

## ИНФОРМАЦИОННЫЕ ТЕХНОЛОГИИ И АРХИТЕКТУРА

Научная статья



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**Цифровое моделирование пешеходных потоков в задачах  
предпроектного анализа и оптимизации городской среды****Дарья Андреевна Репа<sup>1✉</sup>, Елисей Олегович Макеев<sup>2</sup>,  
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**Аннотация.** В статье представлен метод цифрового моделирования и оценки пешеходной активности в условиях городской среды, основанный на интеграции геоинформационных данных («2GIS Pro»), трёхмерного моделирования (Rhino 3D) и алгоритмов многоагентной параметрической симуляции (Grasshopper). Применение метода исключает необходимость проведения трудоемких натурных обследований при выявлении зон градостроительного и функционально-планировочного несоответствия. Апробация метода на репрезентативной выборке из 20 планировочных ситуаций Санкт-Петербурга подтвердила его аналитическую эффективность и послужила основой для классификации различных сценариев поведения пешеходов, а также сопоставления результатов симуляции с реальными физическими наблюдениями: зафиксированными сетями стихийных «народных троп» и участками эрозии почвы.

**Ключевые слова:** пешеходный каркас, многоагентное моделирование, градостроительный контекст, геоинформационные технологии, Grasshopper, «2GIS Pro»

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## INFORMATION TECHNOLOGIES AND ARCHITECTURE

Original article

**Digital modeling of pedestrian flows in the tasks of pre-project  
analysis and optimization of the urban environment****Daria A. Repa<sup>1✉</sup>, Elisei O. Makeev<sup>2</sup>, Aleksandr S. Kruchinin<sup>3</sup>**<sup>1,2,3</sup>Saint Petersburg State University of Architecture and Civil Engineering,  
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**Abstract.** The article presents a method for digital modeling and assessing pedestrian activity within an urban environment, based on the integration of geoinformation data ("2GIS Pro"), three-dimensional modeling (Rhino 3D), and multi-agent parametric simulation algorithms (Grasshopper). The application of the method eliminates the necessity of conducting labor-

intensive field surveys for identifying zones of urban planning and functional-planning discrepancy. Testing the method on a representative sample of 20 planning situations in Saint Petersburg confirmed its analytical effectiveness and provided a basis for the classification of various pedestrian behavior scenarios, as well as correlating simulation results with actual physical observations-recorded networks of spontaneous desire lines and areas of soil erosion.

**Keywords:** planning structure, pedestrian infrastructure, multi-agent simulation, urban context, geoinformation technologies, Grasshopper, "2GIS Pro"

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The effectiveness of pedestrian infrastructure is one of the key criteria for the quality assessment of the contemporary urban environment. The comfort of public spaces is determined by the logic of functional connections corresponding to the actual needs of citizens. However, in design practice, a dissonance frequently arises between the normative routing of the road and path network and the actual scenarios of user behavior. Ignoring the principle of "economy of effort" when organizing transit leads to the formation of structural and planning conflicts: the formation of spontaneous desire lines in landscaped areas and the emergence of underutilized infrastructure sections [1, 2]. The traditional toolkit of pre-project analysis, based on field surveys (visual traffic counting, recording of trampled lawns), possesses a number of limitations. It is characterized by high resource consumption and depends significantly on weather conditions and the human factor. Furthermore, field analysis is predominantly retrospective and discrete in nature: it records already established planning defects "here and now," but does not provide the capability to forecast the distribution of flows in newly designed or reconstructed areas. The development of geoinformation analysis and parametric modeling methods opens up opportunities for transitioning from the recording of problems to their preventive identification [3].

**The research objective is** the development and testing of a methodology for predictive digital modeling of pedestrian activity as an instrument for objective pre-project analysis of the urban environment. It is assumed that the integration of aggregated user data (Big Data) [4, 5] and parametric simulation tools [6, 7] will provide the opportunity to create a reliable digital model of anthropogenic activity capable of identifying zones of spatial conflicts by correlating actual points of attraction and the design geometry of the environment.

#### **Research objectives:**

1. To compile a representative database of 20 actual planning situations in Saint Petersburg demonstrating pedestrian transit conflicts.
2. To develop an algorithm for parametric modeling of pedestrian flows (within the Rhinoceros + Grasshopper environment), simulating scenarios of natural user movement.
3. To analyze existing research methods based on a comparative analysis of the detailing of global and local cartographic geoservices at the micro-level.
4. To verify the method through a spatial cross-analysis of the simulation results with the actually established network of desire lines.
5. To identify the typology of causes for the formation of hidden planning defects and to evaluate the practical potential of the method for adjusting design solutions.

#### **Materials and methods**

The proposed method represents a process of predictive digital modeling that minimizes the need for fieldwork and eliminates errors associated with manual data collection. The following tools are used in conjunction:

- "2GIS Pro" (API / Data export) — extraction of quantitative data on traffic and points of attraction.
- Rhinoceros 3D – construction of the base design geometry of the space.
- Grasshopper – parametric programming of agents and generation of gradient activity heatmaps (fig. 1).

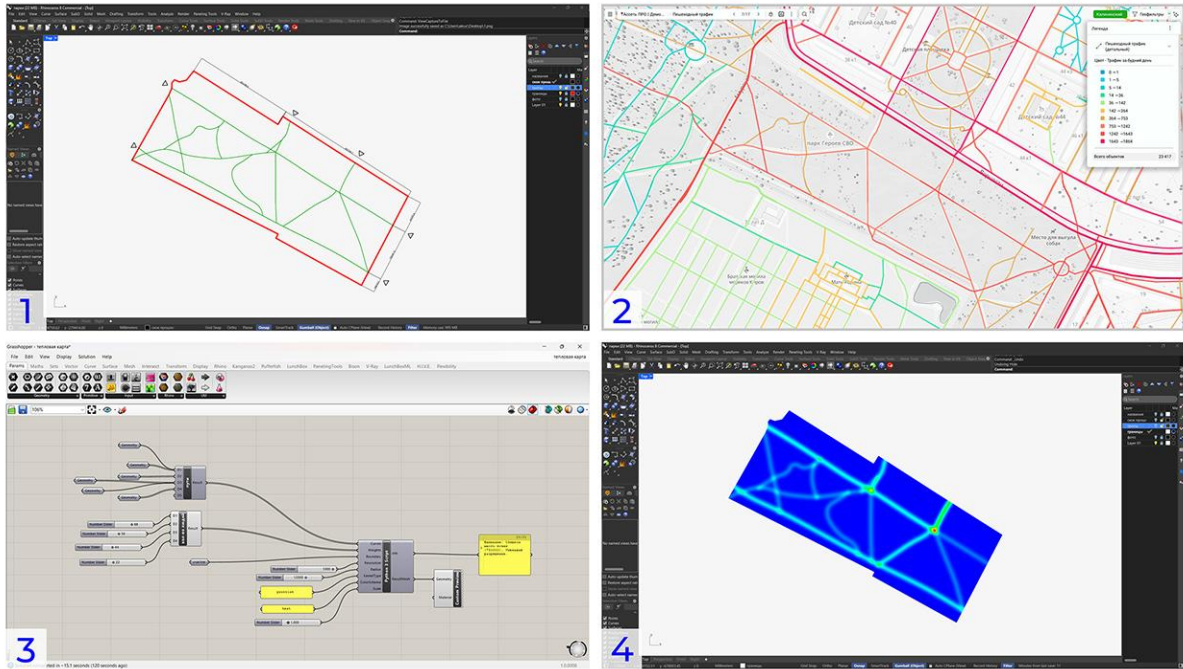


Fig. 1. Stages of predictive parametric modeling of pedestrian flows in the Rhinoceros 3D and Grasshopper environment

To systematize the process of pre-project urban planning analysis, the entire course of the study is structured and divided into four successive stages (fig. 2).

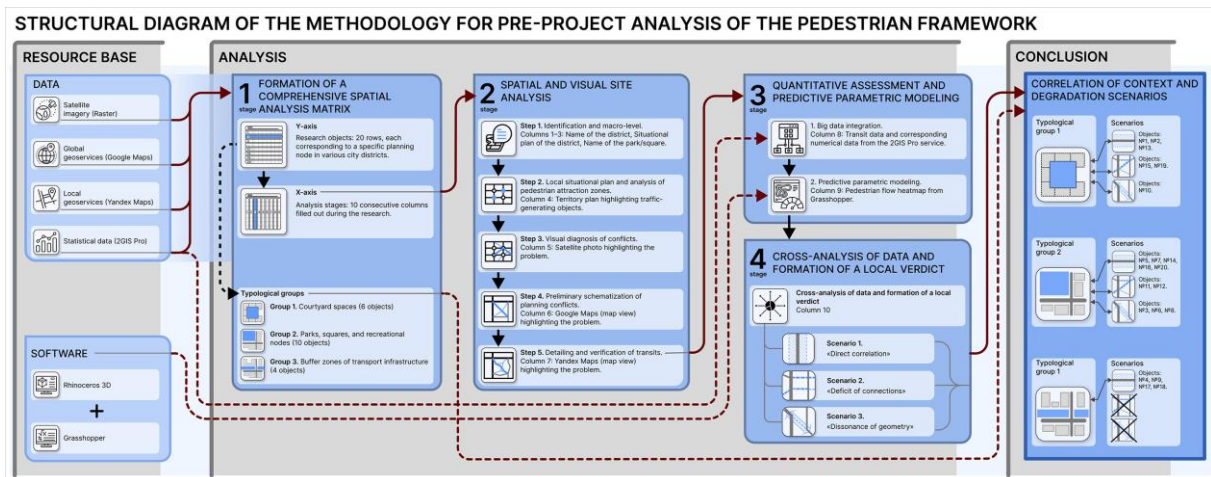


Fig. 2. Structural diagram of the methodology for pre-project analysis of the pedestrian infrastructure

**Stage 1. Formation of a comprehensive spatial analysis matrix and classification of objects**

The main framework of the research is represented by a multilevel analytical matrix, consisting of a representative database of 20 planning situations demonstrating pedestrian transit conflicts (fig.

3). This tool ensures the structuring of data by transitioning from a general urban context to a detailed study of local infrastructure defects.

Structure of the analytical matrix:

- y-axis (Objects of study): 20 rows, each corresponding to a specific planning situation in various districts of the city.

- x-axis (Stages of analysis): 10 sequential columns filled out during the course of the research:

1. Name of the district
2. Situational plan of the district
3. Typological group of the object
4. Local situational plan (highlighting the "functional magnets")
5. Satellite imagery (recording of erosion zones)
6. "Google Maps" diagram (verification of the problem)
7. "Yandex Maps" diagram (detailing of the pedestrian infrastructure)
8. "2GIS Pro" service data (quantitative traffic indicators)
9. Flow heatmap from Grasshopper (simulation result)
10. Conclusion (cross-analysis and verdict)

DISTRICT NAME	SITUATIONAL PLAN OF THE DISTRICT	OBJECT NAME	LOCAL SITUATIONAL PLAN HIGHLIGHTING TRAFFIC-GENERATING OBJECTS	SATELLITE PHOTO HIGHLIGHTING THE PROBLEM	"GOOGLE MAPS" MAP VIEW HIGHLIGHTING THE PROBLEM	"YANDEX MAPS" MAP VIEW HIGHLIGHTING THE PROBLEM	DATA FROM THE "2GIS PRO" SERVICE ON TRANSITS AND THEIR NUMERICAL DATA	HEATMAP OF PEDESTRIAN FLOWS FROM "GRASSHOPPER"	CONCLUSION
VYBORGSKY DISTRICT		OBJECT 1 Landscaping in the Severnaya Dolina residential complex							The hypothesis is confirmed: side entrances are overloaded, forming a spontaneous central shortcut route.
		OBJECT 2 Landscaping in the Severnaya Dolina residential complex							The hypothesis is confirmed: users avoid the northern paths and form a diagonal shortcut toward the eastern path.
		OBJECT 3 Sollertinsky Square							The hypothesis is confirmed: existing paths do not connect key destinations directly, resulting in multiple spontaneous crossing routes.
		OBJECT 4 Landscaping on Engels avenue							The hypothesis is confirmed: overloaded crossings and paths cause direct spontaneous routes toward the residential area.
		OBJECT 5 Polyastrovsky Garden							The hypothesis is confirmed: congestion along main pedestrian corridors leads to additional spontaneous routes.
FRUNZENSKY DISTRICT		OBJECT 6 Isfahan Square							The heatmap reveals congestion at path intersections and a mismatch between the planned network and actual pedestrian movement, causing spontaneous routes.
		OBJECT 7 Alpiysky Square							The hypothesis is confirmed: congestion at the entrances causes spontaneous shortcuts across the lawns.
		OBJECT 8 Budapest Square							The heatmap reveals congestion at the junction of the diagonal path and sidewalk, while mismatched transit directions generate additional spontaneous routes.
		OBJECT 9 Landscaping on Budapestshtskaya Street							The hypothesis is confirmed: congestion along the main path leads to a parallel pedestrian route and additional spontaneous paths.
		OBJECT 10 Courtyard on Alpiysky Lane							The initial hypothesis was not confirmed: spontaneous routes emerge because the single diagonal path does not cover all transit directions.

a)

DISTRICT NAME	SITUATIONAL PLAN OF THE DISTRICT	OBJECT NAME	LOCAL SITUATIONAL PLAN HIGHLIGHTING TRAFFIC-GENERATING OBJECTS	SATELLITE PHOTO HIGHLIGHTING THE PROBLEM	"GOOGLE MAPS" MAP VIEW HIGHLIGHTING THE PROBLEM	"YANDEX MAPS" MAP VIEW HIGHLIGHTING THE PROBLEM	DATA FROM THE "2GIS PRO" SERVICE ON TRANSITS AND THEIR NUMERICAL DATA	HEATMAP OF PEDESTRIAN FLOWS FROM "GRASSHOPPER"	CONCLUSION
KALININSKY DISTRICT		OBJECT 11 Chinghiz Aitmatov Square							The hypothesis is partially confirmed: pedestrians move directly across the square, bypassing the existing path network.
		OBJECT 12 Park of the Heroes of the Special Military Operation							The hypothesis is partially confirmed: additional routes form between path intersections, reflecting actual pedestrian movement.
KIROVSKY DISTRICT		OBJECT 13 Landscaping on Dvinskaya Street, 16k1							The hypothesis is confirmed: spontaneous routes toward the parking area emerge from pedestrian flow intersections.
		OBJECT 14 Kiryano Garden							The hypothesis is confirmed: intersecting pedestrian flows generate additional shortcut routes.
		OBJECT 15 Courtyard on Stachek Avenue							The hypothesis is partially confirmed: the lack of pedestrian infrastructure causes diagonal spontaneous routes across the lawns.
KRASNOSELSKY DISTRICT		OBJECT 16 Vladimir Shalimov Square							The hypothesis is confirmed: underestimated traffic along the narrower path leads to additional spontaneous routes.
ADMIRALTEYSKY DISTRICT		OBJECT 17 Boulevard on Tsiolkovskiy Street							The hypothesis is confirmed: incomplete diagonal paths generate spontaneous route extensions across the boulevard.
TSENTRALNY DISTRICT		OBJECT 18 Peski Territory							The hypothesis is confirmed: a direct spontaneous route forms between the building and the bus stop.
VASILEOSTROVSKY DISTRICT		OBJECT 19 Landscaping on Nalichnaya Street, 30k2							The hypothesis is partially confirmed: congestion and missing pedestrian connections cause additional spontaneous routes.
PETROGRADSKY DISTRICT		OBJECT 20 Matveevskiy Garden							The hypothesis is confirmed: the absence of stairs on one side of the elevation leads to a spontaneous route along the slope.

b)

Fig. 3. Multilevel analytical matrix of spatial analysis of 20 planning situations: a) objects 1-10; b) objects 11-20

Typological classification of the object database (Y-axis): To increase the accuracy of the analysis, the 20 studied situations are divided into three groups based on urban context characteristics:

**Group 1: Courtyard spaces and adjacent territories (6 objects) (fig. 4)**

- context: local areas located between residential buildings, intra-block drives, and parking lots. Compositionally subordinated to the architecture of the building blocks.
- functional objective: provision of the shortest access from entrances to points of attraction (parking spaces, recreational zones, exits from the block).
- objects in the group: 1, 2 (Parnas – transit to parking lots), 10 (Alpiyskiy Lane – discrepancy of the orthogonal layout), 13 (Dvinskaya St. – transit to parking areas), 15 (Stachek Ave. – lack of pedestrian infrastructure in the residential zone), 19 (Nalichnaya St. – formation of paths directly to the entrances).

COURTYARD SPACES AND ADJACENT TERRITORIES				
scenarios	LOCATION	SATELLITE PHOTO HIGHLIGHTING THE PROBLEM	HEATMAP OF PEDESTRIAN FLOWS FROM GRASSHOPPER	PHOTOGRAPHIC DOCUMENTATION
Direct correlation and congestion	<b>OBJECT 1</b> Landscaping in the Severnaya Dolina residential complex Transit across lawns directly to parking zones and central parts of the courtyard			
Critical deficit of connections	<b>OBJECT 10</b> Courtyard on Alpiysky Lane A rectangular courtyard squeezed within a block, where the official diagonal does not cover the residents' demand for movement			
Structural dissonance of geometry	<b>OBJECT 15</b> Courtyard on Stachek Avenue Driveways are separated only by lawn strips, pedestrian infrastructure is absent, residents walk directly to the buildings			

Fig. 4. Visualization of environmental degradation scenarios for Group 1 (Courtyard spaces)

**Group 2: Parks, squares, and recreational nodes (10 objects) (fig. 5)**

- context: large planning units with a territorial-regular structure. They possess their own compositional centers and landscape elements (water bodies, terrain variations).
- urban planning conflict: contradiction between the aesthetic routing of the pedestrian and transport network and the actual pedestrian routes of citizens across the territory.
- objects in the group: 3 (Sollertinsky Square), 5 (Polyustrovsky Garden), 6 (Isfahan Square – structural dissonance), 7, 8 (Budapest Square – corner cutting), 11 (Aitmatov Square – through diagonal), 12 (Park of the Heroes of the Special Military Operation), 14 (Kiryanov Garden), 16 (Shalimov square), 20 (square on the Petrograd Side – unaccounted-for terrain).

PARKS, SQUARES, AND RECREATIONAL NODES				
scenarios	LOCATION	SATELLITE PHOTO HIGHLIGHTING THE PROBLEM	HEATMAP OF PEDESTRIAN FLOWS FROM GRASSHOPPER	PHOTOGRAPHIC DOCUMENTATION
Direct correlation and congestion	<b>OBJECT 6</b> Isfahan Square Severe structural dissonance of the square's rectangular geometry: paths are routed along the short side, whereas pedestrians need to transit along the longitudinal axis			
Critical deficit of connections	<b>OBJECT 11</b> Chinghiz Aitmatov Square A square where pedestrians transit via a direct diagonal across the central zone			
Structural dissonance of geometry	<b>OBJECT 20</b> Matveevsky Garden A park featuring a terrain variation, where designers neglected to provide a staircase to the elevation			

Fig. 5. Visualization of environmental degradation scenarios for Group 2 (Parks and squares)

**Group 3: Buffer zones and transport infrastructure facilities (4 objects) (fig. 6)**

- context: linear landscaped areas along arterial roads, serving as a barrier between the roadway and buildings.
- traffic generators: public transport stops, subway exits, and pedestrian crossings. Characterized by "aggressive" perpendicular routes across lawns.
- objects in the group: 4 (Engels Ave.), 9 (Budapeshtskaya St. – duplication of routes), 17 (Tsiolkovsky St. – diagonal crossing of the boulevard), 18 (Peski territory – absence of a direct connection with the stopping point).

BUFFER ZONES AND TRANSPORT INFRASTRUCTURE FACILITIES				
SCENARIOS	LOCATION	SATELLITE PHOTO HIGHLIGHTING THE PROBLEM	HEATMAP OF PEDESTRIAN FLOWS FROM GRASSHOPPER	PHOTOGRAPHIC DOCUMENTATION
Direct correlation and infrastructure congestion	<b>OBJECT 4</b> Landscaping on Engels Avenue The landscaping is extended longitudinally along the avenue, whereas the transit proceeds strictly from pedestrian crossings directly across the lawns to the residential buildings			
	<b>OBJECT 17</b> Boulevard on Tsiolkovsky Street The linear boulevard is intersected straight through by diagonal transit for access to the opposite side of the roadway			
	<b>OBJECT 18</b> Peski Territory The route proceeds from the building directly to the roadway of Smolny street and the bus stop			

Fig. 6. Visualization of environmental degradation scenarios for Group 3 (Buffer zones)

**Stage 2. Spatial and visual analysis of the territory (Filling columns 1-7)**

The initial stage of working with the analytical matrix represents a sequential study of the territory based on the principle "from macro- to micro-scale," implemented in five steps:

**Step 1. Identification and macro-level (Filling columns 1-3: Name of the district, Situational plan of the district, Name of the park/square)**

The location of the studied node within the planning structure of a specific district is determined. To comprehend the role and function of the surveyed areas in the formation of the district's transport and pedestrian infrastructure, the urban context of the territories is evaluated (character of the surrounding development, functional zoning, presence of major transport "arteries").

Results of macro-level identification: Based on the completion of the first three columns of the analytical matrix, a representative database of 20 planning situations was compiled and structured. The geographical distribution of objects (column 1) covered 9 different districts of Saint Petersburg, which provided a diversity of urban context:

- 50% of the sample (10 objects) are concentrated in the zones of mass residential development in the Vyborgsky (Objects 1–5) and Frunzensky (Objects 6–10) districts.
- 25% of the sample (5 objects) are localized in the Kirovsky (Objects 13–15) and Kalininsky (Objects 11, 12) districts.

- the remaining 25% (5 objects) are distributed point-by-point across the Petrogradsky (Object 20), Tsentralny (Object 18), Vasileostrovsky (Object 19), Admiralteysky (Object 17), and Krasnoselsky (Object 16) districts.

As a result of the analysis, all studied areas were distributed among the three typological groups previously identified (in Stage 1), which served as the basis for structuring the subsequent search for local "functional magnets."

#### **Step 2. Local situational plan and analysis of pedestrian attraction zones (Filling column 4: Situational plan of adjacent territories highlighting traffic-generating objects)**

The scale of the study narrows to the level of the immediate pedestrian environment of the surveyed areas. Within the boundaries of these territories, the strategic level of spatial user behavior is analyzed, at which citizens develop the need for movement and set a specific goal for their route. Within the radius of normative pedestrian accessibility (5-15 minute isochrone), local "functional magnets" – key points of attraction acting as the main generators of transit traffic – are identified and mapped. Such objects include: major interchange hubs (subway stations, complexes of surface public transport stops), centers of business and commercial activity (shopping centers, focal street retail), educational institutions, and recreational zones.

Mapping the locations of these places of attraction reveals the poles of activity within the territory. Based on them, a hypothetical matrix of origin-destination (demand for movement from point A to point B) is formed [8]. The location of the "functional magnets," between which the most stable connections are formed, determines the natural vectors of pedestrian movement. These data are the key to understanding the reasons for the emergence of spontaneous routes (desire lines). They are inevitably formed at points where the road network laid down in the project does not provide the shortest and most logical transit between the identified points of attraction (A and B).

Based on the analysis of the local situational plans of the 20 planning situations, "functional magnets" were determined, and the main points of attraction provoking the emergence of spontaneous transits were classified into three typological groups:

- *transport and infrastructure magnets (40% of the sample, 8 objects)*. In this group, the key traffic generators are public transport stops, pedestrian crossings, and parking zones, a logical connection to which is not provided by the designed road and path network. Thus, transit to pedestrian crossings, stops, and catering facilities is pronounced at Objects 3, 4, 11, and 18; transit through boulevards to streets — at Object 17; and pedestrians' tendency to walk directly to parking spaces through lawns creates traffic problems in Objects 1, 2, and 13.

- *residential development as a factor in increasing pedestrian flow (40% of the sample, 8 objects)*. In a significant number of cases, the magnets are the residential buildings themselves, to which pedestrians pave the shortest routes from external streets or intra-courtyard drives. This scenario is recorded in local courtyard territories (Objects 10, 15, 19), as well as in squares and parks where pedestrian paths do not provide residents of the district with direct access to their homes (Objects 5, 6, 8, 9, 16).

- *intra-park local magnets and transit nodes (20% of the sample, 4 objects)*. The functional and compositional centers of the recreational zones themselves become points of attraction – intersections of main alleys, artificial elevations, or key entrance groups of public squares. The lack of connections or congestion of paths on the approaches to these magnets is recorded at Objects 7 (main entrance zones), 12 and 14 (intersections of diagonal directions), and 20 (spontaneous ascent up a slope to an elevation in the center of the park where stairs are absent).

#### **Step 3. Visual diagnostics of conflicts (Filling column 5: Satellite photo highlighting the problem)**

Satellite images are used to move from abstract diagrams to an analysis of the physical state of the environment. A visual search for urban planning problems is conducted: non-functioning wastelands, zones of critical narrowing of pedestrian paths, and artificial barriers are recorded.

Particular attention is given to the localization of soil cover erosion zones and spontaneously formed transits (desire lines), which serve as a physical indicator of the discrepancy between the design geometry and the actual needs of users. To document the identified defects, a method of manual graphic recording is applied: over the raster satellite base map, using color-coding tools (applying a semi-transparent red fill), the contours of all informal "shortcuts" and trampled lawn sections are highlighted. This method visualizes the actual trajectory of pedestrian movement, assesses the scale of anthropogenic landscape degradation, and forms a clear diagram of planning conflicts for its subsequent analysis.

### **Results of the visual diagnostics of the soil cover**

Based on the utilization of the color-coding method, the presence of physically visible spontaneous passages was recorded across all analyzed areas without exception (100% of the sample, 20 objects). The recorded lawn erosion was classified according to three main geometric patterns reflecting the specific nature of local urban planning conflicts:

- *complex branched networks and intersecting routes (55% of the sample, 11 objects)*. In this group, users massively ignore the planned pedestrian network, forming multiple fan-shaped movement trajectories through central lawns, as well as X- and T-shaped intersections. Such a large-scale structural dissonance is clearly recorded from satellite imagery in squares, parks, and large courtyard territories (Objects 3, 4, 5, 8, 9, 10, 12, 14, 15, 16, 19).

- *extended transit diagonals and straight lines (35% of the sample, 7 objects)*. In these areas, clearly defined, single or paired extended routes are discernible from satellite imagery. They are laid by pedestrians for direct transit to/from parking lots, pedestrian crossings, or along the main directional axes of squares, duplicating inconvenient paths. This scenario (long diagonal or longitudinal lines of erosion) is recorded at Objects 1, 2, 6, 11, 13, 17, and 18.

- *short local shortcuts (10% of the sample, 2 objects)*. Point-specific disruptions of the lawn are recorded at local nodes where the design configuration fails to account for the logic of the shortest path. In satellite images, this is displayed as short red lines directly at the entrance groups of squares (Object 7) or spontaneous ascents up slopes due to the absence of stairs (Object 20).

### **Step 4. Preliminary schematization of planning conflicts (Filling column 6: "Google Maps" (map view) highlighting the problem)**

As the primary cartographic base, the exported schemes of the global geoinformation service "Google Maps" are applied. Since this service is characterized by a relatively low frequency of updating detailed high-resolution satellite imagery, exclusively those spontaneously trampled routes ("desire lines") and zones of soil cover erosion that are actually displayed or visually discernible on the base "Google" scheme are transferred to the vector map. This layer records the most large-scale and apparent areas where the official geometry comes into conflict with the natural behavior of users.

Results of schematization based on Google Maps: The analysis of the "Google Maps" cartographic base clearly confirmed the hypothesis regarding the insufficient detailing of this global service for micro-level urban planning analysis. Out of the 20 studied territories, spontaneous transits are actually displayed on the base vector scheme in only 10% of cases (2 objects):

- only the most large-scale and long-established routes are graphically recorded in red: the branched transit from the side of Amurskaya Street in the Park of the Heroes of the Special Military Operation (Object 12) and the pronounced line of erosion in the western part of the Peski territory (Object 18).

- in the overwhelming majority of cases – 90% of the sample (18 objects) – spontaneous passages are completely absent (not displayed) on "Google" maps, despite their 100% physical confirmation on satellite images.

This fact mathematically proves the information gap of global maps and justifies the necessity of transitioning to local geoinformation services ("Yandex Maps") for the reliable verification of conflicts in the next step.

### **Step 5. Detailing and verification of transits (Filling column 7: "Yandex Maps" (map view) highlighting the problem)**

The concluding stage of the visual and graphic research is the cross-verification of the obtained data using the "Yandex Maps" service. The selection of this geoinformation resource as the final and primary base map is scientifically justified by its specific characteristics: the Yandex cartographic database is updated most expeditiously, possesses the highest spatial accuracy for the territory of the Russian Federation, and details the current pedestrian infrastructure down to minor pedestrian paths. The method of graphic overlay is applied to this highly accurate base: the geometry of urban planning errors is documented in detail and refined in red. The high level of detail of "Yandex Maps" unmistakably localizes hidden desire lines, minor spontaneous shortcuts, and complex intra-courtyard transits, which are fundamentally not recorded on less detailed global maps ("Google Maps"). This correlation forms an exhaustive diagram of zones of functional and planning discrepancy, which serves as the geometric base for the subsequent execution of the algorithmic simulation.

#### **Results of the detailing of transits based on "Yandex Maps"**

The verification process based on "Yandex Maps" demonstrated the high efficiency of the selected tool for micro-level analysis. In contrast to "Google Maps," where only 10% of the problem zones were recorded, the utilization of the Yandex database ensured 100% accuracy (across all 20 objects) in the vectorization of spontaneous routes and their overlay onto the current path grid:

- *complete verification of satellite data (100% of the sample, 20 objects)*. The lawn erosion zones identified on raster satellite images (column 5) were transferred to the vector base map of "Yandex Maps".

- *based on the refined base map, the recording of micro-transits and intra-courtyard connections was conducted (90% of the sample, 18 objects)*. By means of "Yandex Maps," areas that proved to be "blind spots" for global services were recorded. Complex intersecting networks in local courtyards (Objects 10, 15, 19), local routes at the entrance zones of squares (Object 7), and minor diagonals across lawns near parking spaces (Objects 1, 2, 13) were delineated with mathematical precision.

- *geometric accuracy*. Owing to the up-to-date delineation of the pedestrian infrastructure in Yandex, a geometric dissonance of the infrastructure was recorded: for instance, T-shaped and X-shaped spontaneous routes (Objects 12, 14) laid by pedestrians bypassing existing paths.

As a result of compiling column 7, a vector database of urban planning conflicts was obtained for all 20 situations. This database serves as the foundation for the subsequent stages of work.

### **Stage 3. Quantitative assessment and predictive parametric modeling (Filling columns 8-9)**

At this stage, the collected graphic and statistical information is translated into a dynamic mathematical model for simulating the behavior of pedestrian flows within the specified spatial conditions. In accordance with the structure of the analytical matrix, the process is divided into two main steps:

1. *Integration of big data (Filling column 8: Data from the "2GIS Pro" service on transits and their numerical data)*. Real quantitative indicators serve as the basis for a reliable simulation, excluding hypothetical assumptions regarding the intensity of flows. Using the analytical platform "2GIS Pro", the extraction of data on transit traffic between the previously identified (in Stage 2) "functional magnets" is conducted. An origin-destination matrix (distribution of movement demand) is formed: the exact number of pedestrians moving from a specific starting point to a destination point is recorded. To visualize these data in the 8th column of the analytical matrix, a base cartographic background is used, upon which the main transits (movement vectors) are highlighted using graphic arrows. Each of the highlighted directions is accompanied by mandatory textual attribution – the average value of flow intensity (number of people per day) is indicated.

**2. Predictive parametric modeling (Filling column 9: Heatmap of pedestrian flows from Grasshopper).** The compilation of the 9th column represents a complex process combining the topological preparation of the environment and the execution of a multi-agent simulation. This process is implemented in three stages:

- topological modeling (Rhinoceros 3D): A transition to spatial modeling within a coordinate environment is executed [9]. The condition is the recreation of the design geometry initially conceived by the landscaping authors (defects and spontaneous "desire lines" are ignored). A single base plane is created, on top of which the contours of the designed paths are delineated. Applying logical operations of subtraction, an isolated polygonal mesh is formed, representing the officially permeable pedestrian infrastructure.
- algorithmic programming of agents (Grasshopper): Based on the constructed geometry, a mathematical model of pedestrian behavior is created [10]. Generator nodes (starting points) are established at the boundaries of the studied area. Virtual agents are programmed to reach target points (functional magnets) based on the optimal pathfinding algorithm (Shortest Path). A tactical level of decision-making is embedded into the logic of their behavior: striving to minimize effort, agents are given the capability to locally "cut" corners within the specified design boundaries.
- generation of heat maps (Heat Maps): Verified quantitative data of transits (people per day) from column 8 are entered into the configured algorithm. A multi-iteration simulation is launched: agents begin movement along the design network, intersecting and grouping in narrow spaces (bottlenecks). Upon the results of the conducted iterations, the algorithm analyzes the density of digital traces. The result of the simulation (column 9) is a spatial activity heatmap, constructed on the principle of gradient intensity. The red spectrum displays areas with maximum anthropogenic load, while the blue spectrum indicates underutilized infrastructure zones. The resulting algorithmic picture substantiates the reasons for the emergence of desire lines.

### **Results of parametric modeling (columns 8-9)**

For all 20 studied planning situations, quantitative data on transit intensity were collected (column 8), and multi-iteration simulations were conducted in the Grasshopper environment. The result was the generation of 20 unique spatial activity heatmaps (column 9), reflecting the predictive distribution of pedestrian flows within the framework of the design geometry. The obtained algorithmic models form the evidence base for the subsequent final cross-analysis.

### **Stage 4. Cross-analysis of data and formation of a local verdict (Filling column 10)**

At the concluding stage, a synthesis of the collected qualitative (visual) and quantitative (algorithmic) data is executed. The principal objective of this step is to fill in the final, 10th column of the matrix ("Conclusion"). This column represents a formalized local verdict regarding the viability of the designed infrastructure and the causes of spatial conflicts within the specific studied area. The formulation of the conclusion is based on the method of spatial cross-analysis: the vector diagrams of actual defects and spontaneous routes (columns 5, 6, and 7) are correlated with the gradient heatmap of virtual agent activity (column 9). Based on the cross-analysis, a summary classified according to one of three scenarios is entered into the cell of the 10th column:

1. Scenario "Direct correlation": a complete coincidence of the zones of digital footprint concentration with the areas of actual soil erosion.
2. Scenario "Deficit of connections": a high concentration of activity in zones from which, in reality, long desire lines diverge in the absence of designed paths.
3. Scenario "Geometric dissonance": a systemic discrepancy between the planning structure and the actual transit vectors in the absence of explicit network congestion.

The completion of the 10th column ensures an accurate diagnosis of the urban planning problem, identifying the cause of environmental erosion: path congestion, a deficit of connections, or illogical design routing.

## Research results

The proposed method for evaluating pedestrian infrastructure demonstrates efficiency in solving problems of functional and spatial analysis in urban planning. The integration of geoinformation technologies ("2GIS Pro"), three-dimensional modeling (Rhinoceros 3D), and parametric simulations (Grasshopper) constitutes a tool for constructing predictive activity maps. The testing of the method was conducted on a representative sample of 20 planning situations across 9 districts of Saint Petersburg. The cross-analysis confirmed the correlation of the algorithmic model with visual survey data and identified zones of functional and planning discrepancy.

**Based on the results of the analysis of the compiled object database, the following conclusions are drawn:**

### 1. Verification of cartographic data

The selection of local services for micro-level analysis is justified. A comparative analysis of databases revealed an information gap in global geoservices: "Google Maps" records 10% of large-scale erosion zones (Park of the Heroes of the Special Military Operation, Peski territory). Local databases ("Yandex Maps") ensure the verification of 100% of spontaneous routes across all 20 objects, including intra-courtyard micro-transits.

### 2. Typology of planning defects

The typological causes of urban environment degradation are mathematically proven. Based on the cross-analysis of predictive heatmaps and vector diagrams, the causes of the formation of spontaneous desire lines are classified according to three scenarios:

- *direct correlation and congestion (60% of the sample, 12 objects)*. Objects No. 1, 2, 4, 5, 7, 9, 13, 14, 16, 17, 18, 20. A coincidence of the computational models with actual paths is recorded. Erosion is caused by a lack of path capacity and a violation of the shortest route principle.
- *critical deficit of connections (20% of the sample, 4 objects)*. Objects No. 11, 12, 15, 19. Activity is identified in starting zones in the absence of designed infrastructure in the directions of mass demand. This leads to the formation of routes across lawns directly to points of attraction.
- *structural dissonance of geometry (20% of the sample, 4 objects)*. Objects No. 3, 6, 8, 10. The cause of the emergence of intersecting path networks is the illogical shape of planning elements. In Isfahan Square (No. 6), paths are oriented along the short side, whereas the actual transit occurs along the long axis.

### 3. Correlation of context and degradation scenarios

The analysis revealed a typological predisposition of specific object groups to concrete scenarios of environmental degradation:

#### Group 1: Courtyard spaces and adjacent territories (6 objects)

In this environment, a deficit of connections between residential buildings and "magnets" (parking lots, playgrounds) prevails.

- scenario 1 (Congestion): Objects No. 1, No. 2 (Parnas), No. 13 (Dvinskaya st.). The designed paths fail to cope with the flow to the parking zones, which provokes the formation of duplicate routes.
- scenario 2 (Deficit of connections): Object No. 15 (Stachek ave.), Object No. 19 (Nalichnaya st.). The absence of a sidewalk network along the vectors of mass demand determines the formation of routes across lawns directly to the entrances.
- scenario 3 (Geometric dissonance): Object No. 10 (Alpiysky lane). The orthogonality of the planning base does not accommodate the diagonal movement trajectories within the courtyard.

## **Group 2: Parks, squares, and recreational nodes (10 objects)**

This group is characterized by an underestimation of the territory's transit potential in favor of a formal composition.

- scenario 1 (Congestion): Objects No. 5, No. 7, No. 14, No. 16, No. 20. Concentration of flows in entrance zones and on the relief (absence of a stair descent at Object No. 20).
- scenario 2 (Deficit of connections): Objects No. 11, No. 12. The presence of extensive undeveloped zones, which pedestrians cross along the shortest vectors (an extended path across the entire territory).
- scenario 3 (Geometric dissonance): Objects No. 3, No. 6, No. 8. The discrepancy between the orthogonal path network and longitudinal directions (Object No. 6).

## **Group 3: Buffer zones and transport infrastructure facilities (4 objects)**

This group demonstrates aggressive erosion due to the rigid communicational connection "transport hub – residential area".

- scenario 1 (Congestion): Objects No. 4, No. 9, No. 17, No. 18. Due to the high intensity of transit from pedestrian crossings and stops, direct spontaneous paths are formed, crossing lawns and boulevards straight through along the shortest vector. The designed road network fails to cope with the flow: thus, in Object No. 4, the linear routing of the landscaping ignores the perpendicular pedestrian direction from the crossings to the residential buildings, whereas in Object No. 18, congestion arises due to the absence of a direct connection between the building exit and the stopping point.

### **Limitations of the method**

A systemic limitation is the possible deficit or absence of precise quantitative data regarding micro-movements within the "2GIS Pro" databases. However, even when utilizing extrapolated traffic values in local areas, the application of the multi-agent simulation algorithm yields a more reliable result than relying on the heuristic assumptions of designers. The method has proven its suitability for comprehensive pre-project analysis. The transition from a heuristic evaluation of the environment to mathematical substantiation localizes defects and forms a basis for optimizing the structure of urban spaces.

The conducted research confirmed the hypothesis: the integration of multi-agent simulations and current local geodata reveals the causes of pedestrian infrastructure degradation without conducting resource-intensive field observations. Based on 20 planning situations in Saint Petersburg, the accuracy of digital predictive analysis has been mathematically proven. Urban planning errors have been classified with an exact percentage ratio. Individual analysis demonstrated that in 60% of cases, erosion is caused by direct congestion of the infrastructure and the absence of basic landscaping elements (Object 20). In 20% of situations, the algorithm identified a critical deficit of connections in intra-courtyard territories, where pedestrians execute the shortest movement vectors to their buildings (Objects 10, 15). The remaining 20% accounts for the structural dissonance of the design geometry in orthogonal squares (Objects 3, 6). Furthermore, the cross-analysis proved the information gap of global geoservices at the micro-level: "Google Maps" recorded only 10% of large-scale conflicts, whereas the local "Yandex Maps" database ensured 100% verification of the problems.

The developed simulation algorithm is applicable not only for the analysis of existing planning situations but also for the design of new ones. Since the fundamental principles of pedestrian movement (minimization of effort and the tendency toward functional "magnets") are universal, the logic of the model and the behavioral parameters of the agents remain unchanged. Only the input data array changes: instead of the cartographic base of a real site, a design master plan (a BIM model or CAD drawing) is imported into the Rhinoceros + Grasshopper environment, and the coordinates of the "magnets" are defined based on the explication of the projected objects. This

allows for testing the routing of the pedestrian network even at the sketch stage, preventively eliminating the risks of environmental degradation before construction work begins.

The scientific and practical value of the method lies in ensuring the transition from the retrospective recording of the fact of trampled lawns to Evidence-Based Design. The proposed digital tool will provide architects and urban planners the opportunity to test the viability of the path network at the master plan creation stage. The implementation of the algorithm into practice will ensure the justified correction of illogical path routing, the legalization of high-demand routes, and will eliminate the inappropriate spending of budget funds on the landscaping of inefficient infrastructure.

### Источники иллюстраций

Рис. 1. URL: <https://dev.2gis.ru/pro> (в авторской обработке) (дата обращения: 26.02.2026).

Рис. 2. Схема автора.

Рис. 3 а, б) URL: <https://www.google.ru/maps/>, <https://2gis.ru/>, <https://yandex.ru/maps/> (в авторской обработке) (дата обращения: 26.02.2026).

Рис. 4-6. URL: <https://yandex.ru/maps/> (в авторской обработке) (дата обращения: 26.02.2026).

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