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APPLICATION OF THE MATRIX METHOD IN DETERMINING THE SHORTEST ROUTE IN BIM

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Abstract
The research was carried out to determine the shortest route between two points in a maze-shaped room using the BIM model and a script created in Dynamo. The matrix method of route calculation was used to find the optimal relation between the accuracy of the calculated route and the time needed for calculations. In order to indicate the factors influencing the extension of the calculation time and mutual relation of factors, tests were carried out for different variants of the floorplan modification (room area, the surface of internal walls, distance between the entrance and exit in a straight line and within the boundary marked by walls of the maze). The results of all trials were presented graphically. Based on the obtained results, a definition of Benefit Factor was introduced, aimed at assessing and comparing objectively a performance in individual attempts to solve the task. On this basis, the method of assessment and selection of the preferred mesh density for further applications has been proposed.

Keywords: **BIM; Building information modeling; Facility management; FM; Matrix method; Routing in building.**

1. INTRODUCTION

The search for the shortest route is always associated with optimization. For example, the selection of the most beneficial transport routes in terms of the cost of completing the task (Vehicle Routing Problem, VRP) is one of the key issues in delivery companies [1]. This issue may also find its application in the optimization of movement around the building. The feature may be found useful for instance for people responsible for maintaining the technical condition of an object. Choosing the best connection sequence between multiple points in the facility can lead to significant time savings that directly translate into increased performance.

The search for the shortest route between given points A and B can be done using several methods [2, 3]. One of them is the method based on applying a grid of points to the area. From the group of points, the start and end points are selected. Next, beginning at the start point, the points gradually approaching the end point are picked up in sequence in order to determine the connecting polyline.

This paper aims to thoroughly analyze the functionality of the matrix method for creating a mesh, optimal mesh density and main open space features influencing the efficiency of determining the shortest route inside buildings using BIM technology.

2. LITERATURE REVIEW

Although pedestrians have different characteristics of movement than vehicles, the ability to implement issues related to TDVRP (Time-Dependent VRP) to BIM is one of the examples illustrating the usefulness of the BIM model throughout the building's life cycle [4]. For example, it may relate to issues associated with building evacuation [5]. The use of BIM has also been noticed as an aid in maintaining facilities, which was also indicated in the information provided by the Polish Ministry of Infrastructure [6].

There are different methods of decomposing an open space. For instance, the space can be investigated with the use of transformations of its borders. This group contains methods based on a visibility graph [7] [8] and a skeleton method [9]. One can also use another approach, further referred to as a matrix method, which is based on a matrix of points connected with each other either with rectangular grids or grids extended by the Delaunay triangulation that enables the Spider method routing [10]. The study presented in [10] has shown that none of the abovementioned algorithms is universal, but the visibility graph and the Spider algorithm are most promising. Therefore, hereinafter only these two approaches are considered.

Open spaces can be associated with indoor environments as they both concern pedestrian movement. In research on the use of BIM in processes related to building maintenance, the matrix method is often used to determine the shortest route. It is claimed that a higher grid density increases the accuracy of route mapping [11]. This is correct, but increasing the density of the grid is not always profitable from the point of view of optimizing the planning process because it prolongs the calculation time [2]. There are some key advantages of this method such as interpolating points within the interior of the open space and creating routes with the length close to the shortest paths together with the main disadvantage of the precise calculation – the increase in the calculation time [10].

In the literature, the graph of the visibility method is a resultant of an open space borders and a researcher cannot introduce their subjective approach. The case is different in the matrix method, where the density of the grid is usually assumed by the researcher in relation to the analyzed space [10, 12]. The researcher assesses the scale of the space and assumes arbitrarily the “dense grid” and “loose grid”. No attempts are made to find the balance between benefits and drawbacks of the grid-based matrix method in relation to objective criteria.

The aforementioned methods are used to create a set of points and possible connections between them. The next step is to implement an algorithm that will analyze the developed grid in terms of finding the shortest connection between the given points. The algorithm recognized as suitable for such application is an A* algorithm [13].

3. POSSIBLE IMPLEMENTATION

One of the basic assumptions of BIM is to create a set of information about the building that can be used throughout the life cycle of the building. The efficient shortest route planning software closely connected with BIM technology may find its field of applications in facility management systems. The key ability of the program is to use the given model of a building or even a complex of buildings and connect several points in the most effective way in terms of the traveling cost. A field of facility management that has been gaining popularity is outsourcing of work. The owner of the facility can use dedicated software to give instructions to subcontractors that do not need to be familiar with the facility. The shortest path script can also be an important part of software capable of responding to reported failures on an ongoing basis. The ability to designate the shortest route between a series of different points changing in real time can be useful not only for new employees, but also for experienced ones. These checkpoints can consist of a location of the failed element, handheld store, main warehouse or base of the maintenance team. It can be a core element of the software designed to report malfunctions of the building systems and keep track over effective management of the human resources. Route planning based on digital representation of a building can be used in the routing for autonomous robots involved in building maintenance, for instance cleaning, guarding (smoke, fire, security), relocation of resources. The initial stage of routing is considered, as the real-time location needs to be defined according to current situation in building with the use of sensors.

4. RESEARCH TOOL

The study was conducted for a room with one entrance and one exit, built in the shape of a maze. The walls in the room were entered randomly. The research was carried out in Autodesk Revit 2018 with

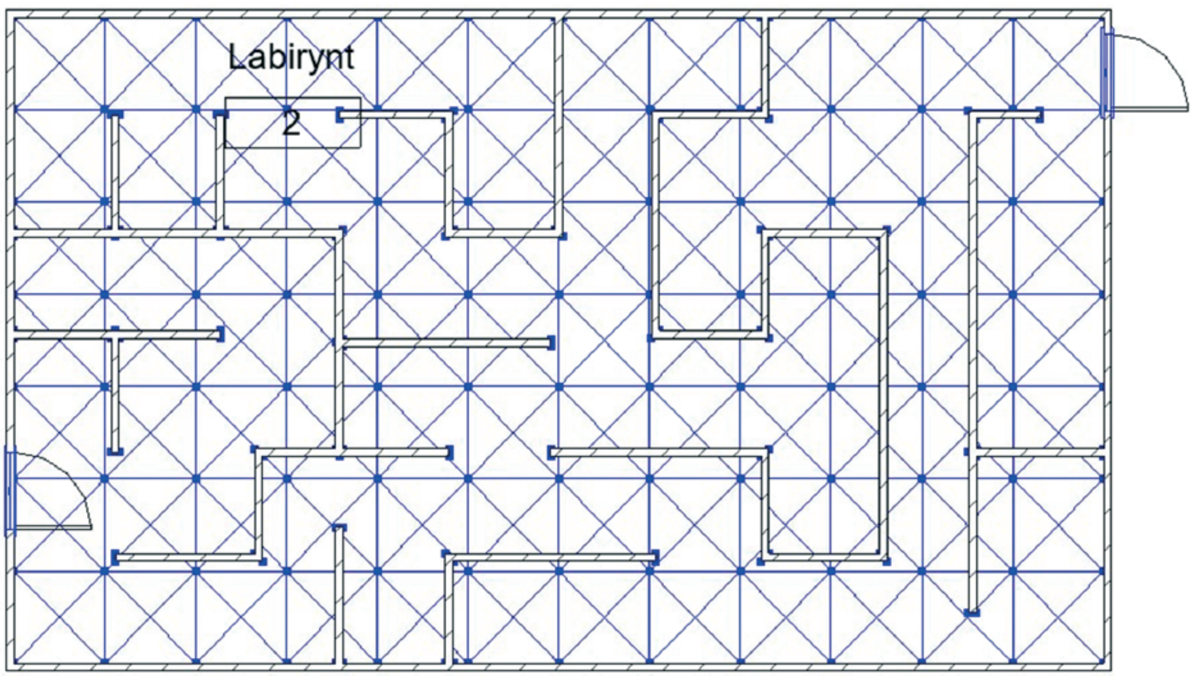

Figure 1.
Floorplan of the maze used in Series 1–4

an integrated add-on for visual programming – Dynamo version 2.0.2.6833. Calculations were made on the same script in Dynamo. This software environment was chosen because Revit is one of the leading BIM programs and is closely connected with Dynamo which is a program for visual programming. Altogether, it was a convenient tool for conducting the research. Nevertheless, the software is not a limitation for the use of the designed tool, as BIM software is able to use .ifc file which is an standardized text file format. Dynamo uses Python Programming Language so there is always a possibility to create a tool with similar functionalities without the need of having specialized and, what is more important, legally licensed commercial software.

During the calculations, the computer was not used for other activities and all tests could be assumed under similar conditions.

The Dynamo script created for the study retrieved information about the doors, which are the entry and exit points, from the BIM model. The door that is the beginning and the end of the route was described in the model data as "entry" and "exit", respectively. The script also retrieved information about the room from the model and transformed the given room into lines that outline the surface. By using a specific room in the script and not all the walls that form its outline, the script could determine the geometric outline of the given surface much faster, as a part of the information which had already been prepared in Revit. Based on the outline, an orthogonal grid of points was applied to the rooms. The grid size and the number of vertical and horizontal partitions were determined by the user. The number of segments along the x and y axes was equal to the rounded down result of dividing the length and width of the room by the variable x representing the "grid density" determined for each test. The densities were changed every 10 from 100 to 10. The units of the grid were centimeters as opposed to the approach found in other experiments regarding the search for the shortest path in a building [14], where the operation is conducted on dimensionless values. This approach relates the accuracy of the division to real values independent of the shape of the room, making it easier to compare different series of tests. The mesh density was defined by a user before starting the test. The set of points forming the mesh was then connected using two Delaunay triangulations, and as a result, each point was connected by lines with all the nearest points (Fig. 1).

Based on the graph prepared in this way, the script performed calculations to determine the shortest route. Next, the route was presented on the model in the form of a line connecting the selected points. The

Table 1.
Description scheme for each test

<table>
<tr><td>Series No.</td><td>Grid density – x [cm]</td><td>Calculation time [mm:ss]</td><td>Distance [cm]</td></tr>
<tr><td colspan="4">Figure – Floorplan of the maze with a grid and a marked exit route</td></tr>
</table>

script provided information on the length of the designated line and the calculation time from the beginning (retrieving information about the room) to the end (drawing a line on the model) of the script.

5. RESEARCH

5.1. Tests in the initial arrangement of the walls

The initial stage of the study consisted of 4 series of 10 tests each. The subsequent tests differed from each other in the degree of compaction of the point grid in the room.

In the first four series, the relationship between the length of the path through the maze and the degree of mesh compaction was examined. The tests in each of the series were carried out on a maze with the same wall arrangement but different location of doors. The doors in the first series were located on two sides of the maze. The doors in the second series were located closer to each other (distance in a straight line) but at a similar distance to the passage of the maze compared to the first test. The doors in the third series were located at a similar distance in a straight line to the doors of the second series, however, the distance to the passage was about twice shorter than in Series 2. The doors in Series 4 were intended to create the longest possible passageway.

For each series, the value of the coefficient x (grid density), Dynamo's script execution time, and the length of the route were recorded. The obtained results can be found in Tables 2–5 below. The description scheme is presented in Table 1.

Table 2.
Results obtained in Series 1

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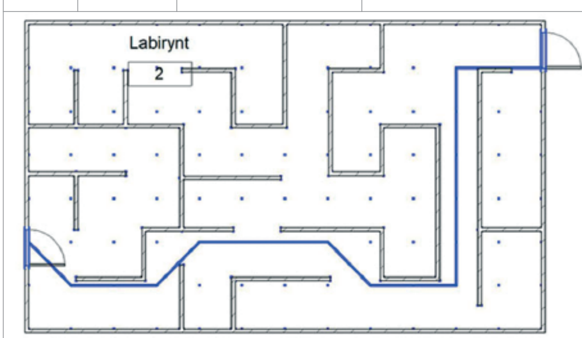
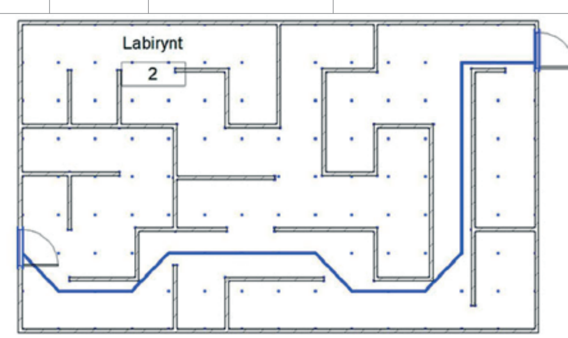
<tr><td>1</td><td>100</td><td>00:05.0</td><td>1975.251343</td><td>1</td><td>90</td><td>00:06.2</td><td>1932.137649</td></tr>
<tr><td colspan="4">
</td><td colspan="4">
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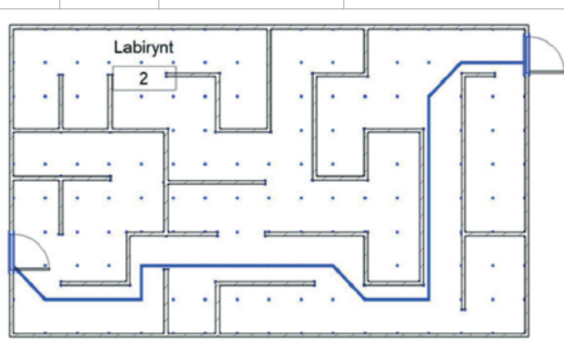
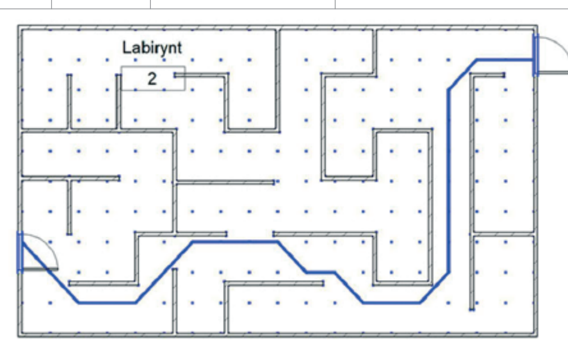
<tr><td colspan="4">
</td><td colspan="4">
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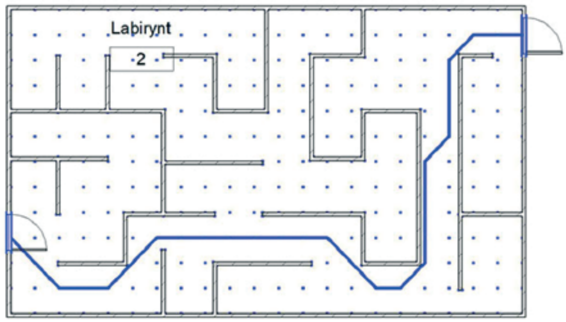				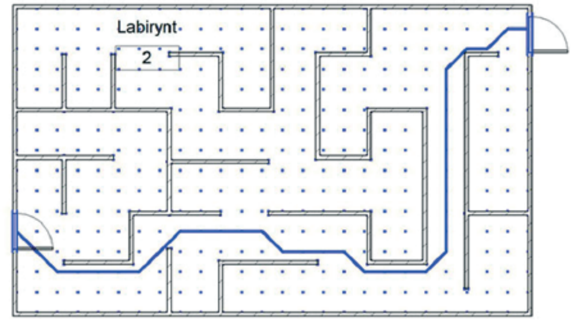			
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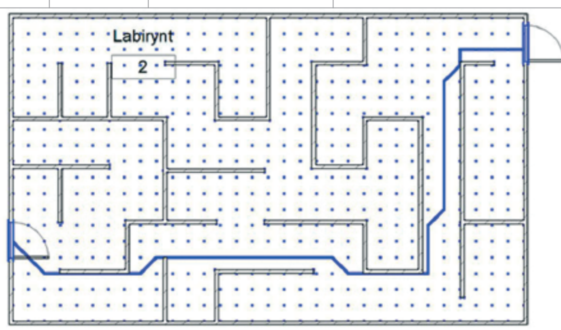				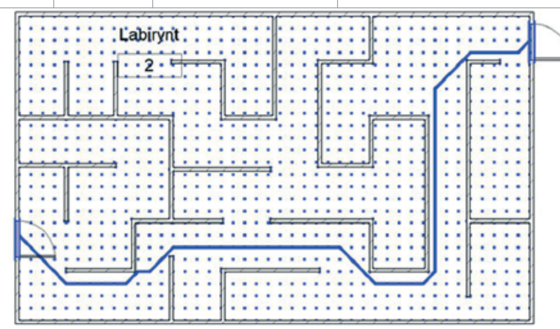			
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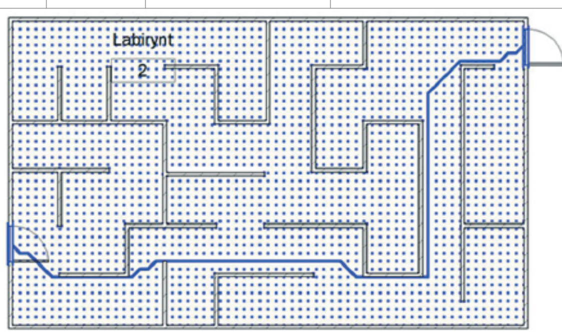				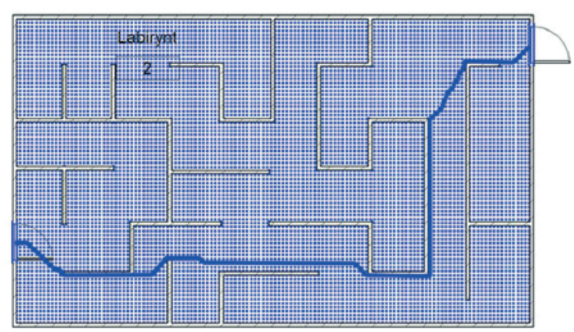			

Table 3.
Results obtained in Series 2

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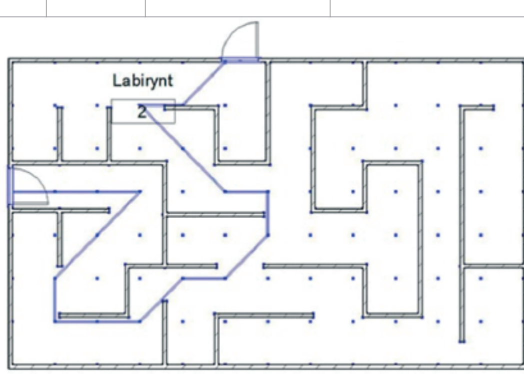				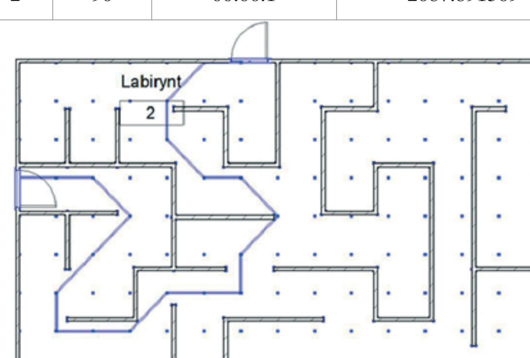			

<table>
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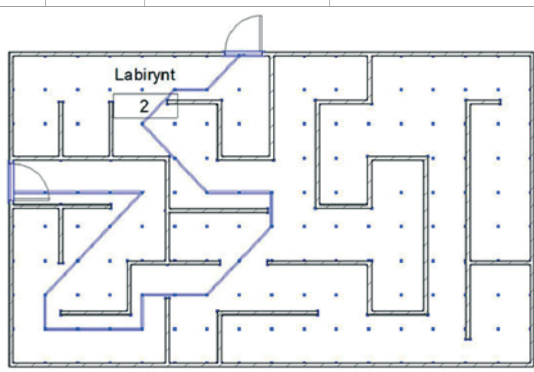
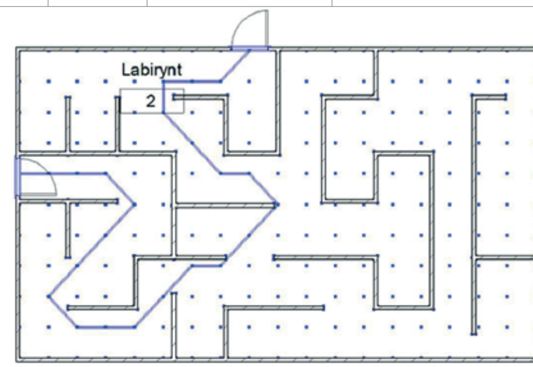
<tr><td colspan="4">
</td><td colspan="4">
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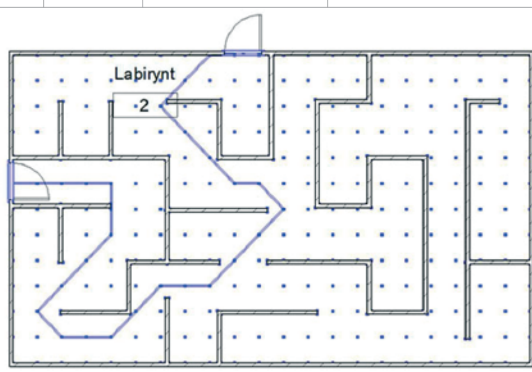
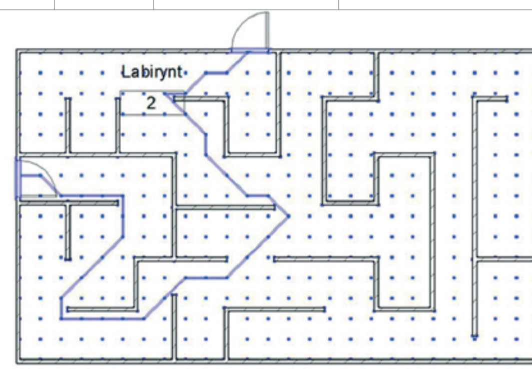
<tr><td colspan="4">
</td><td colspan="4">
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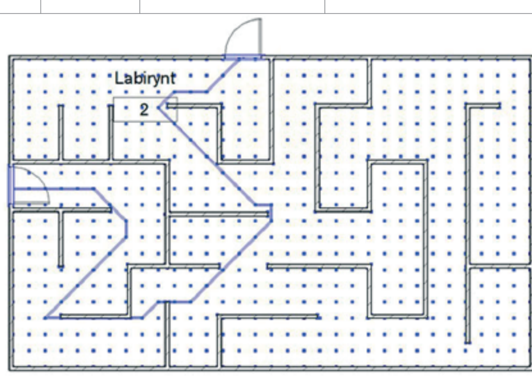
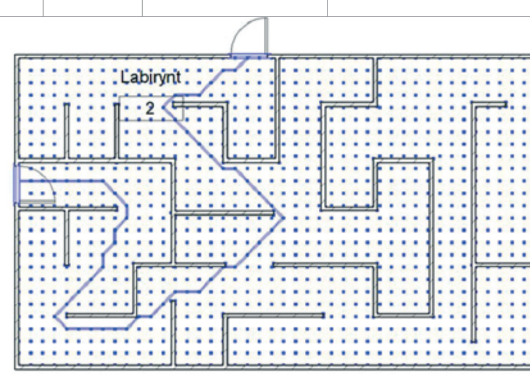
<tr><td colspan="4">
</td><td colspan="4">
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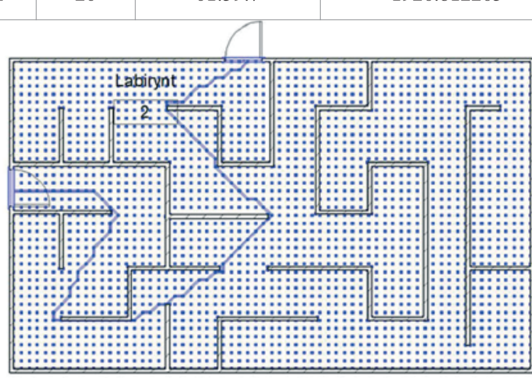
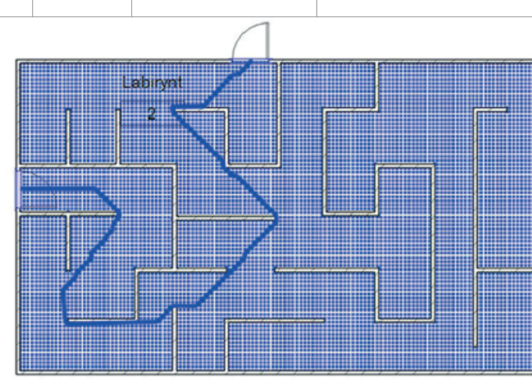
<tr><td colspan="4">
</td><td colspan="4">
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Table 4.
Results obtained in Series 3

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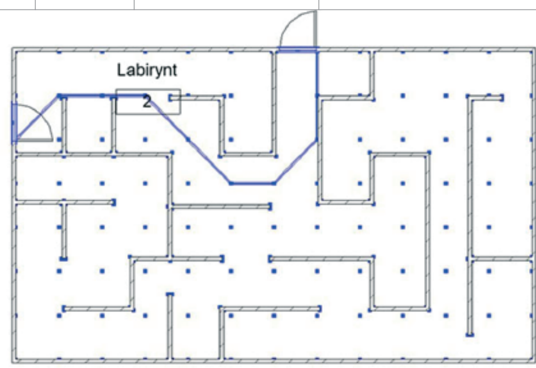
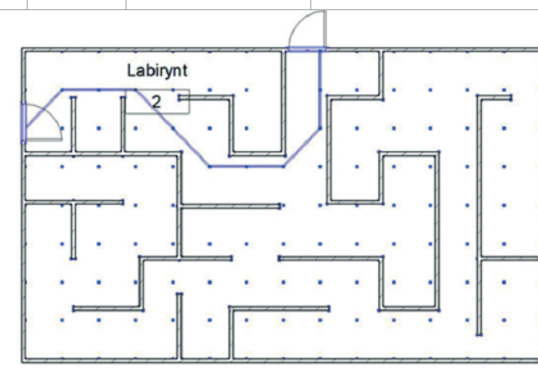
<tr><td colspan="4"></td><td colspan="4"></td></tr>
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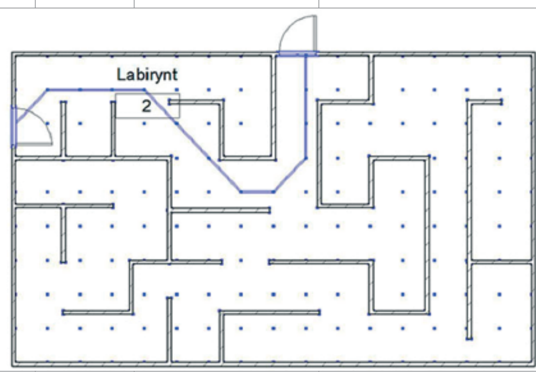
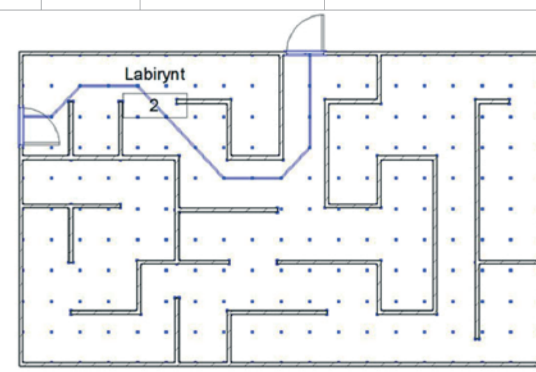
<tr><td colspan="4"></td><td colspan="4"></td></tr>
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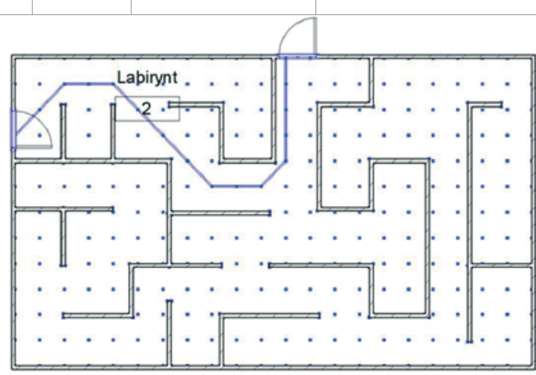
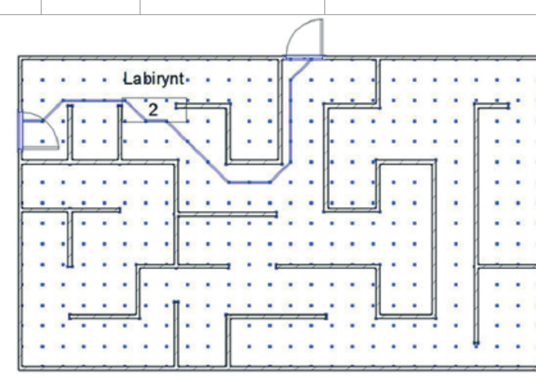
<tr><td colspan="4"></td><td colspan="4"></td></tr>
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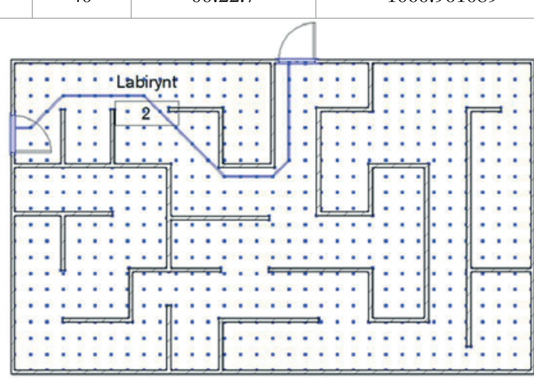
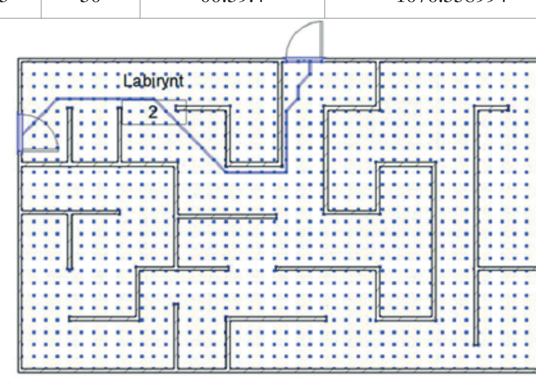
<tr><td colspan="4"></td><td colspan="4"></td></tr>
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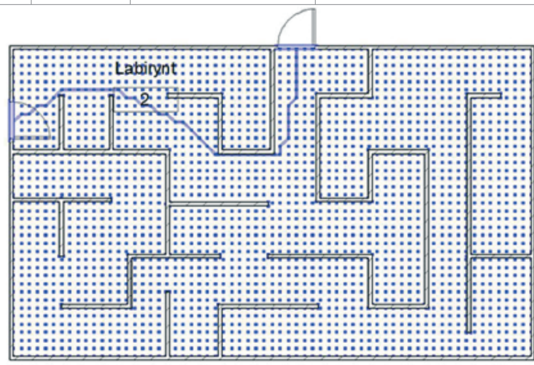

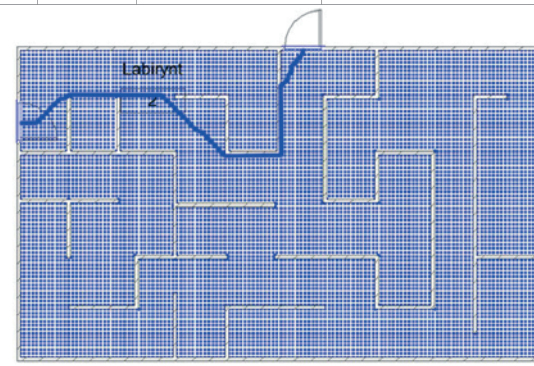

Table 5.
Results obtained in Series 4

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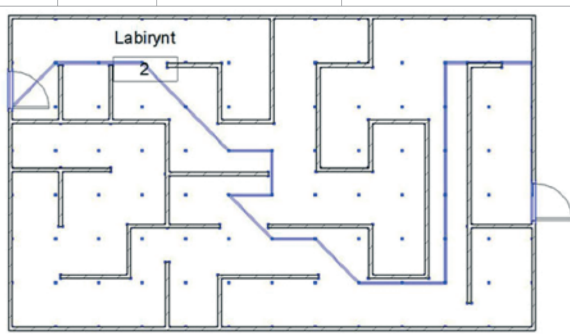

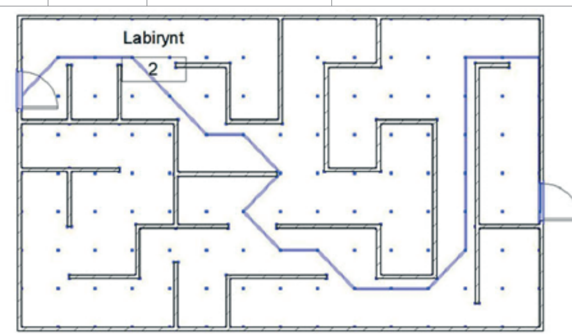

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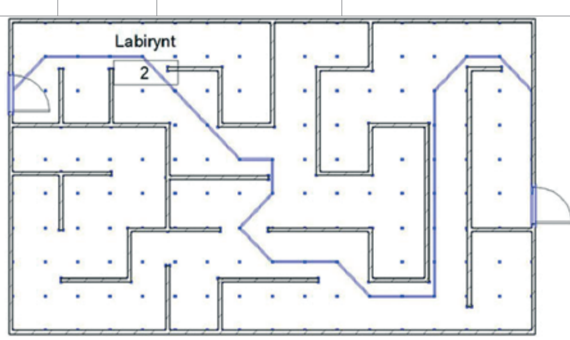

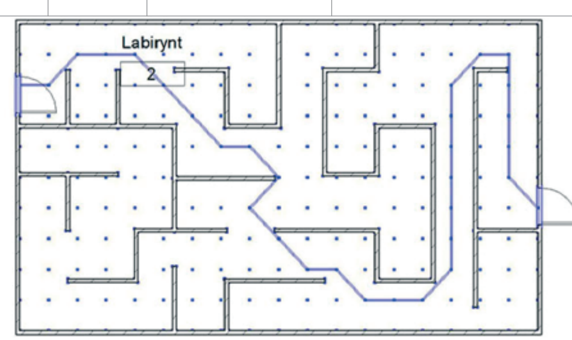

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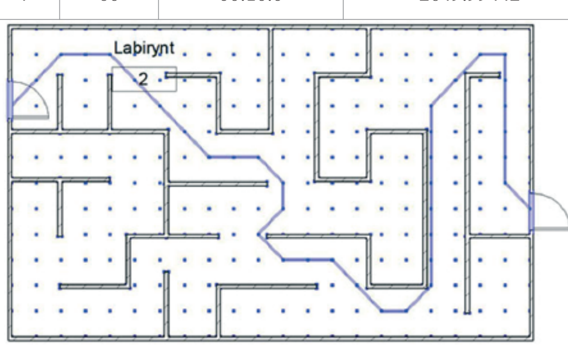

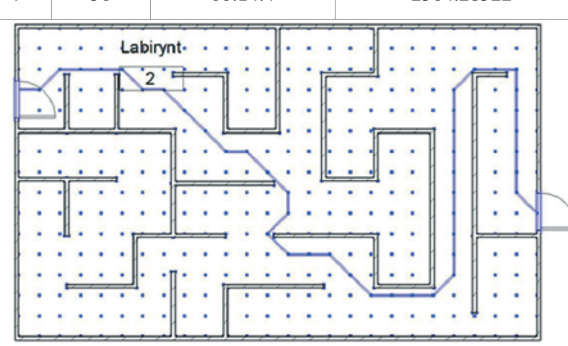

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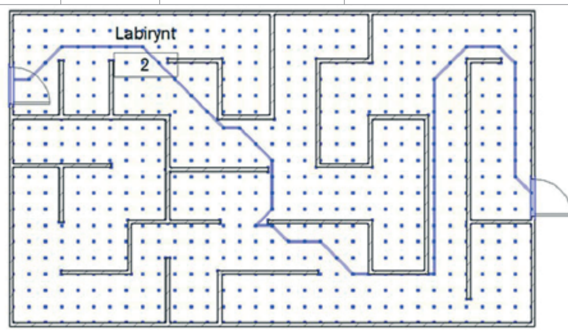
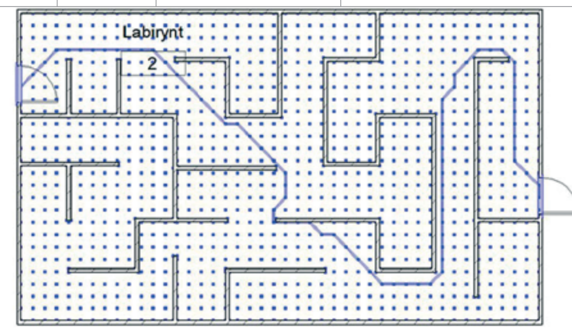
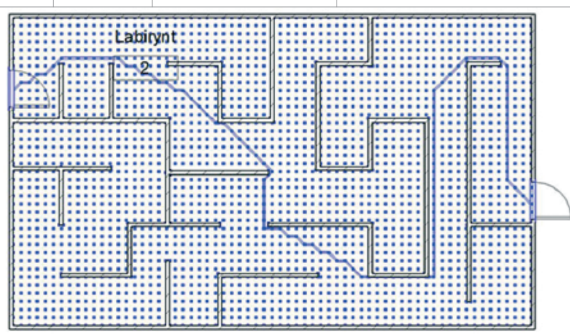
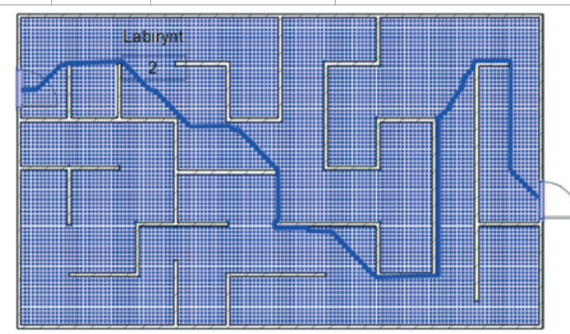
							
4	20	01:47.1	2472.667471	4	10	13:54.5	2421.134435
							

5.2. Dependency of the path length on a grid density

Based on the results obtained in each of the Series 1–4, the general tendency to reduce the length of the route along with the increase in the degree of mesh density was confirmed (Fig. 2–5). However, this tendency was not always visible when comparing two values in consecutive tests (Figure 2–5). For example, the distance in Series 1 for x = 90 (Tab. 2) was 11.1 cm (0.57%) shorter than for x = 30. The reason for these local increases in length was the degree of the regular grid fit to the irregular arrangement of the maze walls. Sometimes a grid with greater dispersion fitted better into the wall layout allowing to determine a more optimal route than the route determined based on a denser grid that was in collision with the wall. However, it can be claimed that higher density nets were more resistant to the randomness of the wall arrangement because the route determined for x = 10 was the shortest in each series. In order to compare the values from the tests within each series, a percentage comparison of the route length in relation to the shortest value was introduced.

5.3. The dependence of the calculation time on a grid density

The next characteristic investigated in the first four series (Tab. 2–5) was the time of calculations. As a result of the tests, the extension of the calculation time was confirmed depending on the increase in the degree of mesh compaction. However, this was not the expected linear relationship (Fig. 2–5). The most noticeable feature of the graph showing the length of the calculation time was the jump in value between the density of x = 10 and x = 20.

In the case of distance, the values of the calculation times were compared in each series in relation to the shortest time for x = 100 that is 100% density grid (Fig. 2–5). The results obtained for particular tests were similar for all series. For example, for x = 40, the time was about 500% longer than the time for x = 100 (a difference of up to 14% between series). For x = 10, time was approx. 18600% of the initial time (maximum difference 121% between series). Such similar values with about two times difference in the length of the designated route show that the calculation time is independent of the length of the designated route.

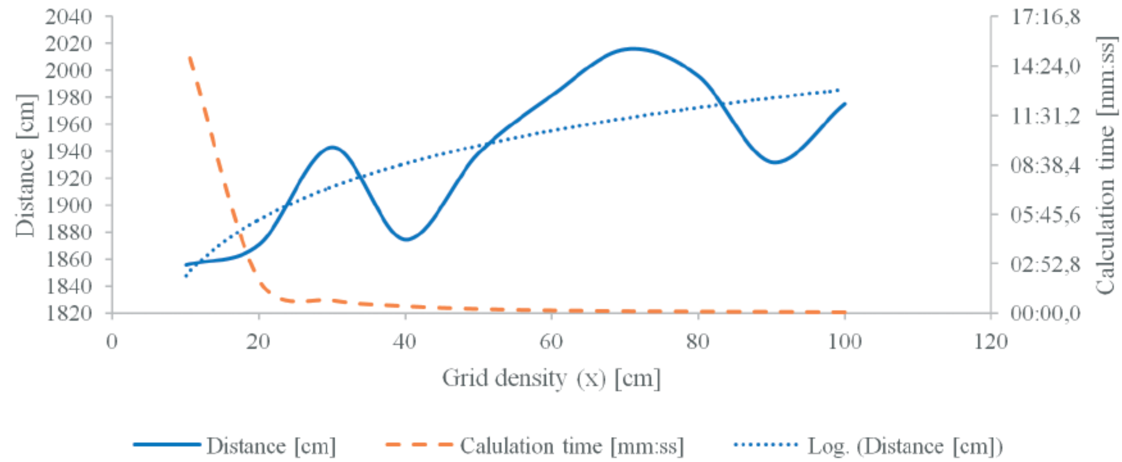


Figure 2.
Visual comparison of results for Series 1

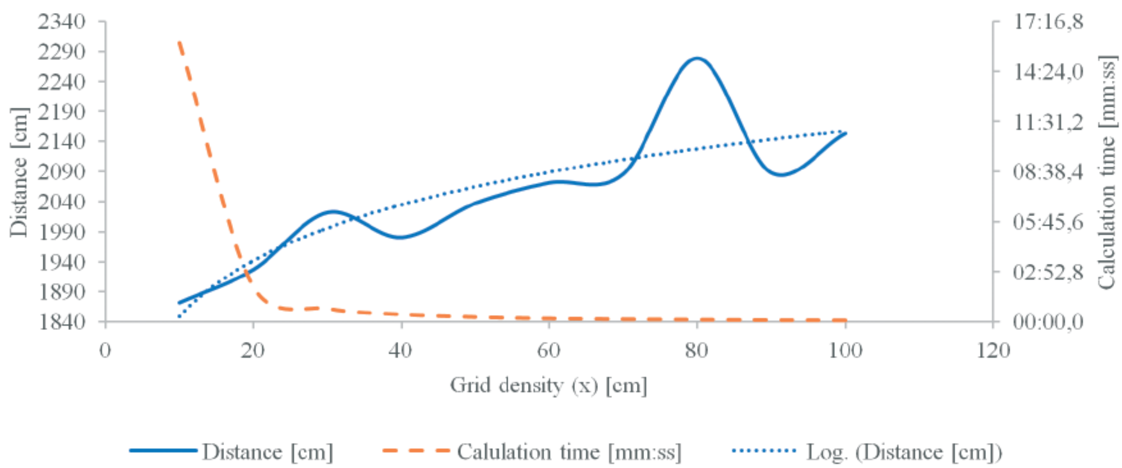


Figure 3.
Visual comparison of results for Series 2

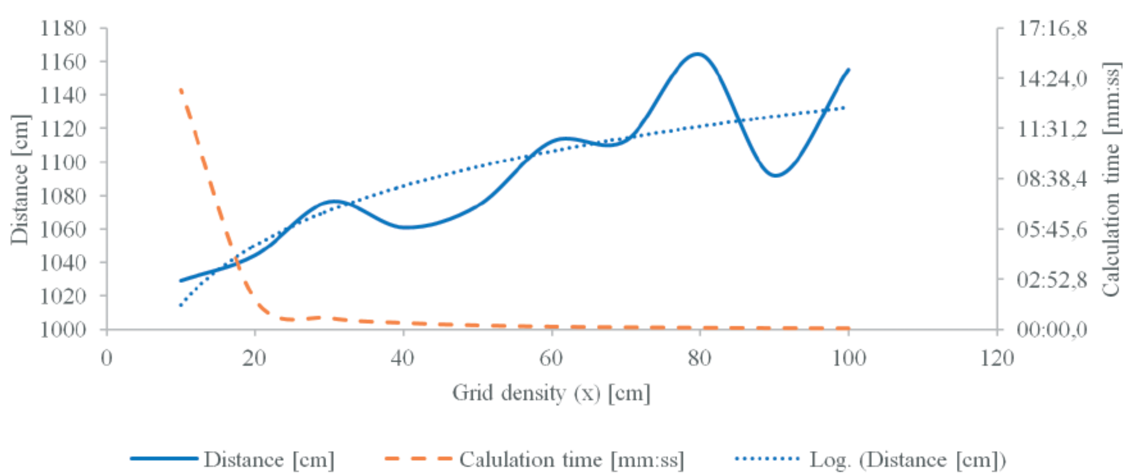


Figure 4.
Visual comparison of results for Series 3

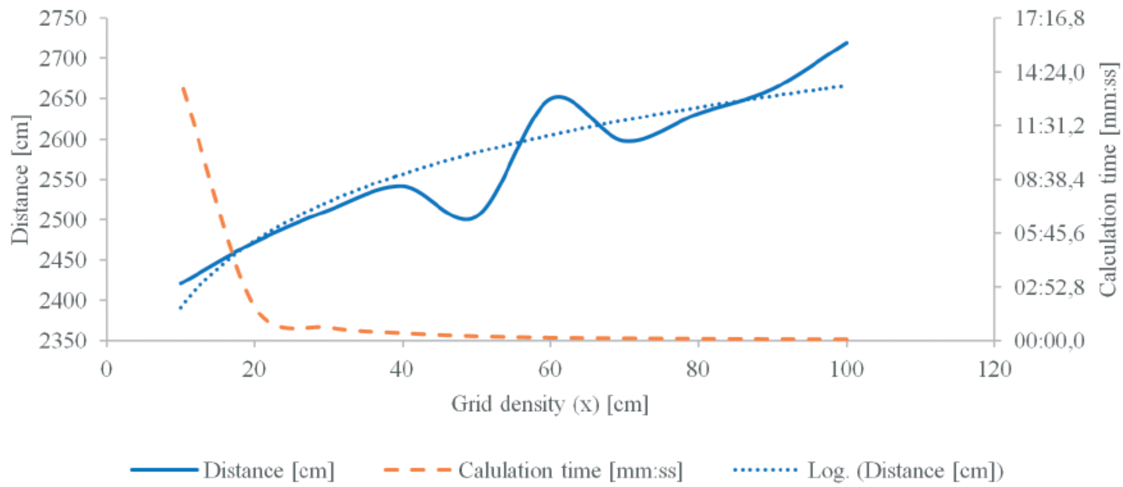


Figure 5.
Visual comparison of results for Series 4

5.4. Benefit Factor

Based on the relative values of the percentage time and distance difference in each trial, the Benefit Factor (hereinafter: BF) was determined as the arithmetic mean of these two values (Tables 6–9). After confirming the general tendency to extend the calculation time and shorten the length of the calculated route along with the increase in the degree of compaction, BF was introduced to compare benefits objectively and drawbacks of densifying the grid and redesigning the floorplan of the maze. The first of the noted implications was a significant increase in the ratio between the results for $x = 30$ and $x = 20$ (by over 100%). This was an important hint for further work showing that the grid of the density $x = 30$ had the right balance between pros and cons. Another noticed trend was the high correlation of BF in all four series, as shown in Fig. 6. This trend was not affected by either the length of the route or the distance between the start and end points in a straight line.

Table 6.
Series 1 results analysis

Grid density – x [cm]	Calculation time [mm:ss]	%	Distance [cm]	%	BF
100	00:05.0	100	1975.251343	106	103
90	00:06.2	122	1932.137649	104	113
80	00:07.1	142	1996.042584	108	125
70	00:08.5	169	2015.721065	109	139
60	00:11.1	221	1981.59189	107	164
50	00:15.9	316	1938.960498	104	210
40	00:25.6	510	1874.509057	101	306
30	00:45.6	908	1943.201165	105	506
20	01:55.2	2294	1871.036883	101	1197
10	15:39.1	18696	1855.726425	100	9398

Table 7.
Series 2 results analysis

Grid density – x [cm]	Calculation time [mm:ss]	%	Distance [cm]	%	BF
100	00:05.2	100	2153.217419	115	108
90	00:06.1	118	2087.891369	112	115
80	00:07.4	143	2278.565251	122	133
70	00:09.2	178	2085.74812	111	145
60	00:11.5	223	2071.238467	111	167
50	00:16.5	320	2037.089775	109	214
40	00:25.9	501	1980.437815	106	303
30	00:46.3	895	2021.708454	108	501
20	01:59.7	2314	1926.812263	103	1208
10	16:01.2	18577	1871.699889	100	9338

Table 8.
Series 3 results analysis

Grid density – x [cm]	Calculation time [mm:ss]	%	Distance [cm]	%	BF
100	00:04.4	100	1155.085124	112	106
90	00:05.2	118	1091.789435	106	112
80	00:06.4	145	1164.110325	113	129
70	00:07.8	176	1112.760388	108	142
60	00:10.0	227	1112.221602	108	168
50	00:14.4	327	1073.829276	104	215
40	00:22.7	515	1060.961089	103	309
30	00:39.4	894	1076.358994	105	500
20	01:42.4	2325	1044.315665	101	1213
10	13:43.8	18698	1029.34886	100	9399

Table 9.
Series 4 results analysis

Grid density – x [cm]	Calculation time [mm:ss]	%	Distance [cm]	%	BF
100	00:04.5	100	2719.490333	112	106
90	00:05.4	120	2662.016369	110	115
80	00:06.6	146	2631.89164	109	127
70	00:07.8	172	2598.076042	107	140
60	00:10.0	222	2649.99442	109	166
50	00:14.4	320	2504.28522	103	212
40	00:24.2	538	2541.489478	105	321
30	00:42.1	937	2512.145307	104	520
20	01:47.1	2380	2472.667471	102	1241
10	13:54.5	18544	2421.134435	100	9322

5.5. Impact of route complexity on the calculation time

Comparing the number of vertices in routes, it can be seen that this feature had no effect on the calculation time (Tab. 2–5). For example, for x =100 in each of the Series 1–4, there were 10, 14, 8, and 14 line breaks at a similar calculation time of approx. 4.8 seconds, respectively.

5.6. Influence of a surface on the calculation time

High compliance of calculation times at the same grid densities in the first four series could indicate the dependency of the calculation time on the area of a tested room. In order to verify this, the maze area was increased in Series 5 by moving the bottom wall of the maze (Tab. 10). No additional walls were added. Only the walls connected to the shifted wall were stretched to its new location The complexity of the maze could be considered the same. The door arrangement was the same as in Series 4. The area of the smaller room was 49% of the area of the new one.

As in the previous four series, ten tests were carried out. Despite the same route to go, the distance in analogous tests of both series did not coincide fully (Tab. 11). The reason for this was the aforementioned division of the room into equal segments depending on the length of the wall, not on the distance between the points. Four tests had 100% compliance, two differed by 1%, one by 2%, and one by 4%.

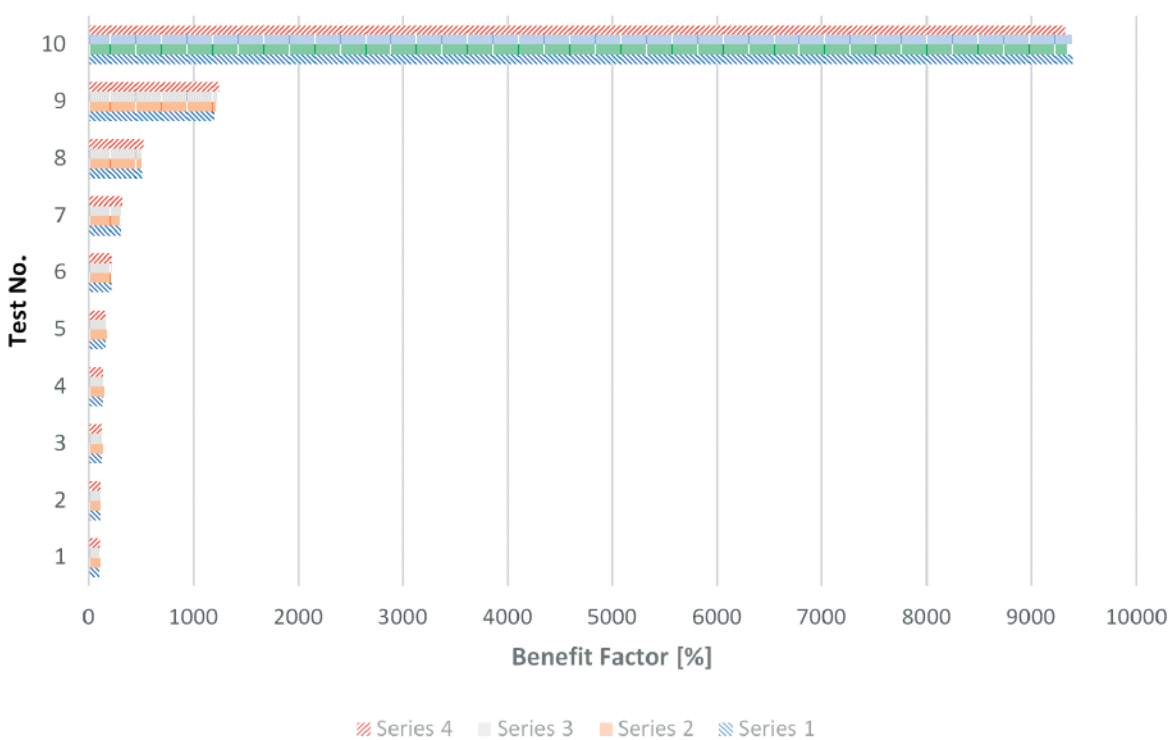
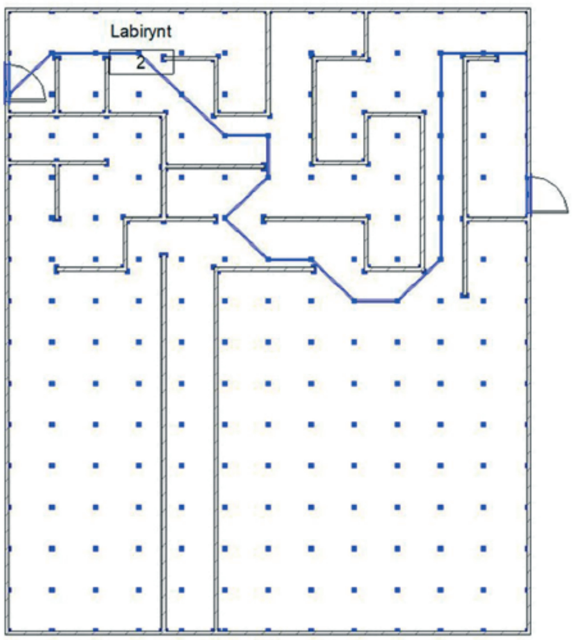
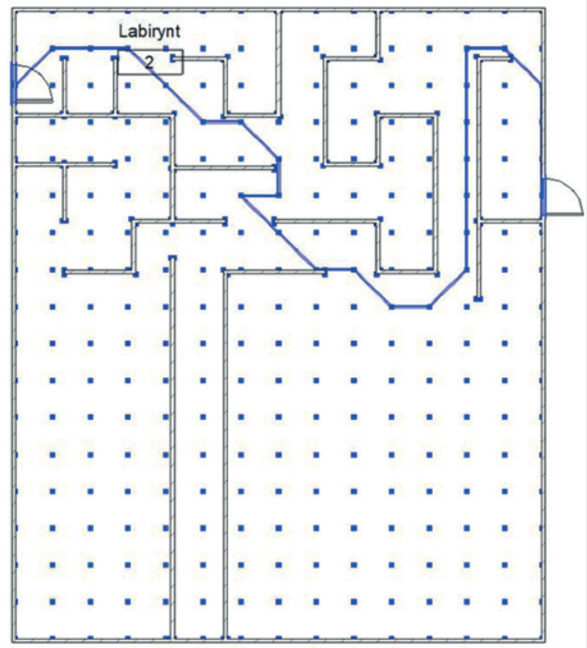
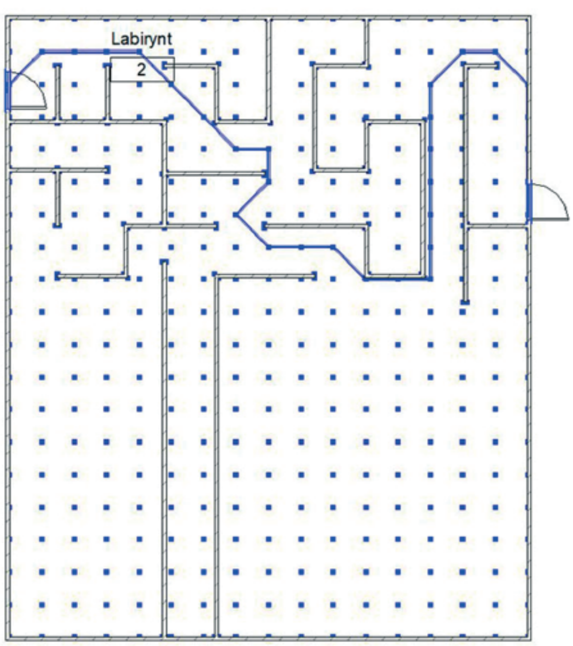
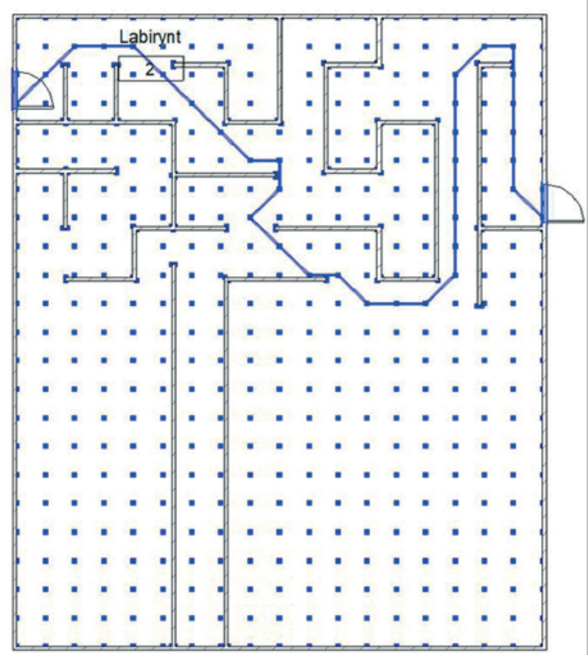
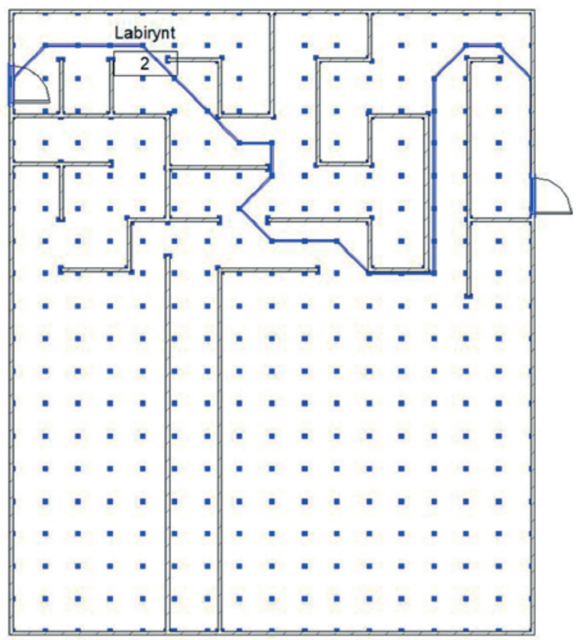
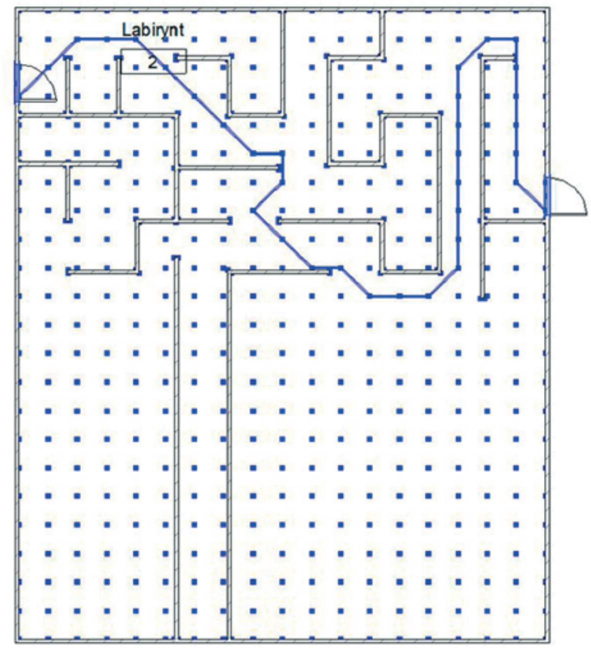
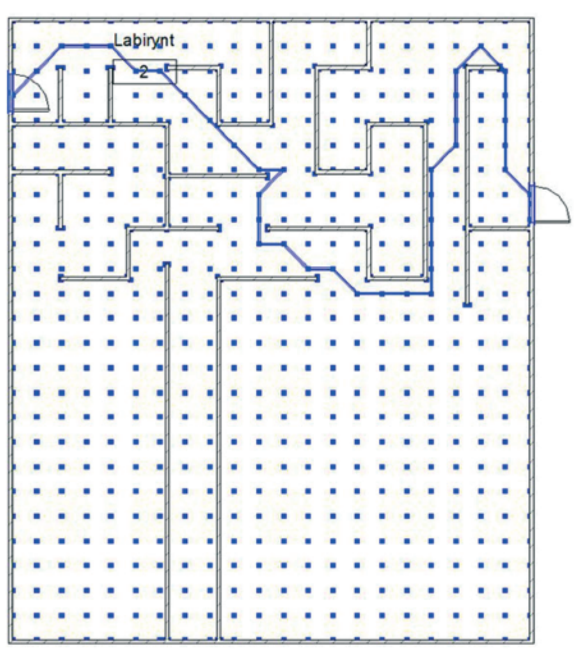
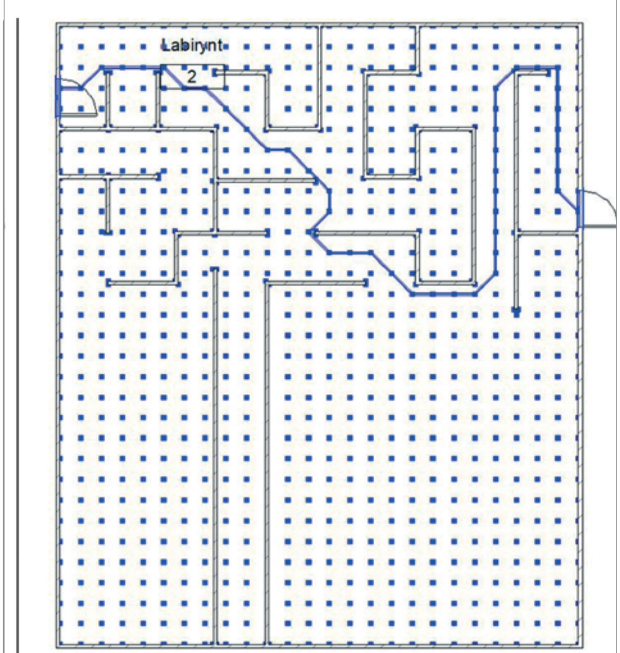


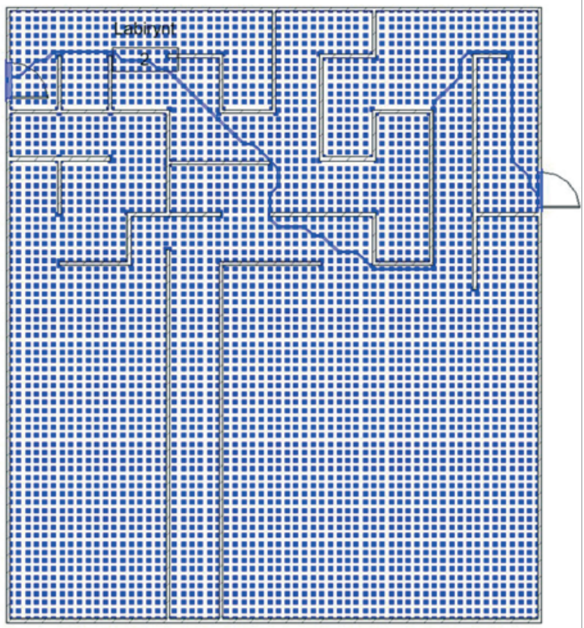
Figure 6.
Comparison of Benefit Factor between Series 1–4

Table 10.
Results obtained in Series 5

5	100	00:08.0	2718.05225	5	90	00:09.9	2714.776496
							
5	80	00:12.0	2647.076965	5	70	00:15.7	2714.917421
							

5	60	00:20.2	2634.078455	5	50	00:27.7	2512.041846
							
5	40	00:46.7	2549.549297	5	30	01:29.0	2510.497186
							

5	20	03:22.0	2468.527079	5	10	24:36.0	2423.765979



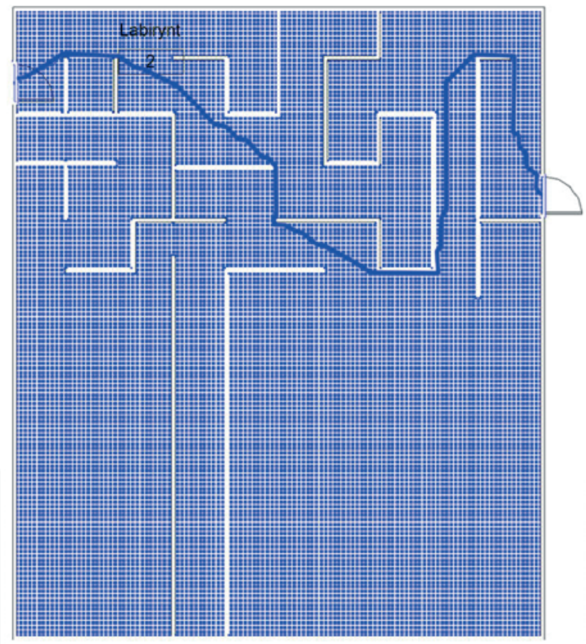


Table 11.
Series 4 results analysis

Grid density – x [cm]	Calculation time [mm:ss]	%	Distance [cm]	%	BF
100	00:08.0	100	2718.05225	108	104
90	00:09.9	124	2714.776496	108	116
80	00:12.0	150	2647.076965	105	128
70	00:15.7	196	2714.917421	108	152
60	00:20.2	252	2634.078455	105	178
50	00:27.7	346	2512.041846	100	223
40	00:46.7	584	2549.549297	102	343
30	01:29.0	1113	2510.497186	100	606
20	03:22.0	2525	2468.527079	102	1313
10	24:36.0	18450	2423.765979	100	9275

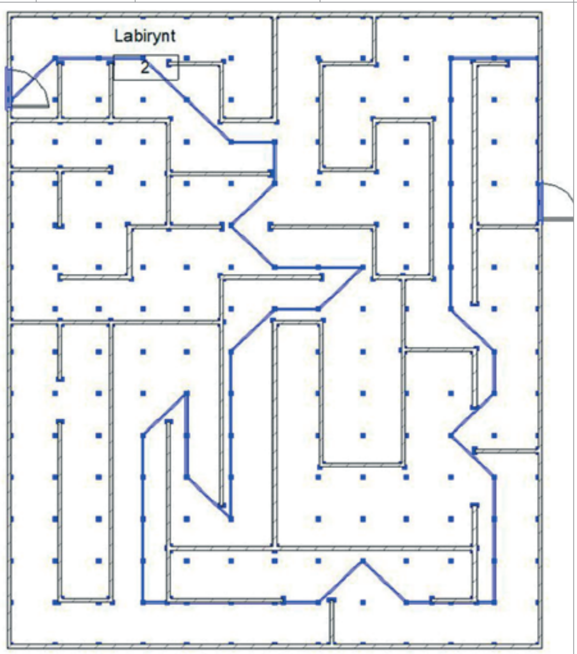
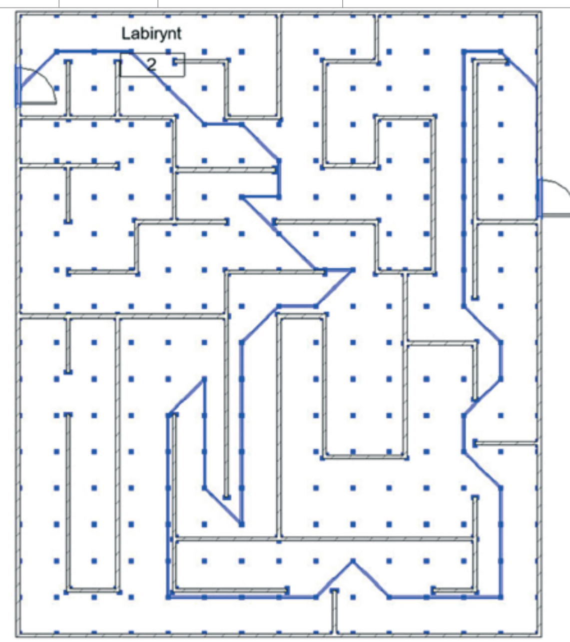
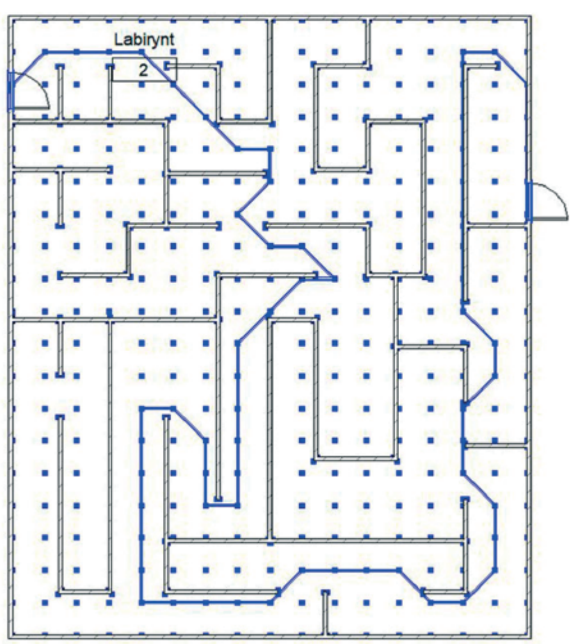
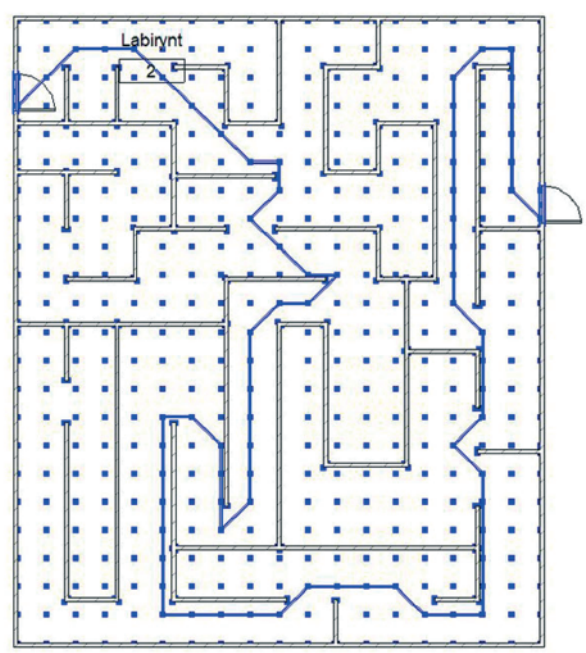
Table 12.
Relation between Series 4 and Series 5 results

Grid density – x [cm]	The ratio of time in Series 4 to time in Series 5	The ratio of distance in Series 4 to distance in Series 5
100	0.5625	1.000529086
90	0.542555332	0.980565573
80	0.546829552	0.994263361
70	0.495182184	0.956963192
60	0.496031746	1.006042327
50	0.520057824	0.996912223
40	0.518142484	0.996838728
30	0.473595506	1.000656492
20	0.530118812	1.001677272
10	0.565359079	0.998914275

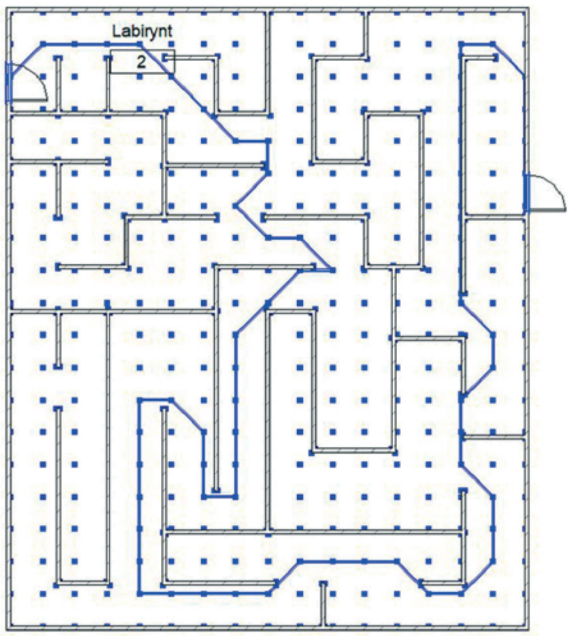
Comparing the analogous calculation times for Series 4 and 5, the values in the former series were from 47% to 56% of the values in the latter series (Tab. 12). This confirms the theory that the calculation time depends on the area of the analyzed room. The area of the room has a direct impact on the number of points that must be computed. This suggests that the most computationally burdensome task of the script determining the shortest route is to find all possible combinations.

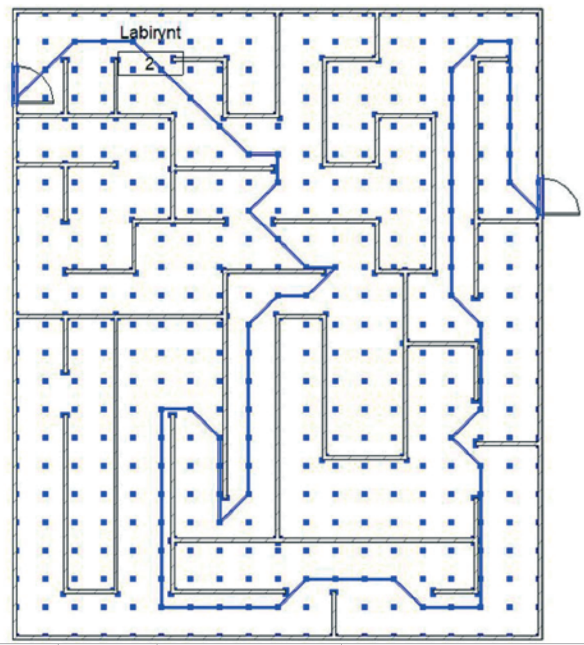
In order to verify the abovementioned theory, in Series 6 additional walls complicating the maze were added to the Series 5 floorplan (Tab. 13). This resulted in a significant increase in the distance of the route and the calculation time because the length of the route increased more than twice. Times obtained in this series were about 50% longer than times in Series 5 (Tab. 14).

Table 13.
Results obtained in Series 6

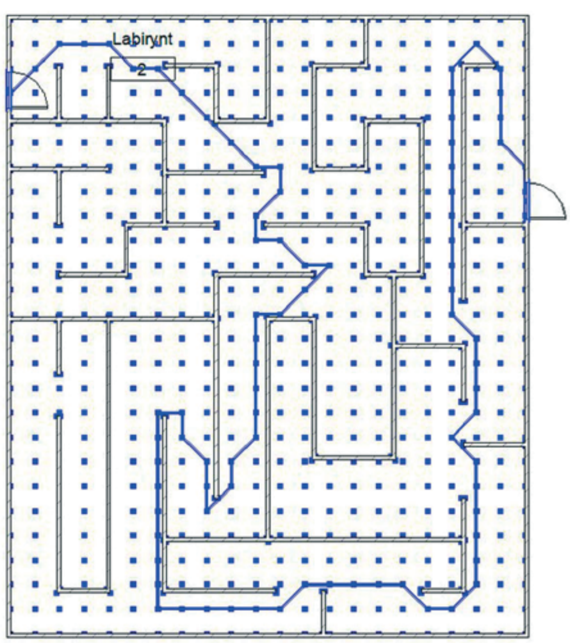
6	100	00:11.8	6052.104499	6	90	00:14.9	5986.315078
							
6	80	00:18.7	5828.572278	6	70	00:24.7	5811.958425
							

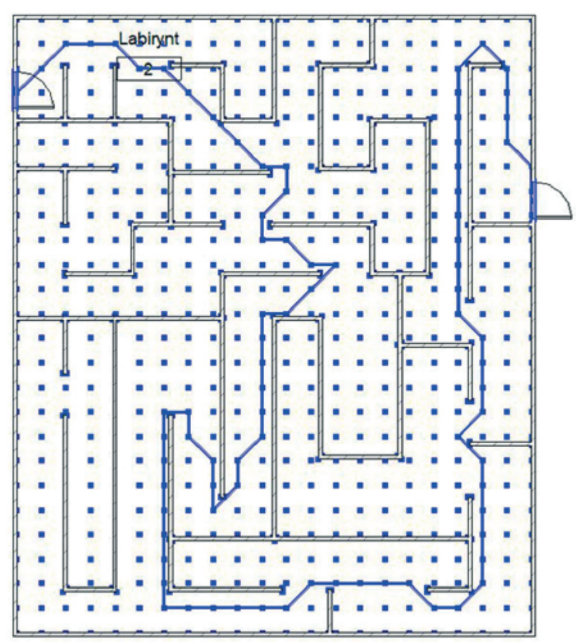
6	60	00:30.4	5633.816646	6	50	00:42.7	5575.643296



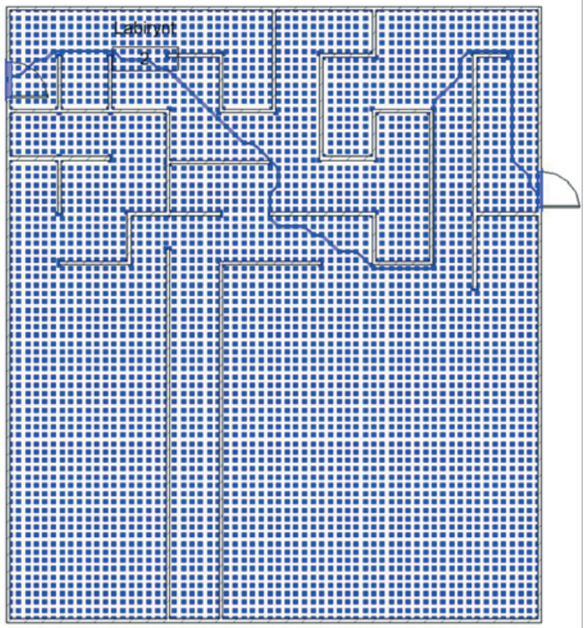


6	40	01:10.1	5445.67272	6	30	02:13.7	5338.039633





6	20	05:10.0	5214.254682	6	10	34:40.0	



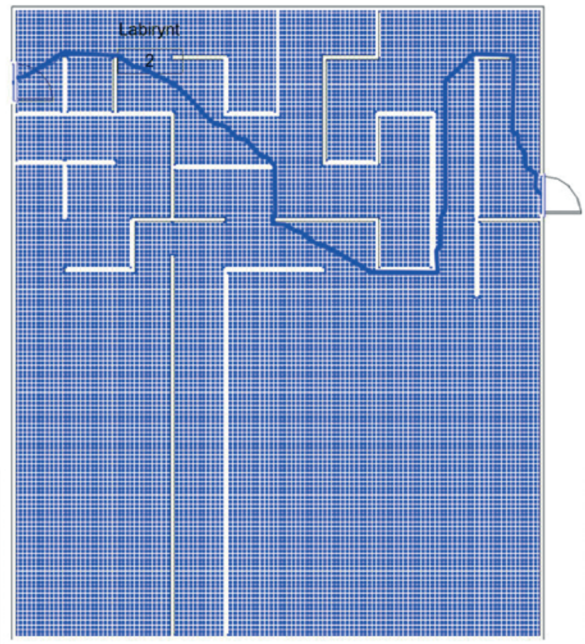


Table 14.
Relation between Series 5 and Series 6 results

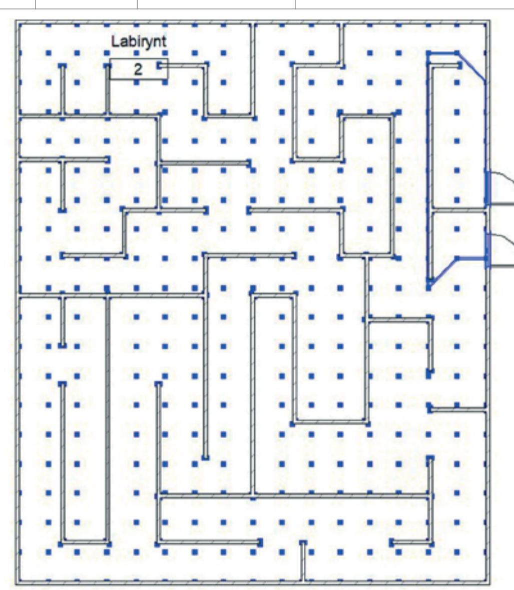
Grid density – x [cm]	Calculation time [mm:ss]	Distance [cm]	The ratio of time in Series 6 to time in Series 5	The ratio of distance in Series 6 to distance in Series 5
100	00:11.8	6052.104499	1.47	2.23
90	00:14.9	5986.315078	1.50	2.21
80	00:18.7	5828.572278	1.56	2.20
70	00:24.7	5811.958425	1.57	2.14
60	00:30.4	5633.816646	1.51	2.14
50	00:42.7	5575.643296	1.54	2.22
40	01:10.1	5445.67272	1.50	2.14
30	02:13.7	5338.039633	1.50	2.13
20	05:10.0	5214.254682	1.53	2.11
10	34:40.0	5155.3749	1.41	2.13

5.7. Impact of the number of internal walls on the calculation time

For comparison, the maze from the Series 6 was left and the x = 80 mesh density test was repeated by changing the door arrangement to close together (Tab. 15). But even with a large reduction in distance, the calculation time remained the same. It can, therefore, be presumed that the complexity of the room (floor area under the walls) may affect the length of the calculations. The area under the internal walls between series 7 and 6 increased 1.5 times, as well as the calculation time.

Table 15.
Results obtained in Series 7

7	80	00:18.3	1362.742249



5.8. The impact of computing power on the calculation time

Considering the fact that the computing power of a particular machine has direct impact on the time needed to complete calculations, the present study shows a method that can be used to assess the performance of a prepared script on a given computer. By carrying out a range of tests on the maze in the floorplan from Series 1, the Benefit Factor can be determined, which helps select the optimal grid density for the following work.

6. CONCLUSIONS

The paper presents the results of research on determining the shortest route between points A and B using the point matrix in the BIM model. The relation reported by the literature about the increase in computation time with the increase in mesh density was expected and confirmed [10, 11]. Nevertheless, the research was carried out to find a wider range of factors affecting the extension of the calculation time and to propose the optimal mesh density that balances the accuracy of the calculation time. Based on the tests carried out, it was found that the calculation time was directly proportional to the area of the tested room and the degree of coverage of the room with internal walls. The distance between points in a straight line and along the road, which had to be traveled between them in the maze did not have a noticeable impact on the performance of the script, as well as the number of direction changes in the course of traveling the maze.

It has been proposed to introduce the Benefit Factor as an indicator of the relation between the accuracy of calculations and the time needed to carry them out.

The degree of mesh compaction does not proportionally increase the calculation time. There is a value of x, after which the time increases significantly as the factor further decreases.

The distance for $x = 30$, which differed by less than 100% from the distance for $x = 40$ and by more than 100% for the distance for $x = 20$, was considered the most optimal mesh density.

7. FURTHER RESEARCH

The described method of creating the graph and the other most promising method [10] – visibility graph are both worth comparing in terms of the relation of route length and the calculation time. Further tests can be carried out on various calculation units by testing the variability of the introduced Benefit Factor. This stage of research should be closed by the choice of algorithm most suitable for creating the graph in indoor and open-space used in Facility Management processes.

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