

OPTIMAL PEDESTRIAN PATH PLANNING IN EVACUATION SCENARIO

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Abstract. Simulation of evacuation plans is a relatively complex problem. It is necessary to simulate a number of separate processes which interact in the result. Namely, they are pedestrian-pedestrian interactions, pedestrian-static object (e.g. wall) interactions and pedestrian-environment (fire, smoke, etc.) interactions. In this case, the evacuation simulation is controlled on the microscopic level. Microscopic level considers each individual separately and pedestrian is planning his/her path to the exit with regard to the above-mentioned interactions. In this article we focus on path planning during evacuation and describe algorithms applied in this area. At the end we propose a method of the space evaluation with linear time complexity and planned path compared with commercial software tools.

Keywords: Particular irregular cellular automata, path planning, evacuation

1 INTRODUCTION AND MOTIVATION

Evacuation plan simulations are crucial in the design of any space in which people may occur. In an emergency situation the behaviour of vulnerable persons is affected by a number of psychological factors (ability to recognize danger, ability of rational thinking, etc.). In this article we focus on path planning during evacuation instead of pedestrian behaviour simulation. There are several ways how to evaluate quality of evacuation plans. Testing in the real world with real pedestrians is difficult, because it is difficult to ensure appropriate objectivity and security of escaping pedestrians. Simulated environment with virtual entities is a significantly easier solution for this

purpose. Pedestrian simulation model includes behavioural patterns of individuals. Pedestrian characteristics can be easily tracked and changed on a microscopic or macroscopic level.

Microscopic level considers each individual separately, taking into account the interaction between pedestrians. According to the study presented in [20], in case of evacuation around 47% of pedestrians escaped according to the evacuation signs and 17% used the door because it was the nearest exit. This means that pedestrians moved mostly to the nearest exits. Path planning is an important research area of many applications. Especially in the field of mobile robotics, path planning is one of the most important parts of the system. However, path planning plays a key role in evacuation simulation, too. Due to the complex and dynamically changing environment, to find an optimal path in evacuation scenario is not an easy task. There are many different techniques to solve the path planning problem.

Visibility graph [1] is an interesting idea, here environment is modeled as a graph. All nodes which are visible from each other are connected by straight-line segments, defining a road map. This means there are also edges along each polygon. Path planning becomes a task of searching the shortest path. The visibility graph offers a minimal length solution, but if the number of obstacles increases, the algorithm slows down. There are many trials to improve the efficiency of this algorithm [2, 3]. Path planning was based on the idea of the Voronoi diagram [4]. This approach optimizes the path between obstacles and represents the distance, but it does not represent the shortest path. The above mentioned works [1, 2, 3, 4] describe algorithms, which are not suitable for evacuation simulation. The reason is that those methods create a path that does not match the trajectory of a human in the same situation. A simple and efficient solution, usable with restrictions in evacuation, is represented by the NF1 algorithm [5]. This algorithm is also known as the grassfire algorithm. The basic idea is to expand a wavefront backward from a destination point to the current position and assigning each cell by a number, which represents the distance between the destination and the cells. In the following section we will discuss the limitations of this approach. Another suitable solution is represented by the fluid flow based approach. This approach is applied in the Fire Dynamics Simulator (FDS) software tool [6] and many more [7, 8]. Hypothetical fluid flow from a current position to the area generates a suboptimal path. The drawbacks of this method will be discussed later.

2 OVERVIEW OF RELATED MODELS

A model by Helbing et al. [10, 11], which belongs to the group of social force models, is frequently cited in evacuation simulations. This model is based on a strong mathematical calculation using agents to determine their movement to destinations (e.g. exits). Helbing's model considers the effects of each agent on all other agents, and the physical environment leading to the computation of $O(n^2)$ complexity, which is unfavorable for computer-based simulation with many agents [12, 13]. In some cases

in this model, simulated pedestrian evacuation path does not represent a pedestrian decision, from the point of movement along the shortest path to the destination (local arrangement of obstacles affects the motion vector more than a global arrangement of obstacles). Kirchner et al. [14] proposed the floor field model that uses computationally more efficient cellular automata (CA) approach. In this model, local movement rules that only consider adjacent cells are defined to translate Helbing's long-ranged interaction of agents into a local interaction. Although this model considers local interactions only, they showed that the resulting global phenomena share properties from the social force model such as line formation, oscillations at bottlenecks, and fast-is-slower effects. The basic data structure of Kirchner model is grid cells; each cell represents a position of an agent and contains two types of numeric values, which the agent consults to move. These values are stored in two layers, a static field and a dynamic field. A cell in the static field indicates the shortest distance to an exit. An agent is in position to know the direction to the nearest exit by these values of its nearby cells. While the static field has fixed values computed by the physical distance, the dynamic field stores dynamically changing values indicating agents virtual traces left as they moved along their paths. Cellular automata, first proposed by Von Neumann, are discrete dynamic systems consisting of a regular grid of cells. Cellular automata evolve at each discrete time step. Variables at each cell are simultaneously updated based on the values of the variables in their neighborhood at the previous time step and according to a set of local rules [27, 28]. At present, cellular automata have been successfully applied to various complex systems, including traffic models and biological systems. Over the last decade, cellular automata models have been applied to describe pedestrian dynamics during evacuations, too. Formally, cellular automata can be described by the following settable [30]:

$$M = \{d, S, N, f\}; \quad (1)$$

where M represents the system itself (cellular automata), d represents the dimension of the automata (usually 2D), S is a set of discrete states of each cell, N defines a neighbourhood (surrounding cells) and f represents a set of rules that allow a cell to change its state.

Evacuation problem can be transformed to a path planning problem. Evacuation scenario is focused on finding a path for each cell of environment to the destination (exit door). Wavefront methods are very useful for this type of tasks. The basic idea of this method is to propagate virtual wave through the environment and mark up all points of space with a number representing the distance between a current place and a start point. Some authors were inspired by cellular automata and propagated a wave in cellular space, too. In [17], Peng and Chou created a static floor field by a simple rule in cellular automata. The adjacent cells in vertical and horizontal directions are assigned a value $N + 1$. This rule represents Neumann neighborhood, in other literature it is marked as a Manhattan metric. Tissera et al. [18] proposed cellular automata for evacuation simulation and their work uses a Moore's neighborhood to estimate distances to exits. NF1 algorithm is a simple

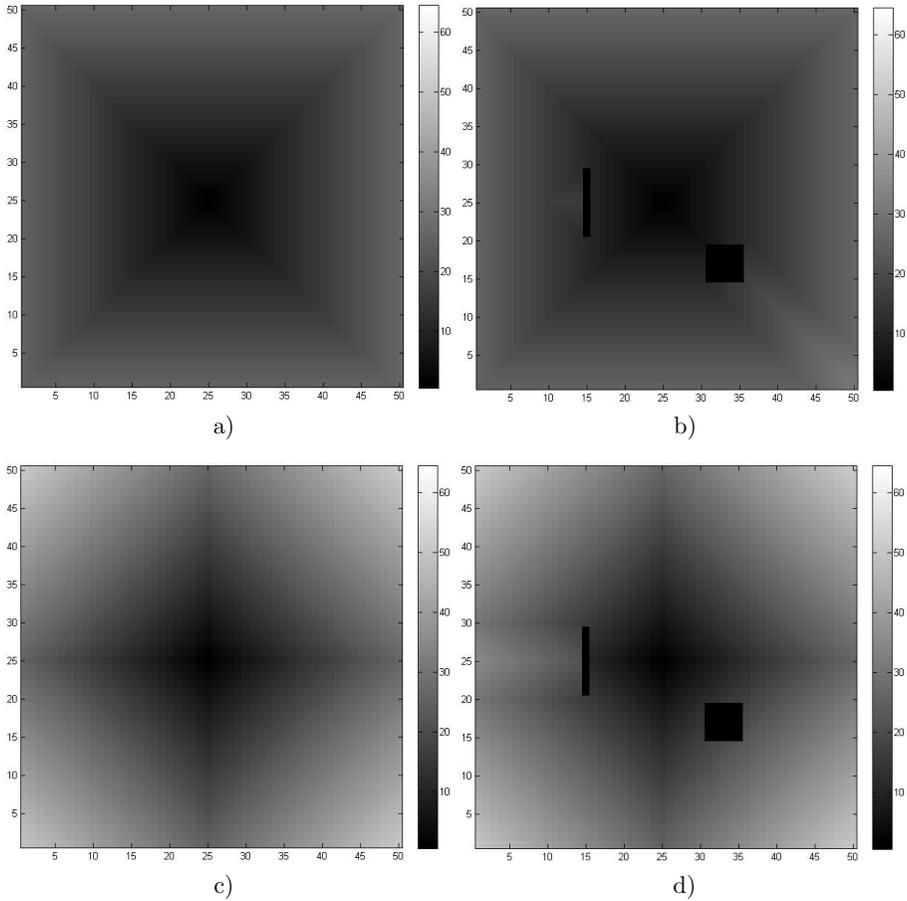


Figure 1. The static floor field created by a), b) Moore or c), d) Neumann neighbourhood in area a), c) without or b), d) with obstacles. The exits are located in the middle of the area. The color spectrum represents the distance between cells and exit. Obstacles in b), d) are filled in black color.

and efficient solution, usable with restrictions in evacuation domain. NF1 has the least complexity $O(n)$ like the previous neighborhoods. Another advantage of NF1 is that it guarantees non local minimum coverage of the space. NF1 algorithm using cellular automata consists of the following simple rule:

Rule 1 (R1). If any of your neighbours is activated then activate yourself in time $t + 1$, and mark up the cell as $t + 1$.

The problem is that the algorithm based on this type of rule replicates the shape of the neighbourhood. In this type of environment, Moore or Neumann neighbour-

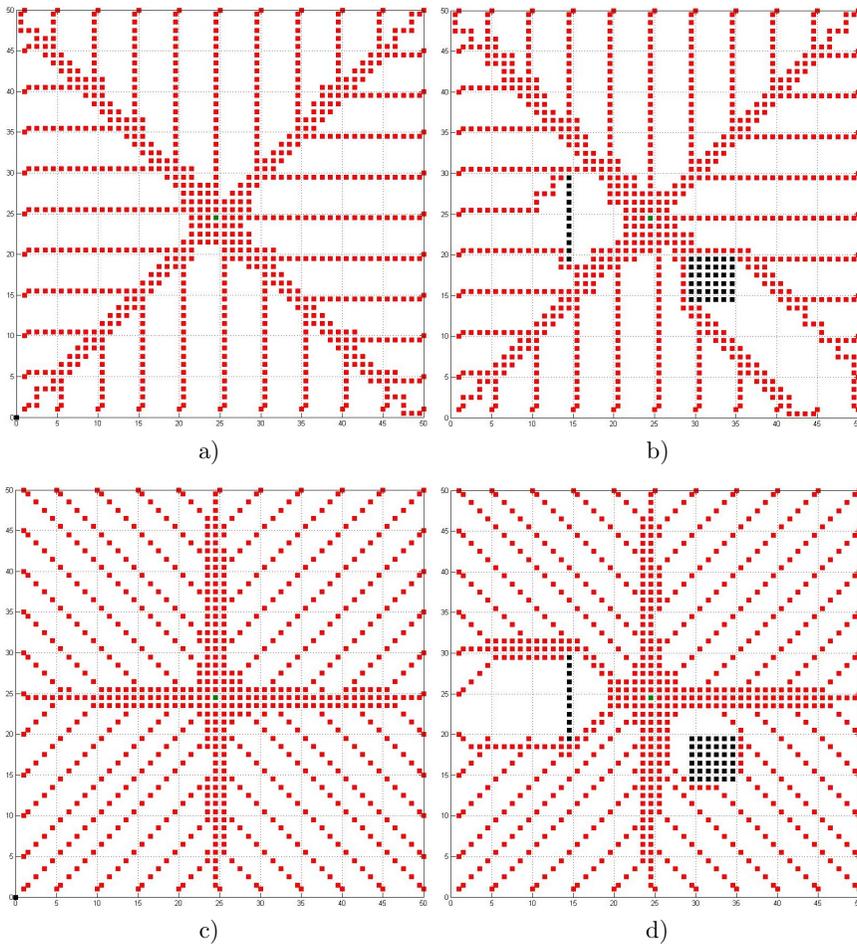


Figure 2. People evacuation simulation results; emergency exit was located in the middle of the area, the static floor field created by a), b) Moore or c), d) Neumann neighbourhood in area a), c) without or b), d) with obstacles

hoods are the usually used neighbourhoods. In both cases, a distributed wave has the shape of the neighbourhood, but different from the circular shape.

In both cases distortions of the environment evaluation arose (distortions are shown in Figure 1). Corners of an obstacle represent new wave propagation source and distortions are multiplied. When we apply the following simple rule to the pedestrians movement:

Rule 2 (R2). Move to the cell with the lowest value in $t + 1$ time;

we can get a trajectory of the pedestrians presented in Figure 2. The trajectory shows the existence of artificial corridors in the evacuation space. At the simulation start the pedestrians were located on the border of the area. The exit was located in the middle of the area. The cell visited by a pedestrian is marked by color square. The figure shows that pedestrians tend to use artificial corridors rather than exits.

Varas et al. [15] present their approach to evaluation of cellular space by the following rules:

Rule 3 (R3). If a cell has value N , then adjacent cells in the vertical and horizontal directions are assigned a value $N + 1$ and value $N + \lambda$ in diagonal direction, where $\lambda > 1$ (in [15] it is $\lambda = 1.5$).

Rule 4 (R4). If there are conflicts in the assignment of a value to a cell, because it is adjacent to cells with different floor fields, then the minimum possible value is assigned to the cell in conflict.

In this case, a distributed wave has a star shape, i.e. the horizontal, vertical and diagonal space will attract a pedestrian movement in space without obstacles. If the space will contain obstacles, then the attractive areas are multiplied. It is a similar way as in the previous case. There are several ways [31, 35] to evaluate a cellular space by a circular shape wave. One of the major techniques is to use potential fields [33, 38]. Potential field is a force field located in the environment whose parameters depend on the obstacles localization only. The repulsive forces vector equals to sum of the partial repulsive forces from individual obstacles in environment with more obstacles. This method has the disadvantage of local minimum creation. It can be available in a space without obstacles only. For geometries used in the paper [14], the static floor field value SFF_{ij} , in Kirchner model for cell (i, j) is based on the Euclidean distance and it can be calculated in the following way:

- the lattice shall be surrounded by obstacle cells, which are not traversable, except for a number of door cells at $((i_{T_1}, j_{T_1}), \dots, (i_{T_k}, j_{T_k}))$; the pedestrians can only leave the room through these door cells; the explicit values of SFF in the examples studied here are then calculated using a distance metric:

$$SFF_{ij} = \min_{(i_{T_s}, j_{T_s})} \left(\max_{(i_l, j_l)} \left(\sqrt{(i_{T_s} - i_l)^2 + (j_{T_s} - j_l)^2} \right) - \left(\sqrt{(i_{T_s} - i)^2 + (j_{T_s} - j)^2} \right) \right).$$

This means that the strength of the static floor field SFF depends on the shortest distance to an exit. $\max_{(i_l, j_l)} \left(\sqrt{(i_{T_s} - i_l)^2 + (j_{T_s} - j_l)^2} \right)$, where (i_l, j_l) runs over all cells of the lattice, is the largest distance of any cell to the exit at (i_{T_s}, j_{T_s}) . This is just a normalisation so that the field value increase with decreasing distance $\sqrt{(i_{T_s} - i)^2 + (j_{T_s} - j)^2}$ to an exit and is zero for the cell farthest from the door [14].

In this case a space is evaluated by the Euclidean distance from the cell to the nearest exit. This method works well in a space without obstacles. Song et al. [16] use a simple formula to create the static floor field $SFF_{ij} = |x_i - x_{exit}| + |y_i - y_{exit}|$ from the cell to an exit. The SFF value of exit cells is 0 and increases with the distance of the cell from exit cells. To calculate static floor field, Yanagisava and Nishimari [19] use Euclidean distance between cell and target cell calculated by $SFF_{ij} = \sqrt{|x_i - x_{exit}|^2 + |y_i - y_{exit}|^2}$ where (x_{ij}, y_{ij}) and (x_{exit}, y_{exit}) are the coordinates of the cell (i, j) and the exit cell, respectively. However, when there is an obstacle on the way to the exit, SFF is calculated by making a detour around it. Detailed description is given in [20]. Zhang et al. [21] and Kirchner [14] also use Euclidean distance in their works. This case is comparable with the method used in the Kirchner model. These methods can be applied in a space without obstacles. In [22], Wang et al. use Euclidean distance for static floor field calculation, but in space with obstacles they use the Dijkstra's algorithm. Dijkstra's algorithm is also used by Kirchner et al. in [23], where an extended stochastic cellular automata model to simulate friction effects and clogging during evacuation of a large room with one door is proposed. In [24], the authors propose a cellular automata model for pedestrian dynamics with friction to simulate competitive egress behavior. Nishinari et al. [20] proposed the use of well-known Dijkstra and Manhattan metrics for computing the static weight of cells in a cellular environment. However, it is time-consuming to construct a static field using the Dijkstra metric for a large space [40]. Hence, Alizadeh [40] also reported that the metric proposed by Varas et al. [15] using a simple recursive process performed faster in computation structure and was capable of achieving similar results as the Dijkstra metric.

An alternative to this concept is represented by the theory of chemical waves [32, 37] (oscillating chemical reaction that spreads a wave in the space). There are many chemical wave simulation experiments powered by cellular automata [34, 36, 41] but they focus on simulation of chemical processes. As can be seen from the work which deals with the chemical waves, activation of molecules has a circular shape. The molecules are distributed more or less randomly in a space. Therefore, we decided to use a similar principle in the design of our method. This fact leads to artificial corridors in space as we discussed previously. Our solution for this problem is to use modified irregular cellular automata. The use of random points in cellular automata instead of regular cell was described for the first time in [25, 26] or [41]. This type of algorithm was named irregular cellular automata (ICA). ICA approach is based on developing a Voronoi diagram over the random points. The author also creates Neumann and Moore neighbourhoods into the Voronoi diagram space:

- Neuman neighborhood of polygon contains those polygons that share a line segment;
- Moore neighborhood of polygon contains those polygons that share vertex segment.

Wave propagation in this type of area (the Voronoi diagram) is shown in Figure 3. Random point distribution results in circular wave shape deformation. In some cases random distribution may lead to isolated area which could affect the simulation process (for example researched issues similar to pedestrian movement are also addressed in [27]). This isolated area is a local minimum which means that “deadlock” may occur for the navigated agent. The isolated area is demonstrated in Figure 3. This is why this method cannot be used to create static floor field. The time complexity of the Voronoi diagram creation represents $O(n \times \log(n))$ [42].

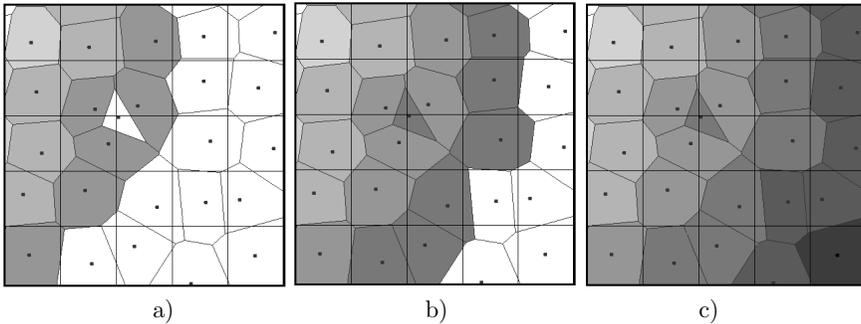


Figure 3. Evaluation of the Voronoi diagram with Moore neighbourhood and the illustrated problem with development of an isolated area

The main goal of our research was to eliminate drawbacks of the methods presented above. We address the following problem areas:

- computational complexity;
- optimal path as to access approaching the path selected by a human;
- building a complex map (path) for the whole evacuation area;
- building a complex map (path) to avoid local minimum or artificial corridors.

3 DESCRIPTION OF THE SUGGESTED METHOD

We try to design the wave propagation system, which is based on the same representation of the environment such as the classical cellular automata. The area is divided into regular square cells, but cell activation depends on activation of a random point which is placed inside the square cell. This solution creates partial irregularity in the configuration of the cells, but from the global perspective the distribution is much closer to equidistant distribution. Let A be the size of the square side of a cell in this area. For Neumann and Moore neighbourhoods in the square area we define the following radius of the circle (see Figure 4), which will represent our neighbourhood. The circle radiuses for the Neumann neighbour-

hood and for the Moore neighbourhood are given by Equations (2) and (3), respectively.

$$r_{Neuman} = A\sqrt{(5)}; \tag{2}$$

$$r_{Moore} = A\sqrt{(8)}. \tag{3}$$

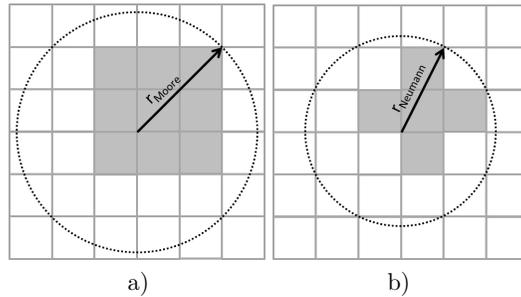


Figure 4. Selection of the radius for the a) Moore and b) Neumann neighbourhoods

Figure 5 shows the wave propagation principle. Activation point can activate only those points of cells witch are closer than the radius r ($r_{Moore}, r_{Neumann}$), thus the points with an Euclidean distance smaller than r will change their status to active at time $t + 1$, but if an obstacle is located between the activation point and the new point, then the new point remains inactive in time $t + 1$. This case is shown in Figure 5 c), where the obstacle (grey cell) is located between activation and new points. In Figure 5 d) wave propagation in area can be observed. The result of the evaluation process of the whole area with obstacles is shown in Figure 11. Due to the fact that distribution of the activation points is not random, activation of all points can be ensured based on the selected neighbourhood. If we decide to use random point distribution we would face the problem when the neighbourhood of the point was not large enough to propagate a signal.

If the following assumption is satisfied, then the radius of the neighbourhood given in Equation (2) or (3) evaluates whole cell space.

Assumption 1. Let as assume that obstacles are included in the cell space so that each obstacle can neighbour an obstacle only if the two obstacles have a common edge.

The time complexity can be formalized by the following reflection. Let n be the number of all cells in the area and x be the number of neighbourhoods. In the proposed method the number of neighbourhoods $x_{Moore} \in \langle 15, 31 \rangle$ and $x_{Neumann} \in \langle 11, 24 \rangle$. In each iteration the algorithm expands to all neighbourhoods and examines them. In the worst case x will have the maximum possible value; so for the worst

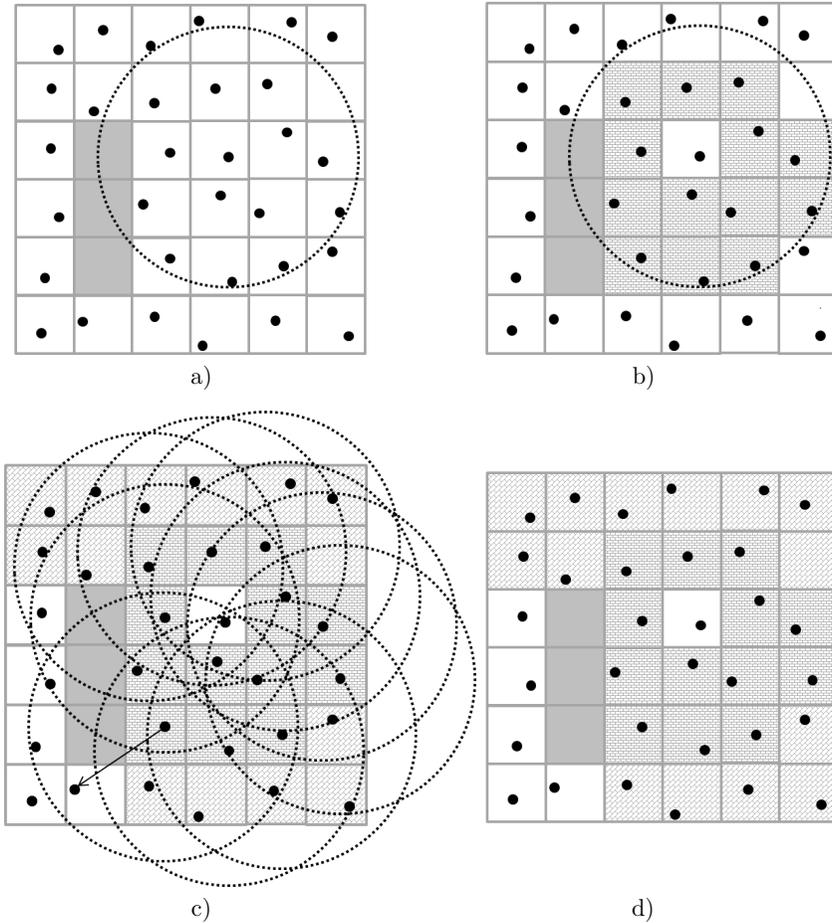


Figure 5. The wave propagation principle in partly irregular cell space, case a), b), c), d)

case we can set all x 's to the maximum neighbourhood value, x_1, x_2, \dots, x_i where $i \in \langle 1, n \rangle$ and x acquires the value 31. So we can write:

$$f(n) = x_1 + x_2 + \dots + x_n = n * x = O(n). \tag{4}$$

We have shown that the algorithm has linear time complexity $O(n)$.

4 COMPARISON OF THE PROPOSED METHOD WITH OTHER ALGORITHMS

We select four candidates from wide field of path planning algorithm. The selected algorithm handles the path planning problem very much like our method. At the

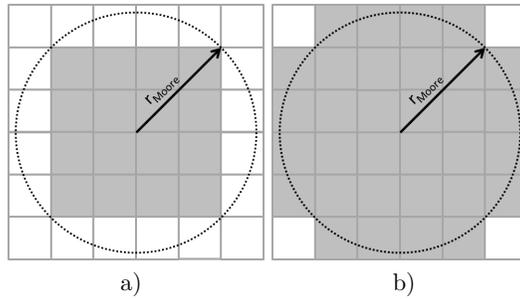


Figure 6. Minimal and maximal number of Moore neighbourhoods determination

end of Section 2 we present the problem areas which we try to solve by help of our algorithm and the comparison criteria are based on the four rules specified earlier. The methods are compared in Table 1.

Method	Computational complexity	Existence of artificial attraction corridors	Existence of local minimum
Dijkstra algorithm	$O(n^n)$	no	no
Moore neighbourhood	$O(n)$	yes	no
Neumann neighbourhood	$O(n)$	yes	no
Voronoi diagram	$O(n \times \log(n))$	no	yes
the proposed method	$O(n)$	no	no

Table 1. Comparison of the proposed method with other algorithms

The proposed method has linear complexity; this fact guarantees good performance, also in large simulations. Like Dijkstra algorithm, our method does not generate any artificial attraction area or local minimum. For path testing purpose we developed a simple pedestrian simulator. This simulator is based on cellular automata. An interaction between individual pedestrians is simple and does not reflect a complex real human behavior. There are three rules, which coordinate pedestrians in evacuation simulation:

Rule 5 (R5). in each iteration move to the next cell, which has the lowest value;

Rule 6 (R6). if the value of the cell in your neighbourhood is the same as or higher than the value of the actual cell, then select the farthest cell of your neighbourhood in the movement direction;

Rule 7 (R7). if the cell is occupied by more than one pedestrian, select one of them randomly in the next step.

This is a primitive and basic set of rules, which can be easily extended in the future. For a complex simulation it is necessary to develop rules which will control social

interactions and interaction between dangerous environment (fire, smoke, radiation, chemical contamination, etc.) and pedestrians. The simulation results shown in Figure 2 were generated by this simulator. In the next part of this section we compare this method with other commercial software using a static floor field to simulate the pedestrian movement. Current overview of the evacuation software tools is available in [7]. We chose two most widely used commercial software tools. The first one is the Fire Dynamics Simulator (FDS) and its evacuation module EVAC. FDS+Evac [6] is a combined agent-based egress calculation model and a computational fluid dynamics (CFD) model of fire-driven fluid flow, where the fire and egress parts interact. The evacuation module of FDS has been developed and is currently maintained by VTT Technical Research Centre of Finland. It is intended for the simulation of the egress problem in fire conditions (fire evacuation), but can also be used just to simulate egress without any fire calculation (fire drill). The SIMULEX is the second software tool we chose. SIMULEX uses “distance map” to control pedestrian movement. The distance map represents a mesh of $0.2\text{ m} \times 0.2\text{ m}$ squares spread over the entire building space. The numerical value assigned to each block is equal to the total travel distance to an exit from that block. The distance-to-exit value from the center of each square is calculated by SIMULEX. The distance values are shaded in bands of 1 meter, which results in the display of “distance contours” throughout the building. When a person tries to find a way out of the building then he/she heads at right angles to these contours [43]. For comparison we chose the following building structures illustrated in Figure 7 with one emergency exit.

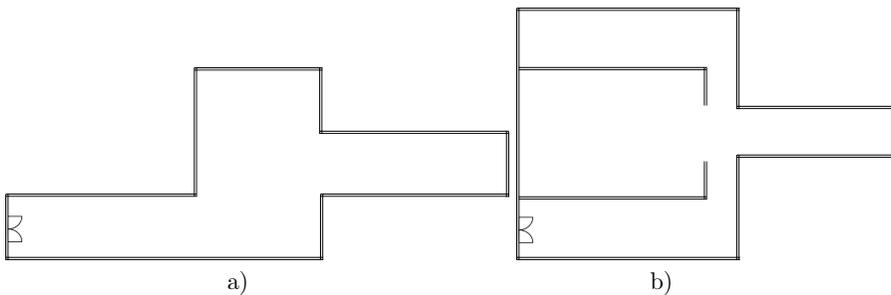


Figure 7. The test building structures

In the FDS+Evac method, agents are guided to exit doors by the preferred walking direction vector field, v_{0i} ; this field is obtained using the FDS flow solver. This vector field is obtained as an approximate solution to a potential flow problem of a two-dimensional incompressible fluid to the given boundary conditions, where all walls are inert and the chosen exit door acts as a fan, which extracts fluid out of the domain. This method produces a directional field for egress towards the chosen exit door [6]. In some cases of specific building distribution this vector field creates a ripple and it affects the simulation of pedestrian movement. Evacuees movement is

not natural. The simulation results of the test building structure shown in Figure 7 are given in Figures 8 and 9. The result in the form of a vector is shown in each cell. $0.2\text{ m} \times 0.2\text{ m}$ cell size was chosen and illustration of all flow fields is not clearly visible. Therefore we illustrate a part of the area only. In this case, the area of the upper part of the corridor attracts a pedestrian (Figure 8). If evacuation of one or several persons sufficiently distant from each other to influence agent to agent does not occur, then the evacuees movement does not look realistic. On the other hand, if large group of static persons are located in the highlighted part of the corridor, the vector will help to circumvent obstacles (pedestrian group). The pedestrian movement is realistic in this case. A similar problem occurs in the second building structure illustrated in Figure 9. Of course, in these considerations the fire impact is not assumed.

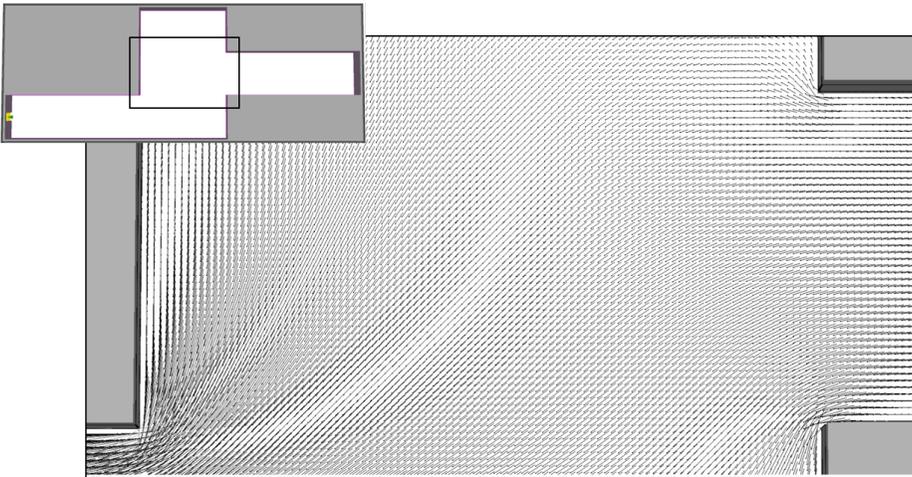


Figure 8. The simulation result of the vector field obtained by FDS+Evac software tools

The obtained result of the static field (distance map) by the method used in SIMULEX software tool is shown in Figure 10. Creation of the static floor field by the proposed method for individual test building structures is illustrated in Figure 11. Graphical results of the proposed method were modified to allow comparison with the SIMULEX result. The results of the static field obtained by the proposed method or by the method used in SIMULEX software tool are comparable. The method used to generate the distance map by help of the SIMULEX software tool is not specified in the available document about software tool. Thus we are unable to compare this method in agreement with the conditions illustrated in Table 1.

The evacuation paths (EP) derived by individual software tools and by the proposed method are compared in Figure 12. Broken line represents the simulation result of the SIMULEX software tools. The path moved represents the shortest

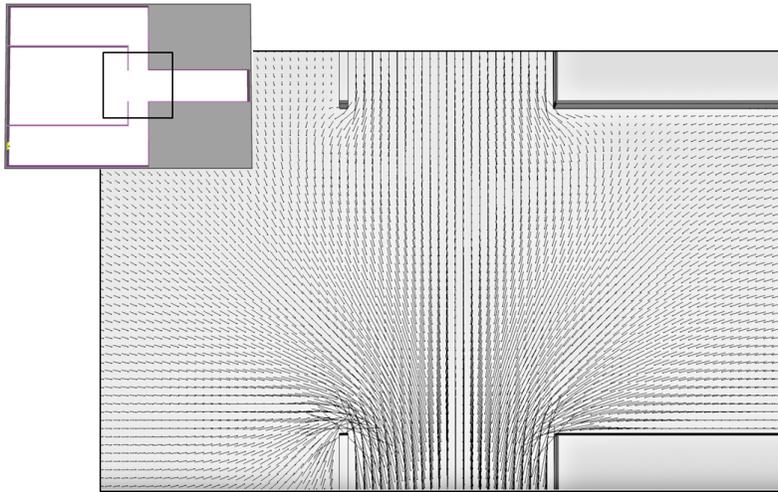


Figure 9. The simulation result of the vector field obtained by FDS+Evac software tools

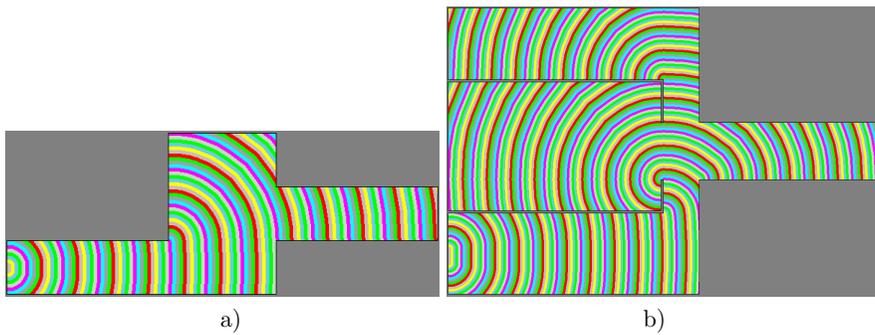


Figure 10. The simulation results of the static floor field obtained by SIMULEX software tools

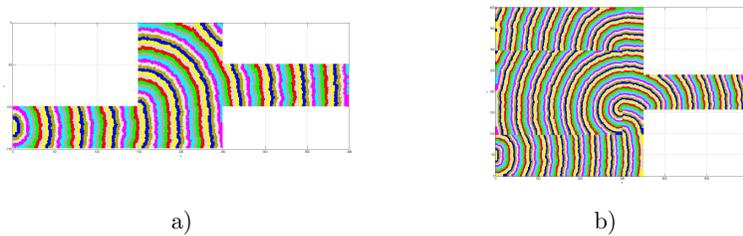


Figure 11. The simulation results of the static floor field obtained by proposed algorithm

path to the exit. The dash-and-dot line represents the evacuation path obtained by FDS+Evac software tools. As illustrated in Figure 12, this vector field creates a ripple and affects the pedestrian movement. Resulting pedestrian movement is not a natural motion of persons during evacuation. Solid line represents the simulation result of pedestrian movement with static floor field calculated by the proposed method. The pedestrian movement was controlled by simple rules (R5–R7) described earlier in this section. In this case, the evacuation path has a partial irregularity caused by random point distribution; but from global point of view, the path is similar to the shortest path to exit.

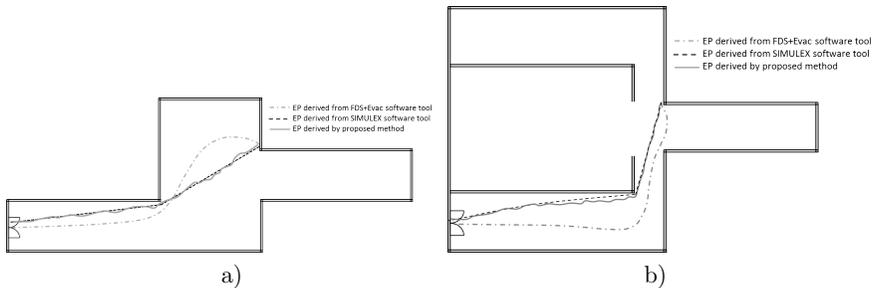


Figure 12. Comparison of the evacuation path derived by FDS+Evac, SIMULEX and the proposed method

5 CONCLUSIONS

The work describes new algorithm for finding an optimal path in space with obstacles. The algorithm was developed for the purposes of deployment in pedestrian navigation during evacuation process, but can be applied in areas where autonomous entities coordination is required. Finding optimal path is dependent on the assessment criteria. In the presented work, existing path planning approaches are summarized and analyzed in terms of usability in the pedestrian evacuation process. Problem analysis of the optimal path design during evacuation is presented in the paper. The focus is on establishment of criteria which are necessary for correct path planning during people evacuation. The proposed algorithm satisfies all requirements defined in the end of the first section. The proposed algorithm is compared with the existing methods and it achieves the best results. The presented algorithm has low computational complexity $O(n)$. Another advantage of the algorithm is that it covers entire inspected space. The gradient map which is the result of this algorithm allows to navigate pedestrians from any point to the destination (exit). Pedestrian evacuation has been intensively studied and therefore several software tools are available and frequently used in practice. The presented algorithm is compared with the most significant software tools allowing pedestrian evacuation. The simulation results achieved show that the proposed algorithm is as efficient as the

existing solutions, and it even achieves better results in some areas (computational complexity).

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