for developing methodology for creating dynamic urban models (Batty, 2017). They combine knowledge related to describing complex processes (transportation, infrastructure, economy) with the mathematical apparatus of data analysis. In the taxonomy created by Batty, we find categories corresponding to different strategies for representing urban dynamics. These are primarily Agent-Based Models, Cellular Automata, and Land Use Transport Models. Batty draws attention to the previously described mechanism of the usefulness of models in empirical reasoning. A model that has passed the calibration and validation meets the criteria of a scientific experiment. Thanks to this, it can be an effective tool to support planning, also in the context of ethical relations with residents.

Lev Manovich (2006) described the concept of the medium present in every digital representation. He characterized the digital medium by listing its five essential features. From the point of view of the model methodology, the most important of them are variability, the ability to automate and the ability to transcode. Since the digital medium is coherent at an elementary level, it can record any available message, which, in turn, is always subject to algorithmic processing, and thanks to parameterization, it allows the generation of extended families of digital prototypes. The digital medium transcodes information. This leads to the interdisciplinarity of models, which increases their usefulness in representing urban phenomena.

Digital models support the contemporary urban design skillset. They dynamically illustrate the functioning of motorized, bicycle, and pedestrian traffic flows and track changes resulting from corrections of the road network (traffic models). They support forecasting infrastructure loads depending on the distribution and size of user groups (absorption models and infrastructural models). They help to assess environmental effects in the context of new investments. They support interdisciplinary analyses and reinforce sustainable development (ventilation, ecosystem activities, temperature). They help to represent the perception of the city and the comfort of use (Space Syntax, Agent-Based Models). In addition, when built with a socio-technical perspective and not just a purely technology-centric approach, digital models can have a significant role in supporting policy-making and implementation (Nochta et al., 2021).The latest stage in the evolution of the formal model methodology is strongly related to automatic and self-learning processes. An important element here is data acquisition, which uses participation (Deggim et al., 2017), as well as machine learning, big data analysis and artificial intelligence. These techniques are perceived as essential in predicting the effects of design activities, which is a condition for the sustainable development of cities (Ortega-Fernández et al., 2020).

3. MULTIPLE-CASE STUDY

In this part of the article, the authors present two cases of using a model to study urban problems. The cases come from the authors' own experiences, and they can be analysed in terms of skillset contribution effectiveness and the efficiency of transferring information about dynamic city phenomena.

The first example is a model used for historical research, in which data from archaeological excavations were used. The parametric digital model was built based on traditional documentation (extensive resources of drawings and data). Its dynamics refer here to the land use process (settlement of new houses, negotiating common space) and constant change of town scheme in time (seventeen subsequent phases).

The second example concerns city planning in the context of the reconstruction of the public transport system. Using resources given by the city, the authors developed a parametric tool to map accessibility and suggest solutions based on alternative infrastructures.

In the scope of the algorithmic concept of models, in both cases, the programming platform for building models was a visual programming language editor, Grasshopper for Rhinoceros. In this environment, the original schemes of algorithms were established and refined. The specific procedures in both cases required external libraries and components individually programmed by the authors. In the case of Pułtusk, the basic algorithm was an automatic generator of buildings (in given locations, by examining space availability, it created buildings corresponding to the rules taken from archaeological research). In the case of San Sebastián, the base algorithm calculated the travel time between the given points. In both models, core algorithms were developed to represent reality more accurately. For Pułtusk, this meant automatically partitioning the buildings into wooden elements (to enable comparison with excavation data). For San Sebastián, the original scheme of connections was broken down into a hierarchy of graphs: pedestrian traffic, public transport and a graph of connections between them.

In the communication layer, both models required projection onto a general model of the city, for which a similar mechanism was applied. First, the quantification was based on orthogonal grids. For Pułtusk, a 10 × 10 m grid, consistent with the archaeological methodology, was used, while in the case of San Sebastián, a more adequate 100 × 100 m grid was implemented. Based on the analysis of the grid cell parameters, it was possible to validate the data and optimize the calculation. Secondly, automatically generated data, arranged in relation to grids, was displayed on a map. It made it possible to consider additional factors relevant to the analysis. In the case of Pułtusk — the archaeological accessibility of individual zones and, consequently, the credibility of the reconstruction. In the case of San Sebastián — the development intensity pattern and the location of natural barriers (topographic, infrastructural, technical).

3.1. Proto-town in Pułtusk; parametric reconstruction model

Digital reconstructions of historical cities and settlement systems were created already in the initial phase of development of CAD techniques. They were initially created for visualization purposes and later also for virtual exploration. Contemporary work in this area focuses on the dynamics of development processes and the standardization of the description (Koszewski et al., 2021). The study presented below is an example of a methodological approach in which the model is not the goal but a way of solving interdisciplinary problems at the interface of archaeology and architecture.

In the second decade of the 21st century, the team of the Faculty of Architecture of the Warsaw University of Technology under the direction of Stefan Wrona, in cooperation with Dorota Stabrowska, an archaeologist conducting research in Pułtusk, dealt with the creation of a model representing the state of the settlement organism on the castle hill that had existed in the pre-incorporation era. These works were summarised in a monograph (Słyk and Wrona, ed., 2015) and an exploratory exhibition at the Regional Museum in Pułtusk.

The reconstruction works were based on the results of excavations carried out in 1976–1985 by the Warsaw Archaeological Group. During the renovation works carried out in the seat of the bishops of Płock during the creation of the Polonia House, the area of the castle courtyard, part of the cellars, and the surrounding areas were examined. The discovered relics of wooden buildings were found in excellent condition thanks to favourable hydrogeological conditions. Extensive documentation of the urban structure's preserved elements and layers was made. The interpretation of the finds led archaeologists to hypothesize a transitional form in this area between a medieval settlement and a town. The degree of organization of the urban structure was relatively high. It made it possible to formulate rules for which the settlement network changed.

The difficulty of building a reconstruction model resulted from the need to map the dynamic growth process of the proto-town. According to the original hypothesis, archaeologists distinguished six settlement levels divided by layers of fires. The determinants for the subsequent phases of development were the levels of the so-called eastern road. Creating a model that matched the results of the excavations, the team began by identifying methods for constructing wooden rooms and joining them into two-room huts. Sławomir Kowal developed a parametric tool, Pułtusk Rekonstruktor, which automatically generates variations of solutions. Based on the coordinates of selected corners (taken from archeologic documentation), the program generated configurations of the vestibule versus the main room, corresponding to the geometric rules determined based on the analysis of excavation relics. After determining the primary projection and its correlation with the archaeological plan, the program created elements of a 3D structure: foundations, walls with openings, and a roof. Pułtusk Rekonstruktor also generated internal walls and elements of horizontal divisions for large rooms.

Automating the construction of hut models allowed the team to proceed with the recreation of the proto-town growth process in a parametric model. Successive levels of the eastern road (a total of seventeen chronological states) determined successive locations of nodal points of the urban matrix. BasedHuts were generated based on the location of the corners, huts were generated. As a result, the recipient of the model obtained a three-dimensional visualization with a time slider. They could freely move in chronology, observing changes in development.

As the excavations on the castle hill did not cover the entire area of the proto-town, not all architectural relics were discovered, documenting the complete picture of the buildings. The parametric model also allowed for the creation of reconstruction variants in this respect. Less archaeological evidence reduced the likelihood of hypotheses. Nevertheless, the team was striving to create them. Thanks to the tool that automatically generates the building structure that meets the rules, it was possible to present the entire urban complex in variants corresponding to the hypotheses, with the simulation of undiscovered elements such as the palisade.

For the needs of the exhibition at the Regional Museum in Pułtusk, the elements of the digital model were 3D printed. The physical model, complementing the visualization, was based on the sectorization taken from archaeological methodology. The base of the model was divided according to the area grid scheme. In the sectors explored by excavations, the veracity of the reconstruction was high. In the others, it was only a prediction. Thanks to the mobility of individual grid sectors, the physical representation of the parametric model can be transformed as the state of knowledge increases, and new hypotheses may be created.

3.2. Donostia / San Sebastián: Parametric model of public transport accessibility

Urban policies are shifting from automobile-focused designs to urban models that encourage proximity and active mobility, such as the 15-minute city, which proposes that all daily essential needs should be accessible within a short walk from home (Abbiasov et al., 2024). However, it is difficult to have all the basic needs within a 15-minute radius because the users of a city are often not in control over where they work or where their acquaintances live. To nuance and complement this urban model, the concept of '45-minute territory' (Puig et al. 2020) proposes a distributed network, a city or a polycentric territory, which must be able to be imagined in such a way that it does not presuppose a waste of land, energy and time.

With these two scales in mind, the city of Donostia / San Sebastián is currently (as of 2023) working on a project called Datorren Donostia (Upcoming San Sebastián). Two new central metro stations are expected to be operational by 2025, and the city wants to rethink the mobility guidelines in the most central areas of the city. It implies implementing a Low Emissions Zone, reducing the space for cars, and rethinking the bus network.

Reshaping a public transport network requires understanding the strengths and weaknesses of the current network and the different proposals. To do this, a parametric model of public transport accessibility was developed, which focused on two main aspects: the metrics and the medium, that is, the index and the model. The index is based on the accessibility indicators of the International Transport Forum (ITF), and its details lie beyond the scope of this article. This article focuses on the analytical georeferenced mobility model for Donostia / San Sebastián, which was used to compare the current bus network with possible future scenarios through different indicators.

The model calculates the time needed to connect any pair of origin and destination points in the city by public transport. It was designed in Rhinoceros through its Grasshopper visual programming interface and uses several urban open data sources. Based on this open data, the model recreates door-to-door trips between different origins and destinations (Ill. 3), where the trips are characterized by different phases and modes of transport.[1] To calculate the travel time, the model uses the Dijkstra algorithm (Dijkstra, 1959) to determine the shortest path in a graph consisting of three layers of connections, with different costs to traverse them:

- Pedestrian graph: We replicated the network of pedestrian paths of the city to link any point in the city with the public transport stops/stations. To calculate the cost of traversing each connection, the average speed was set to 4 km/h (ITF, 2019), and the maximum walking time from origin to stop and from stop to destination was limited to 8 minutes (Kortabitarte, 2011).
- Public transport graph: It is the public transport network, where the nodes are the bus/train stops, the segments are the routes between them, and the cost is equal to the travel time, according to the data collected from the GTFS files.
- Connection graph: Virtual connections join the pedestrian and public transport graphs. The crossing cost equals the average waiting time (frequency in minutes divided by two). When more than one line with identical travel segments overlaps, the method recalculates the waiting time considering the total service.

The model establishes a 100 × 100 m grid and calculates the optimal travel time between each point on the

[1] The walking time from the trip's origin to the public transport stop, the waiting time at the public transport stop, the journey inside the vehicle until the drop-off stop, the transfer time, if applicable, and the walking time from the public transport stop to the destination.

grid and all other points. This way, it determines the accessibility isochrone (for this project, 30 minutes) for each of them.

However, accessibility also depends on urban development patterns (ITF, 2019). Therefore, the project also analysed land use around each pair of origin and destination points by measuring how many people live within a certain radius from each point, along with the number of jobs and facilities. The concept of 'urban intensity' was used as the weighted average of this information. The index used in the project, which we called CAI (Combined Accessibility Index), represents the urban intensity accessible for each location in 30 minutes by public transport in comparison with the total urban intensity of the city.

In this way, the methodology determines not only the urban area that is accessible in 30 minutes by public transport but also the resulting accessible activities (the population intensity, the intensity of jobs, and the intensity of accessible facilities within that isochrone). By measuring these indicators while evaluating different scenarios, the methodology detects urban areas with worse access to public transport. It thus helps to propose network redesign proposals that reduce geographical inequality and provide better opportunities to the most disadvantaged areas.

In addition, coupling a parametric model with the Combined Accessibility Index proved to be a helpful tool not only to evaluate changes in the network design but also to communicate findings and design decisions to stakeholders through data-visualization techniques. The graphics presented in this paper illustrate the transportation model (Ill. 3, 4) developed by authors for a specific set of parameters. The objective of these visually intuitive user interfaces is to allow interdisciplinary audiences, from civil servants to neighbours, shopkeepers and activists, to participate in decision-making processes and influence them. This way, stakeholders accept technical constraints more easily, and citizens feel their insights are being taken into consideration.

4. DISCUSSION

The genesis of both models presented in the article is similar. External stakeholders turned to a team of architects — urban planners with the problem of visualizing dynamic urban phenomena. In both cases, the problem was well described with data and had a systemic structure. However, it needed to be presented in a legible model embedded in a spatial, recognizable image of the city.

While carrying out the work and analysing the results, the authors asked themselves whether the architectural and urban spatial image of the city is the most appropriate starting point for solving interdisciplinary problems. They also sought to identify common and methodologically different modelling techniques. The conclusions in this regard, presented below, have been expressed to improve the author's modelling skillset, define the limits of their own competencies, and find the strengths and weaknesses of the modelling workshop being created.

1. The comparison of the two models, different in content, shows that the methods based on a pseudocode generator (with a systemic structure) make it easy to synthesize the content and algorithmic mechanisms. If this generator operates on geometric definitions, then the data can be visualized in a way that is consistent with the natural perception of the city, and it is relatively easy to conduct an interdisciplinary dialogue.
2. The power of using a universal, easy-to-use toolkit creates significant limitations. In both cases, the complexity of the modelled process slowed down the interactive functions of the model.
3. The specificity of the disciplines involved in the process (transport engineering, archaeology) required the use of specific tools both at the level of algorithms and data presentation. The authors conclude that high precision increases the need to create a custom, discipline-specific modelling apparatus. The modular structure of the model (and algorithm) is a solution that allows to partially overcome these limitations. In the studied cases, common elements were noticed (e.g., modularization on a grid, projection onto a topographic/geodesic model of the city) and will be treated as universal components in subsequent works.
4. In both examined cases, the implementation requirements had a significant impact on the data presentation interface. The San Sebastián model required more automation to produce an accessibility zoning map. The Pułtusk model was less automated but highly parameterized. It is because the recipient of the latter, an archaeologist studying the past, moves in the sphere of uncertainty. When examining hypotheses, they are given a visualization tool but maintain high control over the entire process. In the case of San Sebastián, certain parts of the process were based on validated data, and the model performed larger parts of the data processing automatically. In terms of interfaces, the authors achieved satisfactory results, thanks to consultations and corrections made based on feedback from stakeholders (archaeologists, transport engineers, the Regional Museum in Pułtusk, the City of San Sebastián)
5. The possibility of mutual benefiting from the achievements of both cases was observed, despite

the differences regarding the object of representation. Examples of such activities that will be tested in subsequent projects include presenting data for chronological states (date slider) and the use of motion graphs for historical (including non-existent) transport systems. The condition for greater efficiency and flexibility in this area is the modularization of models.

As a result of the work done, the authors became convinced that models created in the environment of parametric spatial modelling tools can effectively represent dynamic urban processes. Particularly satisfying were the effects of a comprehensive, general presentation of data in a manner adequate to the needs of stakeholders, which is in line with the shift in focus from a purely technical towards a socio-technical perspective of City-Scale Digital Twins (Nochta et al., 2021).

Both presented models are examples of support for analytical and design methods. This results in the need to verify data and output. Validation of information about the historical state is described by Apollonio et al. (2024). For these reasons, the Pułtusk model was generated iteratively, testing, and modifying hypotheses. In the case of the Donostia model, the most important was validation by comparison with actual transport data collected by the city authorities.

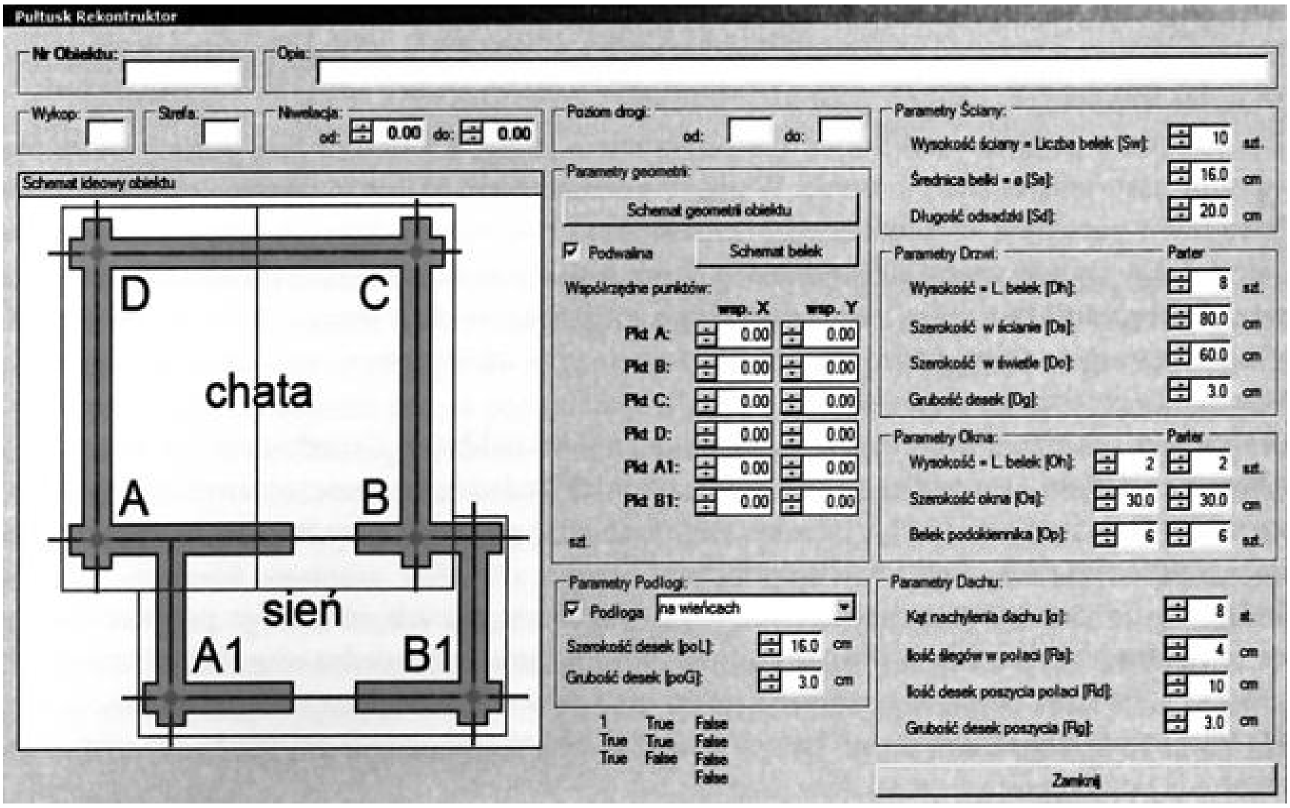
Limitations were encountered in increasing the precision of mapping interdisciplinary processes. They resulted from the need to implement specific algorithms (in the form of external libraries or own code) and from partial inconsistency between the universal pseudocode editing tool and the requirements of external components. The need for modularization of the models and the possibilities existing in this regard, despite the differences in the content of the two examined models, were confirmed.

5. CONCLUSIONS

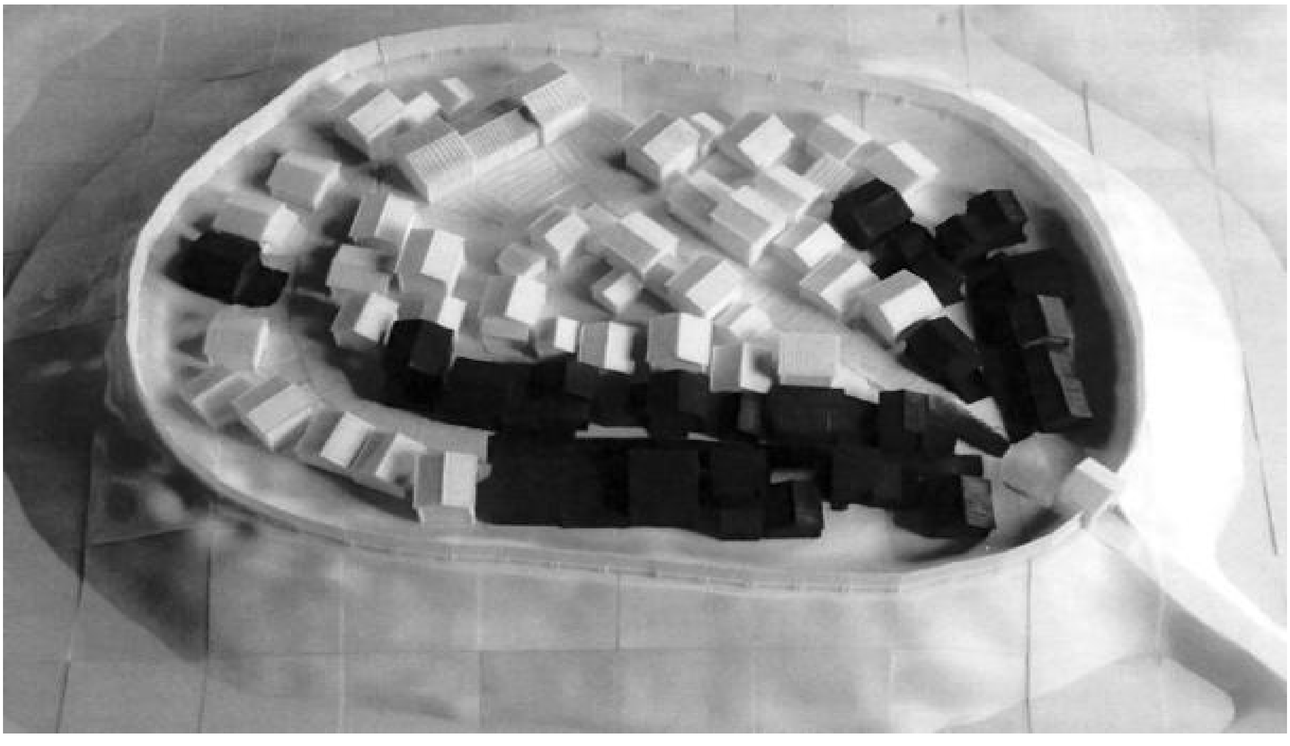
Thanks to the development of digital techniques, parametric models representing urban processes have become more common as cities experiment with them in a wide range of fields. The cases cited in the paper and other experiences of contemporary urban planning practice indicate that it is possible to describe specific urban phenomena algorithmically. Programming environments for building urban models have become more user-friendly and open for collaborative, interdisciplinary workflows.

In addition to this potential as decision-making enablers, digital techniques have the potential to challenge historically rigid planning rules as well. While most urban regulations (zoning rules, parking requirements, service provisions) depend on preset intervention areas and fixed coefficients, algorithmic models can enable more dynamic regulations. A good example is the Webcat planning tool by Transport for London, which determines both permitted parking standards and development densities depending on their Public Transport Accessibility Level.

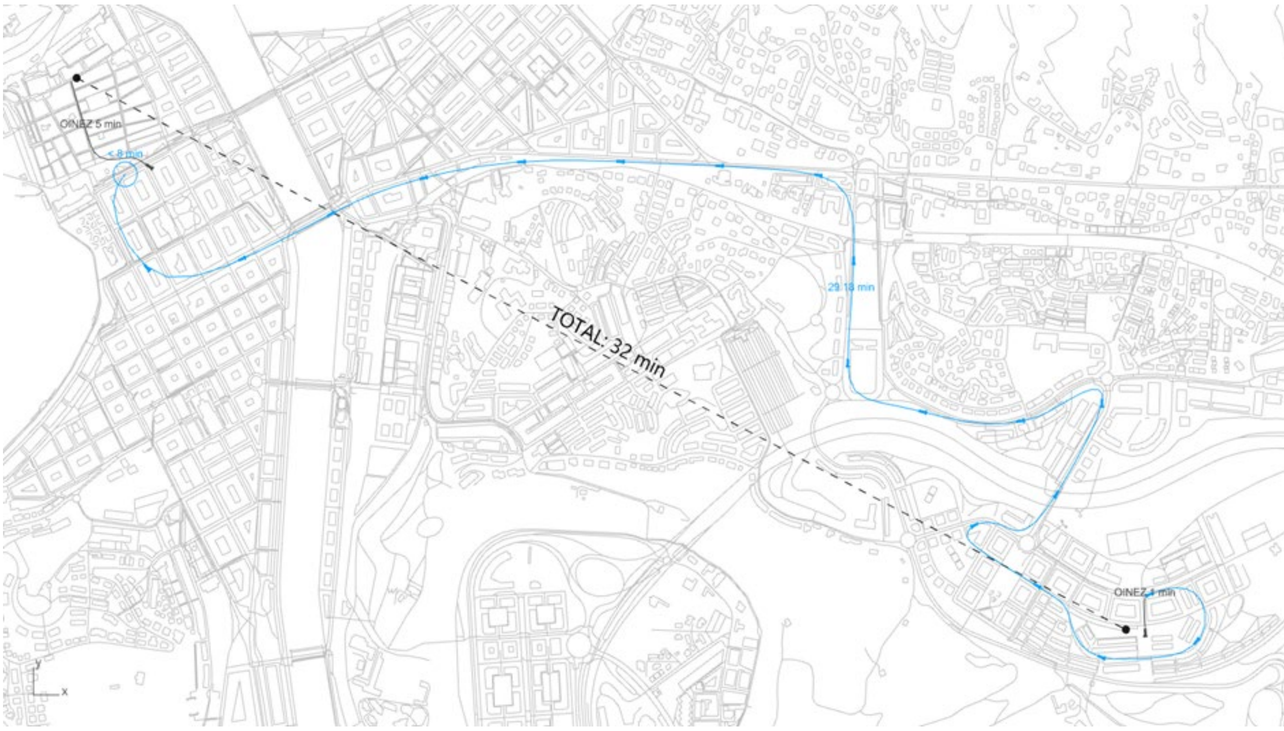
The relation between standardization and individualization is also worth mentioning. Although the applications of digital models are often based on standard methodological foundations, they always require individualization. Modularization of modelling algorithms might help to overcome constraints while transferring methods between different models. In calibrating the algorithm for individual needs, it is important to precisely recognize the rules and develop an interface that allows it to be used in planning processes related to interdisciplinarity and participation.



Ill. 1. Program interface for Pułtusk Rekonstruktor. Source: original work.
Il. 1. Interfejs programu Pułtusk Rekonstruktor. Źródło: opracowanie własne.

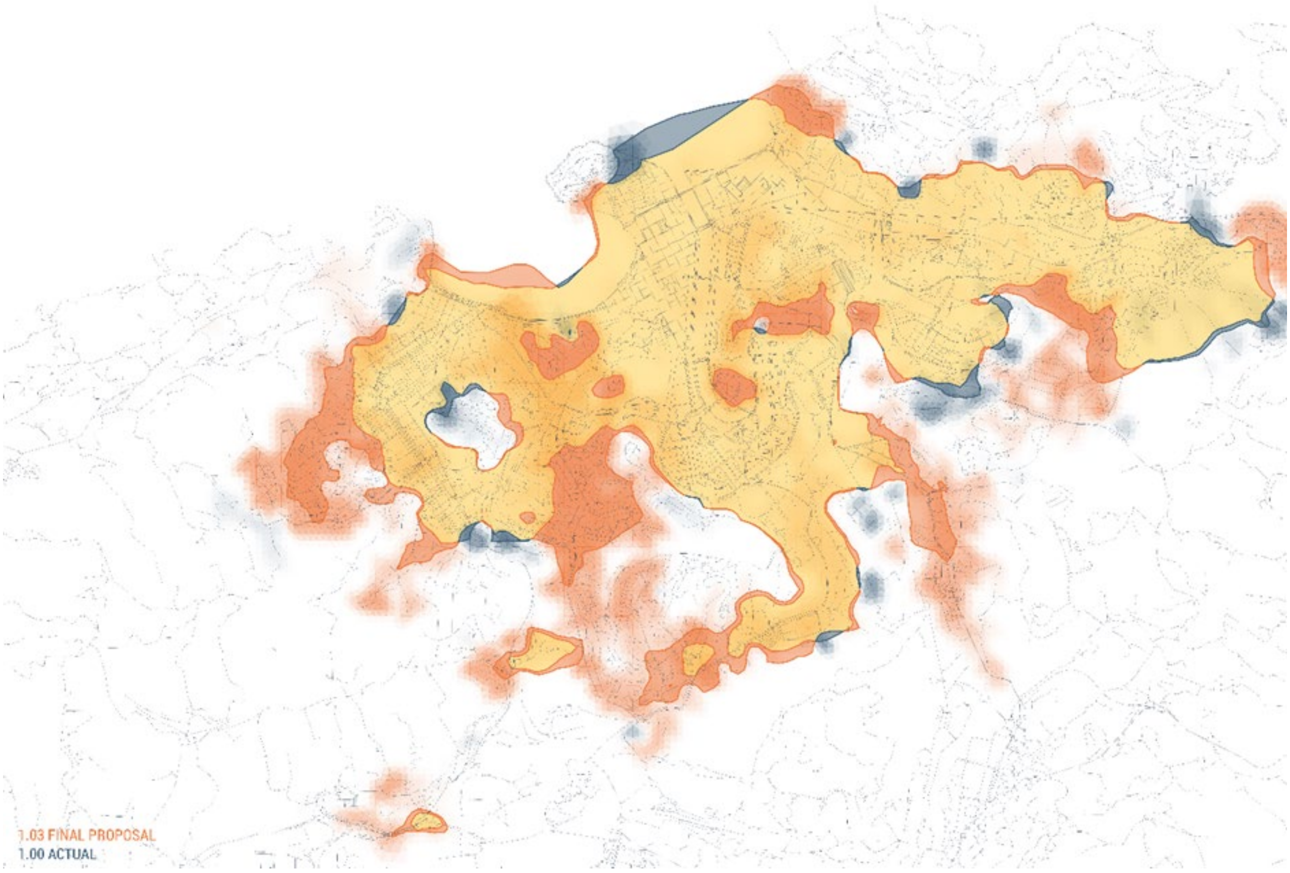


Ill. 2. Physical model of the proto-town of Pułtusk produced by 3D printing. Source: original work.
Il. 2. Model fizyczny protomiasta Pułtusk wykonany w druku trójwymiarowym. Źródło: opracowanie własne.



Ill. 3. Route and travel time between origin and destination points. Source: original work.

Il. 3. Trasa i czas podróży pomiędzy punktem początkowym i końcowym. Źródło: opracowanie własne.



Ill. 4. Comparative heat maps of the Combined Accessibility Index between the benchmark scenario and a design proposal. Source: original work.

Il. 4. Porównawcze mapy cieplne Całkowitego Wskaźnika Dostępności pomiędzy scenariuszem bazowym a koncepcją projektową. Źródło: opracowanie własne.

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