Hindawi Publishing Corporation
Journal of Applied Mathematics
Volume 2012, Article ID 765270, 17 pages
doi:10.1155/2012/765270

Research Article

Simulating Evacuations with Obstacles Using a Modified Dynamic Cellular Automata Model

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Received 7 November 2011; Accepted 1 April 2012

Academic Editor: Zhilong L. Huang

A modified dynamic cellular automata model is proposed to simulate the evacuation of occupants from a room with obstacles. The model takes into account some factors that play an important role in an evacuation process, such as human emotions and crowd density around the exits. It also incorporates people's ability to select a less congested exit route, a factor that is rarely investigated. The simulation and experimental results show that modifications to the exits provide reasonable improvement to evacuation time, after taking into account the fact that people will tend to select exit routes based on the distance to the exits and the crowd density around the exits. In addition, the model is applied to simulations of classroom and restaurant evacuation. Results obtained with the proposed model are compared with those of several existing models. The outcome of the comparison demonstrates that it performs better than existing models.

1. Introduction

The use of cellular automata (CA) in modeling crowd movement has attracted considerable attention in transportation science. Since simulations of real-life evacuations are nearly impossible to conduct, different modeling methods have been used to develop simulations for studying human behavior during evacuation.

Research has shown that the complex behavior of pedestrians can be studied from a physical point of view [1–3]. Dynamic crowd behaviors that have been studied include jam transition, clogging, lane-like formation, and the "faster-is-slower" effect [4–9]. Numerous situations have been investigated, such as evacuation from fires, evacuation in poor visibility [10], evacuation in panic situations [11], egress from aircraft [12], pedestrian counter-flows [6, 7, 13, 14], movement in a T-junction [15], motion through a bottleneck [16], kin behavior effects [17], and cooperative or competitive behavior [12].

Similarly, numerous models have been proposed to study these systems, such as those based on particle flows [18–20], social forces [11, 15, 21–23], and cellular automata (CA) [4, 24–31]. The CA model is one of the most popular choices owing to its simplicity of computation and its ability to model the dynamic behavior of pedestrians individually and collectively, and it is considered a more complex model [11, 25, 27, 32–35]. Guo et al. [31] proposed a method to predict pedestrians' route selection behavior during evacuation from indoor areas. However, the model is mainly focused on tracking the route rather than exit selection behavior. Fu et al. [33] introduced an evacuation processes in large classroom using a modified floor-field equation for exit selection behavior, but the work is more on investigating the optimal parameter in order to yield the better results. Furthermore, the authors in [33] reported that their work is applicable in the particular classroom cases and still not suitable to apply in study of more common buildings evacuation processes.

The majority of CA models divide the floor into rectangular cells and assign a weight to each cell for every time step. Weight assignment is based on the location and width of exits, human emotions, and the position of obstacles. There are two types of floor fields: static and dynamic fields. A static field does not change with time, even in the presence of pedestrians. Nishinari et al. [36] proposed using the 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 as reported in [25]. Hence, Alizadeh [25] also reported that the metric proposed by Varas et al. [27] that used a simple recursive process performed faster in computation structure and capable of achieving similar results as the Dijkstra metric. We obtained similar result as reported by [25, 27] through experiment by building a floor field for a room with 100×100 cells using both of these metrics, where the metric proposed by [27] taking 50% less times compared to Dijkstra metric were observed.

Dynamic floor fields, on the other hand, change with time and with the presence of pedestrians. During weight assignment at each time step, certain parameters have to be considered, such as pedestrian behavior, distribution, and density in the exit area, as well as distance to the exits. Then, the movement of pedestrians is decided based on the rules of pedestrian interaction and the weight assigned to the cells. Most existing models make the assumption that pedestrians are uniformly distributed in a room; only a few models consider the distribution of pedestrians around the exit area or in a room without obstacles.

We propose a model in which the weight of cells at each time step is affected by crowd distribution. We use the metric of Varas et al. [27] to construct a static field and include a modified version of the dynamic field constructed by Alizadeh [25]. Some related questions considered include where to place the obstacles and exits in a room to improve evacuation time. These questions have been examined in [37] to determine the optimal exit location and width in a room without obstacles that would produce the shortest evacuation time.

In this study, the proposed model is used to investigate the effect of obstacles on the evacuation process with the aim of creating a safer environment and reducing fatalities. The next section briefly describes the static field model for determining pedestrian premovement, Section 3 introduces the modified dynamic CA model, and Section 4 discusses the results of simulations. Finally, Section 5 concludes the paper.

2. The Static Floor Field

The static floor field consists of a room represented by a bidimensional grid with a cell size of $0.5 \times 0.5\,\mathrm{m}^2$, a typical pedestrian space in a crowded situation. The mean speed of pedestrians is assigned as 1.0 m/s for a normal situation, as reported in [4, 26, 28, 29], which means a pedestrian moves at 0.5 m per time step Δt, yielding $\Delta t = 0.5$ s.

The model of Varas et al. [27] consists of a room with fixed dimensions. A floor-field value, or weight, is assigned to each cell in relation to its distance from the exit following the rule that pedestrians will always move to a lower-weight cell from their current cell. In summary, the floor field is a rectangular grid with the weight for each exit assigned as 1, while values for neighboring cells are assigned based on the rules of static fields defined by [27] as follows.

If a cell is assigned a value M, *adjacent cells in the vertical or horizontal directions are each assigned a value* $M + 1$. *For diagonal directions, a value of* $M + \lambda$ *is assigned to adjacent cells, where* $\lambda = 1.5$.

Weight assignment is repeated until the value for every cell is calculated. In addition, the walls in the field are assigned very high weights to ensure pedestrians will never occupy them. During simulations, only the positions of occupants are updated at each time step while the floor-field values remain the same.

In addition, we set some intelligent local rules as introduced in [27] to the proposed model to produce a nondeterministic model. The rules are as follows.

As mentioned above, the weight of a cell depends on its location in relation to obstacles and the exits. Since the obstacle's parameters are constant, the floor-field value of the obstacle is independent of time and set to be static (Figure 1). We require the floor field to update itself with respect to time for crowd distribution. Figure 2 shows the values of the floor field in Figure 1 computed following the above static field rules. Simulations using the floor-field values in Figure 2 show that pedestrians move to exit A only and none to exit B, which does not reflect real situations. A floor field which takes into account pedestrian distribution is needed.

3. The Dynamic Cellular Automata Model

A dynamic floor field is established by considering pedestrian distribution in the evacuation process. Assuming there are y $(l = 1, 2, 3, \ldots, k, \ldots, y)$ evacuation exits, this model is able to determine the weight of cell x with respect to exit y at the ith step, $W_i^{(y)}(x)$. Three variables are considered.

Therefore, we define the dynamic floor field in mathematical terms as

$$W_i^{(y)}(x) = W_{\text{static}}^{(y)}(x) + P_i^{(y)}(x) D_i^{(y)}(x), \tag{3.1}$$

where

$$\begin{aligned} D_i^{(y)} &= \frac{\left|\alpha_i^{(y)}(x)\right| + (1/2)\left|\beta_i^{(y)}\right|}{E_{(y)}}, \\ Z_i &= \{m \mid m \text{ is the cell occupied by a person in } i\text{th step}\}, \\ \alpha_i^{(y)}(x) &= \left\{m \mid W_{\text{static}}^{(y)}(m) < W_{\text{static}}^{(y)}(x),\ m \in Z_i\right\}, \end{aligned}$$

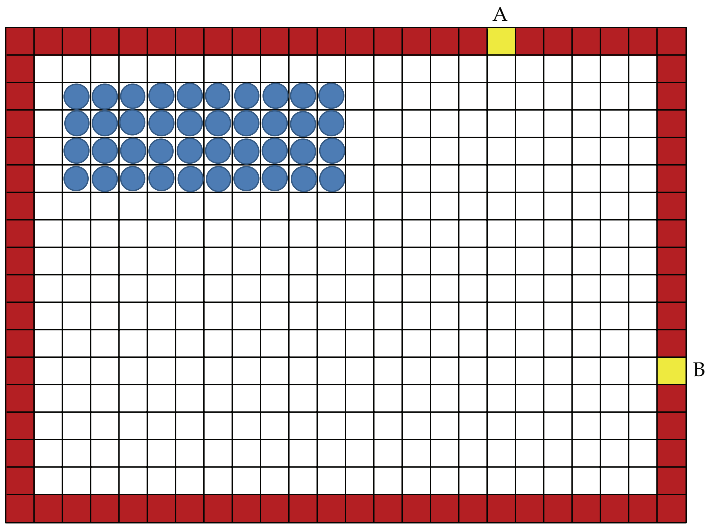

Figure 1: An 18 × 24 floor field with 40 pedestrians near the left side of exit A.

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500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	1	500	500	500	500	500	500	
500	17.5	16.5	15.5	14.5	13.5	12.5	11.5	10.5	9.5	8.5	7.5	6.5	5.5	4.5	3.5	2.5	2	2.5	3.5	4.5	5.5	6.5	500	
500	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3.5	3	3.5	4	5	6	7	500	
500	18.5	17.5	16.5	15.5	14.5	13.5	12.5	11.5	10.5	9.5	8.5	7.5	6.5	5.5	5	4.5	4	4.5	5	5.5	6.5	7.5	500	
500	19	18	17	16	15	14	13	12	11	10	9	8	7	6.5	6	5.5	5	5.5	6	6.5	7	8	500	
500	19.5	18.5	17.5	16.5	15.5	14.5	13.5	12.5	11.5	10.5	9.5	8.5	8	7.5	7	6.5	6	6.5	7	7.5	8	8.5	500	
500	20	19	18	17	16	15	14	13	12	11	10	9.5	9	8.5	8	7.5	7	7.5	8	8.5	8	7.5	500	
500	20.5	19.5	18.5	17.5	16.5	15.5	14.5	13.5	12.5	11.5	11	10.5	10	9.5	9	8.5	8	8.5	8	7.5	7	6.5	500	
500	21	20	19	18	17	16	15	14	13	12.5	12	11.5	11	10.5	10	9.5	9	8	7	6.5	6	5.5	500	
500	21.5	20.5	19.5	18.5	17.5	16.5	15.5	14.5	14	13.5	13	12.5	12	11.5	10.5	9.5	8.5	7.5	6.5	5.5	5	4.5	500	
500	22	21	20	19	18	17	16	15.5	15	14.5	14	13	12	11	10	9	8	7	6	5	4	3.5	500	
500	22.5	21.5	20.5	19.5	18.5	17.5	17	16.5	15.5	14.5	13.5	12.5	11.5	10.5	9.5	8.5	7.5	6.5	5.5	4.5	3.5	2.5	500	
500	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	B
500	23.5	22.5	21.5	20.5	19.5	18.5	17.5	16.5	15.5	14.5	13.5	12.5	11.5	10.5	9.5	8.5	7.5	6.5	5.5	4.5	3.5	2.5	500	
500	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3.5	500	
500	24.5	23.5	22.5	21.5	20.5	19.5	18.5	17.5	16.5	15.5	14.5	13.5	12.5	11.5	10.5	9.5	8.5	7.5	6.5	5.5	5	4.5	500	
500	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6.5	6	5.5	500	
500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	

Figure 2: Values of the floor field in Figure 1 computed based on static field rules.

$$\beta_i^{(y)}(x) = \left\{ m \mid W_{\text{static}}^{(y)}(m) = W_{\text{static}}^{(y)}(x),\ m \in Z_i \right\},$$
$$P_i^{(y)}(x) = \left(1 - n_i^{(y)}(x)\right) P_1 + n_i^{(y)}(x) P_2, \tag{3.2}$$

where P_1 is the probability of reaching the nearest exit, P_2 is the probability of congestion occurring in the exit area, n_i is the degree of impatience of pedestrian x at the ith step, and $E_{(y)}$ is the width of exit y. Here, $|\alpha_i^{(y)}(x)|$ and $|\beta_i^{(y)}|$ denote the number of elements of $\alpha_i^{(y)}(x)$

and $\beta_i^{(y)}$, respectively. The parameter $W_{\text{static}}^{(y)}(x)$ corresponds to any other proper metric such as Euclidean, Manhattan, or Dijkstra, but in this simulation, we use the metric introduced in Section 2 for computation. Also, $n_i^{(y)}(x)$ is defined as

$$n_i^{(y)}(x) = \left| \frac{v_i^{(y)}(x) - v_0^{(y)}(x)}{v_{\max}^{(y)}(x) - v_0^{(y)}(x)} \right|, \tag{3.3}$$

where $v_i^{(y)}(x)$ is the speed of pedestrian x at the ith step, $v_0^{(y)}(x)$ is the initial speed of pedestrian x, and $v_{\max}^{(i)}$ represents the maximum free-flow speed for pedestrian x.

We incorporate the defined degree of impatience into this proposed model because research has shown that emotions such as impatience could affect pedestrians' choice of evacuation route [11, 22, 28]. When $n_i^{(y)}(x)$ approximates 0, pedestrian i is in normal mood. When $n_i^{(y)}(x)$ approximates 1, pedestrian i is in extremely impatient mood and in a rush to get out from the system as fast as possible. The probability of reaching the nearest exit, P_1, is defined as

$$P_1 = \frac{d_i^{(y)}(x)}{d_{\max}^{(y)}(x)}, \tag{3.4}$$

where $d_i^{(y)}(x)$ is the distance of pedestrian x to exit y at the ith time step, and $d_{\max}^{(y)}(x)$ is the maximum distance measured from all pedestrians that are nearer than pedestrian x to exit y. Equation (3.4) indicates that the shorter the distance of pedestrian x to exit y, the higher the probability of the pedestrian selecting exit y as the evacuation route. Conversely, if the distance is longer, the probability of selecting exit y becomes lower. The probability of congestion occurring in the exit area is defined as

$$P_2 = 1 - \frac{N_i^{(y)}(x)}{N_i^{\text{Total}}}, \tag{3.5}$$

where $N_i^{(y)}(x)$ corresponds to the number of pedestrians that are nearer than pedestrian x to exit y at the ith time step, and N_i^{Total} is the total number of pedestrians remaining in the evacuation system at the ith time step.

As the proposed model is dynamic, some of the pedestrians may change their choice of exit after a number of time steps, regardless of their current location. Figure 3 shows the values of the floor field in Figure 2 for the model at the first time step. Figure 4 is a snapshot of the simulation after 70 time steps for the dynamic behavior mentioned above. It can be seen that 11 pedestrians are moving from exit A to exit B. The evacuation times for the floor field in Figure 2 are 104 and 190 time steps, respectively, for the proposed dynamic model and the static model.

4. Simulation Results

One of the most important problems in pedestrian evacuation study is where to place the exits for speedy evacuation. Many existing models do not consider crowd distribution in

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500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	1	500	500	500	500	500	500	
500	249	227	205	185	165	146	127	110	94	77	58	41	27	16	8.5	4.1	2.4	4.1	8.5	16	27	41	500	
500	257	153	145	137	129	120	111	102	92	82	67	49	33	21	12	8.5	5.9	8.5	12	21	33	49	500	
500	265	154	146	139	131	123	114	105	96	87	75	58	41	27	21	16	12	16	21	27	41	58	500	
500	273	155	148	141	134	126	118	109	101	92	82	67	50	41	33	27	21	27	33	41	50	67	500	
500	282	159	150	143	136	129	122	114	105	97	88	77	67	58	49	41	34	41	49	58	67	77	500	
500	290	270	249	228	208	188	169	151	133	117	102	93	84	76	67	58	51	58	67	76	67	58	500	
500	299	280	260	239	218	198	179	161	143	127	117	108	100	92	85	77	69	77	67	58	49	41	500	
500	308	289	270	250	229	209	190	171	154	143	133	124	116	108	101	94	84	67	50	41	33	27	500	
500	317	299	280	261	241	220	201	183	171	161	151	141	133	124	108	92	76	58	41	27	21	16	500	
500	326	309	291	272	253	232	213	201	190	179	169	153	135	117	101	85	67	49	33	21	12	8.5	500	
500	335	319	302	284	265	245	232	220	202	185	165	146	127	110	94	77	58	41	27	16	8.5	4.1	500	
500	344	329	313	296	277	258	239	220	198	177	158	139	121	104	87	69	51	34	21	12	5.9	2.4	1	B
500	353	339	324	307	290	272	249	227	205	185	165	146	127	110	94	77	58	41	27	16	8.5	4.1	500	
500	362	349	335	319	300	279	257	235	213	192	172	153	135	117	101	85	67	49	33	21	12	8.5	500	
500	371	359	343	325	306	286	265	243	221	200	180	161	142	124	108	92	76	58	41	27	21	16	500	
500	377	363	348	335	313	294	273	252	230	209	189	169	151	133	116	100	84	67	50	41	33	27	500	
500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	

Figure 3: Values of the floor field in Figure 2 for the proposed dynamic model at the first time step.

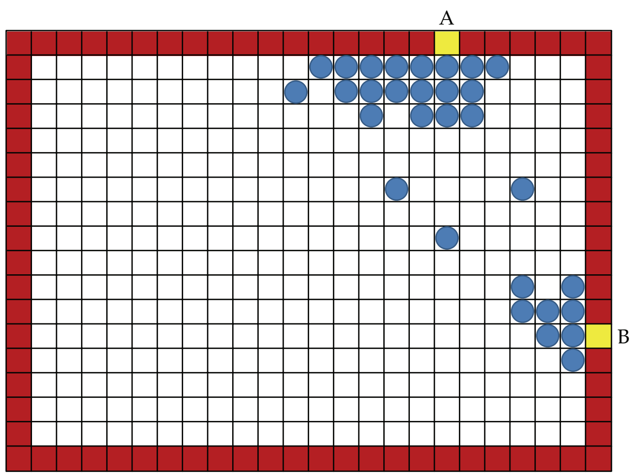

Figure 4: Snapshot of a simulation performed using the proposed model of the floor field in Figure 1 after 70 time steps, showing 11 pedestrians moving toward exit B.

a room, assuming uniform distribution in a large room without obstacles. However, obstacles are an important factor to consider in determining the optimal exit location.

In this section, we report the results of a series of simulations performed for a room without obstacles to test and validate our proposed dynamic model against the findings of Daoliang et al. [37] and Varas et al. [27]. Another series of simulations is performed for a room with two single-door exits in the presence of obstacles to validate our model against the results of Song et al. [38] and Alizadeh [25]. Finally, the model is applied to simulate evacuation from a restaurant in order to determine the optimal locations of the exits that allow evacuation in minimal time.

500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
500	40.7	47	53.8	60.5	67.7	75.5	88.5	102	117	132	149	166	184	203	223	243	260	273	500
500	28.9	34.4	40.2	47.2	54.6	67.7	81.1	94.6	109	124	140	157	175	194	214	234	253	268	500
500	19.8	23.9	28.8	34.8	47.2	60.5	74.2	87.5	102	117	133	149	167	186	205	225	246	263	500
500	12.5	15.8	19.9	28.8	40.2	53.8	67.2	80.9	94.8	110	125	142	159	178	197	217	238	257	500
500	7.27	9.87	15.8	23.9	34.4	47	60.7	74.8	88.5	103	118	135	152	170	189	209	230	251	500
500	3.83	7.27	12.5	19.8	28.9	40.7	54.6	68.4	82.6	96.9	112	128	145	163	182	209	222	244	500
1	2.43	5.32	9.94	16.1	24.4	35.3	48.4	62.5	77.1	91.2	106	122	139	157	175	195	215	236	500
1	2.43	5.32	9.94	16.1	24.4	35.3	48.4	62.5	77.1	91.2	106	122	139	157	175	195	215	236	500
500	3.83	7.27	12.5	19.8	28.9	40.7	54.6	68.4	82.6	96.9	112	128	145	163	182	202	222	244	500
500	7.27	9.87	15.8	23.9	34.4	47	60.7	74.8	88.5	103	118	135	152	170	189	209	230	251	500
500	12.5	15.8	19.9	28.8	40.2	53.8	67.2	80.9	94.8	110	125	142	159	178	197	217	238	257	500
500	19.8	23.9	28.8	34.8	47.2	60.5	74.2	87.5	102	117	133	149	167	186	205	225	246	263	500
500	28.9	34.4	40.2	47.2	54.6	67.7	81.1	94.6	109	124	140	157	175	194	214	234	253	268	500
500	40.7	47	47.7	60.5	62.6	75.5	88.5	102	117	132	149	166	184	203	223	243	260	273	500
500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500

Figure 5: Floor-field values generated using the proposed model for a room with a central exit in the left wall.

4.1. Simulations for a Room without Obstacles

We test the model in a room divided into 14×18 cells with N occupants who are initially randomly distributed. The number of occupants and the room size are chosen to match those reported in Daoliang et al. [37]. An exit door of width W is placed at the center of the left wall (Figure 5). The average evacuation time of 10 runs of simulation is calculated for various values of W. The initial distribution of the occupants is varied for each run.

Figure 6 is a snapshot showing occupants moving toward the exit, and Figure 7 is a plot of evacuation time against exit width. It can be seen from the graph that evacuation time decreases nonlinearly when W increases, eventually reaching saturation (at $W \approx 8$) where further increase in exit width has only a minor effect on evacuation time. The speed of evacuation is also affected by the number of occupants, N. These results are consistent with those of Daoliang et al. [37] and Varas et al. [27]. We found from observation of the simulation that the rapid increase in evacuation time when $W < 4$ is due to the behavior of impatient pedestrians and collisions between pedestrians. Furthermore, behaviors such as pedestrian interaction that hinder movement to occupied cells were also observed.

4.2. Simulations for a Room with Obstacles

To further test and validate our model's dynamic capability for multiple exits, we performed simulations with a room that has obstacles. Consider a classroom of 13×28 cells with 30 students, 10 tables, and two single-door exits (Figure 8). The size of the room and the number of occupants are chosen to match those of Alizadeh's study [25]. The two exits with width $W = 1$ are placed near the upper left and lower left corners of the room. The average evacuation time of 10 runs of simulation is computed. A snapshot of the simulation shows occupants moving toward the alternative exit (Figure 9).

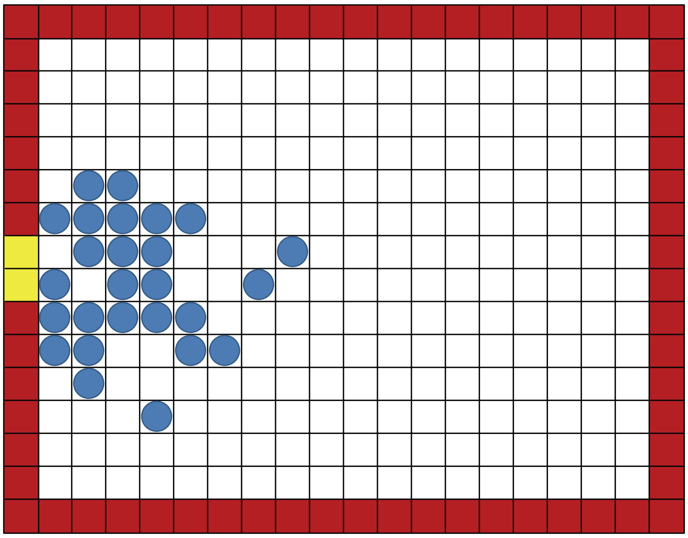

Figure 6: Snapshot of a simulation for the floor field in Figure 5 with $N = 150$ occupants after 65 time steps.

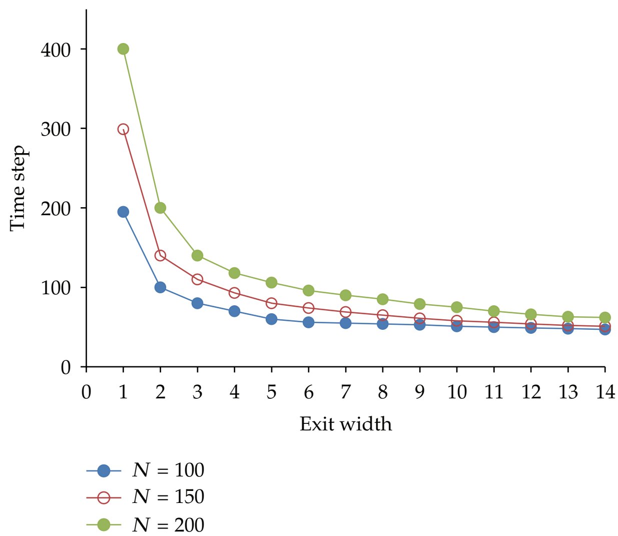

Figure 7: Relationship between exit width and evacuation time (in time steps) for the room in Figure 5, with 100, 150, and 200 occupants initially distributed randomly.

The proposed model includes various forces due to human behaviors, such as attraction, clogging, and repulsion. A plot of the relationship between the mean speed of occupants and evacuation time for classroom illustrated in Figure 8 shows that, at low speeds, moving faster reduces evacuation time (Figure 10). However, after a certain speed is reached, moving faster leads to longer evacuation time as congestion becomes severe. This is known as the faster-is-slower effect.

Consider J (1/ms) as the outflow, or the number of occupants leaving the room per second per meter of door width, and V (m/s) as the speed of occupants. A plot of

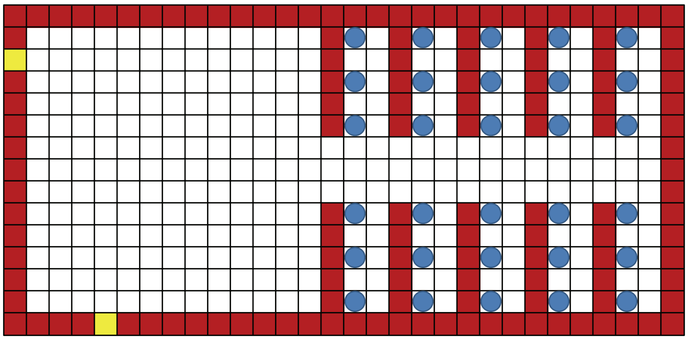

Figure 8: A room with 30 occupants and two single-door exits.

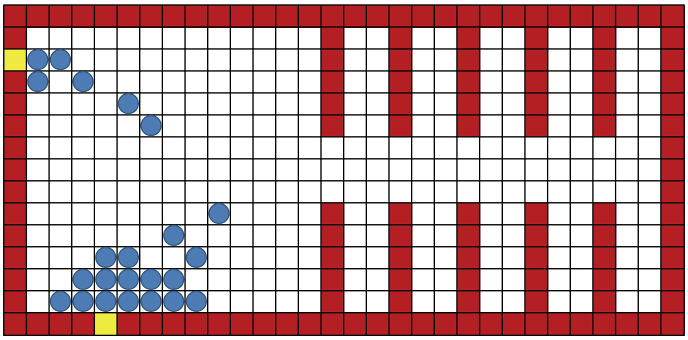

Figure 9: Snapshot of a simulation for the room in Figure 8 after 35 time steps.

the relationship between the effectiveness of evacuation, which corresponds to J/V $(1/\mathrm{m}^2)$, and the speed of occupants shows that, when speed exceeds $1.3\,\mathrm{m/s}$, the effectiveness of evacuation decreases (Figure 11). These results are consistent with those of Song et al. [38] and Alizadeh [25].

4.3. Simulations for a Restaurant

Consider a restaurant of 18×28 cells with 109 occupants and 18 tables, with the tables representing obstacles. Possible locations for the exits are labeled from 1 to 78 in Figure 12. The dynamic field values at the first time step are given in Figure 13. According to Varas et al. [27], the presence of obstacles can cause occupants to change the exit route they take, which would affect parameters such as the optimal exit width, exit locations, and evacuation time. Modifications to these parameters can be made by the proposed model by recalculating the field values to account for the presence of obstacles.

Evacuation time is calculated for different locations of the exits, with the obstacles being fixed and the 109 persons distributed in the room. For evaluation purposes, we consider two cases: (i) one double door or two single doors; (ii) one quadruple door or two double doors. Here, a single door is defined as an exit that allows one person to leave through it at one time, while a double door allows two persons to leave through it simultaneously (Figure 14). Next, a series of simulations are performed by changing the position of the exits in order to determine the optimal location. Since Alizadeh [25] reported that the static field

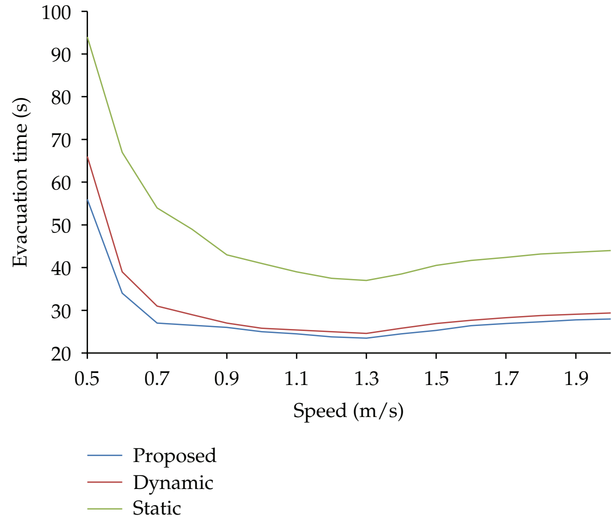

Figure 10: Relationship between the mean speed of occupants and evacuation time for the room in Figure 8.

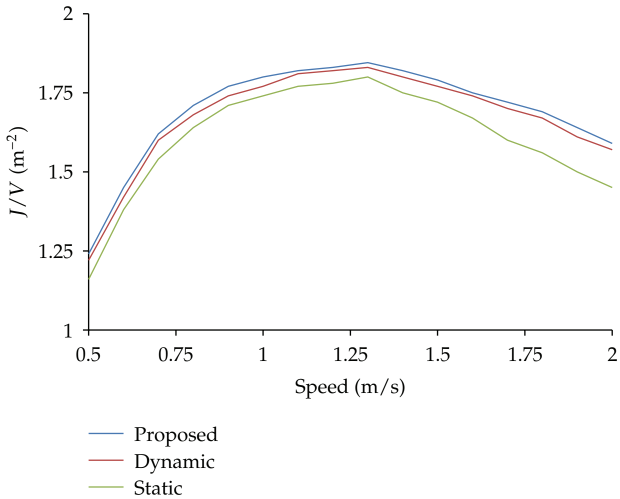

Figure 11: Effectiveness of evacuation, J/V, from the room in Figure 8 at different speeds.

and dynamic field behave the same way if there is only a single door, regardless of its width, we use only our proposed dynamic model to analyze the relationship between exit location and evacuation time.

Figure 15 shows the evacuation time for the restaurant with and without obstacles for different single-door exit locations. In order to clearly see the effect of obstacles, the occupants are positioned in the same spots even if there are no tables. The sharp changes in the plot are due to the distance of occupants (i.e., further or nearer) to the exit. The other effect seen is the dip that forms when the door is located in cells 2–9 and 64–75 (as labeled in Figure 12) in the presence of tables. The presence of a walkway next to the door helps speed up evacuation as

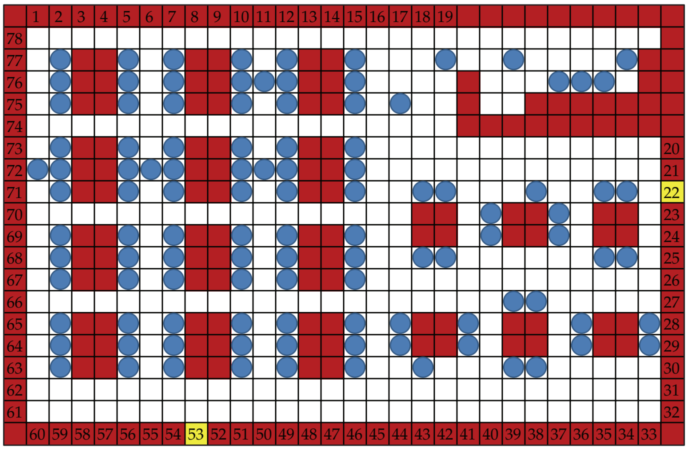

Figure 12: A restaurant with 18 tables and 109 persons.

500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
500	408	404	387	390	382	366	365	365	379	366	382	382	372	347	325	300	291	265	255	247	254	257	258	260	257	256	255	254	500
500	390	385	500	500	356	341	341	500	500	341	356	359	500	500	305	278	268	244	235	227	233	238	240	241	242	241	240	500	500
500	371	367	500	500	332	315	315	500	500	315	332	334	500	500	302	273	248	225	219	500	240	242	241	241	236	233	230	500	500
500	347	343	500	500	306	287	285	500	500	287	306	309	500	500	281	255	230	199	191	500	246	235	500	500	500	500	500	500	500
500	324	320	301	281	277	260	259	259	274	260	277	281	302	306	277	252	230	197	165	500	500	500	500	500	500	500	500	500	500
500	300	295	500	500	252	235	236	500	500	235	252	255	500	500	260	235	203	170	140	114	90	70	54	40	28	18	12	8.4	500
500	274	268	500	500	230	203	202	500	500	203	230	230	500	500	257	236	202	169	138	112	81	63	48	34	23	14	8.4	4.1	500
500	249	244	500	500	197	170	169	500	500	170	197	199	500	500	234	210	176	145	118	94	73	56	42	28	18	12	5.9	2.4	1
500	226	223	195	167	165	162	160	139	162	162	165	167	195	223	226	234	239	500	500	112	81	500	500	34	23	500	500	4.1	500
500	197	192	500	500	156	114	112	500	500	114	156	160	500	500	197	227	228	500	500	114	108	500	500	40	33	500	500	8.4	500
500	166	162	500	500	109	90	81	500	500	90	109	112	500	500	166	196	227	197	165	135	109	79	62	53	40	27	18	14	500
500	161	133	500	500	79	70	63	500	500	70	79	90	500	500	138	166	197	199	167	138	112	90	78	61	47	34	28	23	500
500	134	110	88	70	62	54	48	53	60	54	62	70	80	109	133	162	192	199	195	164	134	110	88	70	54	47	40	34	500
500	110	105	500	500	47	40	34	500	500	40	47	54	500	500	129	135	164	500	500	168	162	500	500	80	70	500	500	48	500
500	90	78	500	500	34	28	23	500	500	28	34	41	500	500	107	112	138	500	500	197	190	500	500	110	90	500	500	63	500
500	79	62	500	500	23	18	14	500	500	18	23	34	500	500	79	109	135	165	197	227	196	166	139	134	112	110	90	81	500
500	70	54	40	28	18	12	8.4	5.9	8.4	12	18	28	40	54	70	90	114	140	170	203	227	184	168	164	138	135	114	112	500
500	63	48	34	23	14	8.4	4.1	2.4	4.1	8.4	14	23	34	48	63	81	112	138	169	202	234	216	199	195	167	165	140	138	500
500	500	500	500	500	500	500	500	1	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500

Figure 13: Floor-field values for the room in Figure 12 generated by the proposed model for the first time step.

it guides pedestrian movement and reduces interaction. This observation is similar to those reported in [25, 27].

The effect of exit width with a door located at the center of the left wall in the presence of obstacles is then analyzed for the static, dynamic, and proposed models. As seen in Figure 16, the critical value above which further increase in exit width would not contribute to much reduction in evacuation time is lower in the presence of obstacles (approx. 6 versus 8 without obstacles). Beyond an exit width of 6, no significant difference in evacuation time is seen because the obstacles hinder pedestrian movement.

Restaurants commonly have quadruple doors, which are defined here as a door that lets four persons go through simultaneously. The results for double-door and quadruple-door exits are plotted in Figures 17 and 18. Similar minimal evacuation time is obtained for both

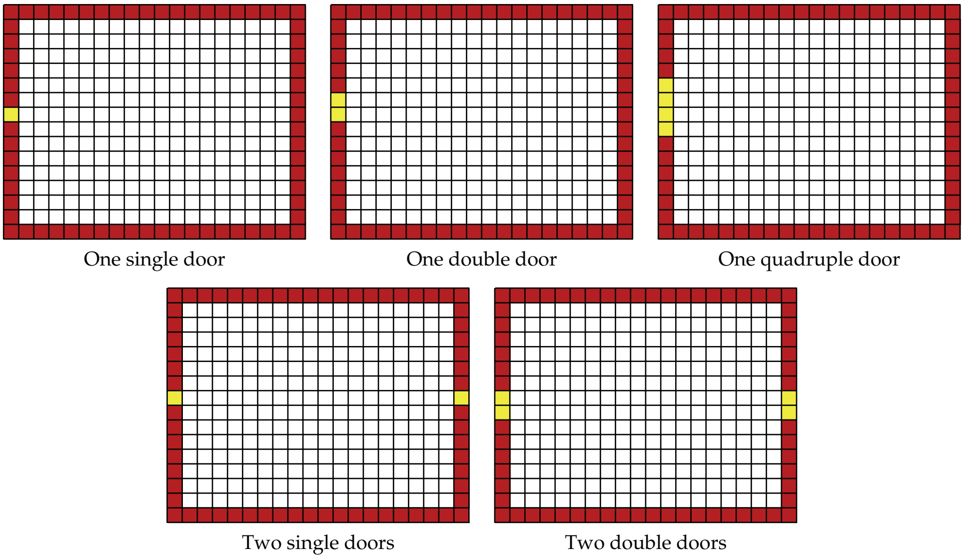

Figure 14: Types of exit doors.

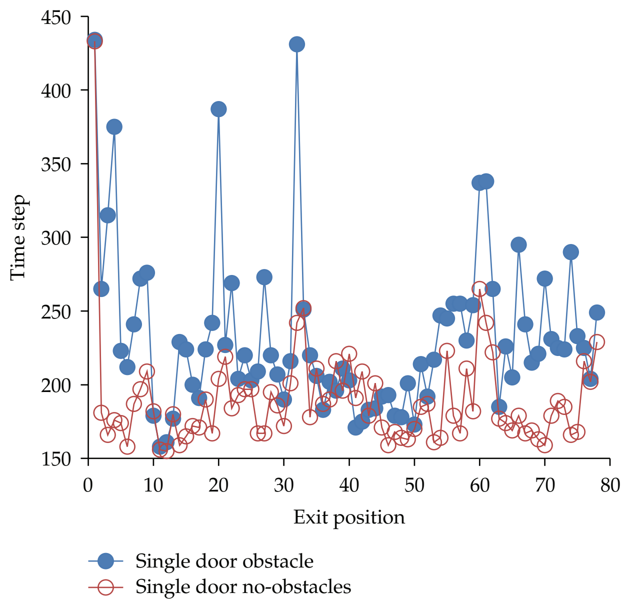

Figure 15: Evacuation time (in time steps) for 112 persons in the restaurant shown in Figure 12 with (filled circles) and without (open circles) obstacles for varying locations of one single-door exit (average of 10 runs for each exit location).

double and quadruple doors located either in cells 8–13 or 40–49, both in the presence and absence of obstacles. The worst situation (longest evacuation time) occurs when the exit is located at the corner of the room with single doors or double doors occupying cells 1 and 59–60, respectively, while the optimal situation is when the exit is located near the center of the side of the room with single or double doors occupying cells 11 and 9-10, respectively.

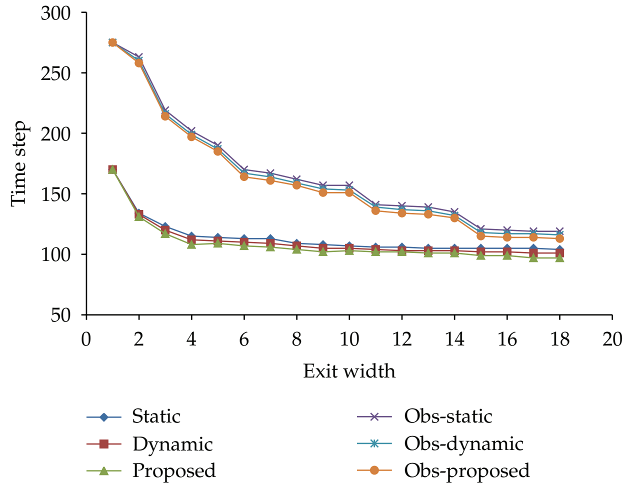

Figure 16: Variation in evacuation time (in time steps) with increasing exit width in the restaurant shown in Figure 12.

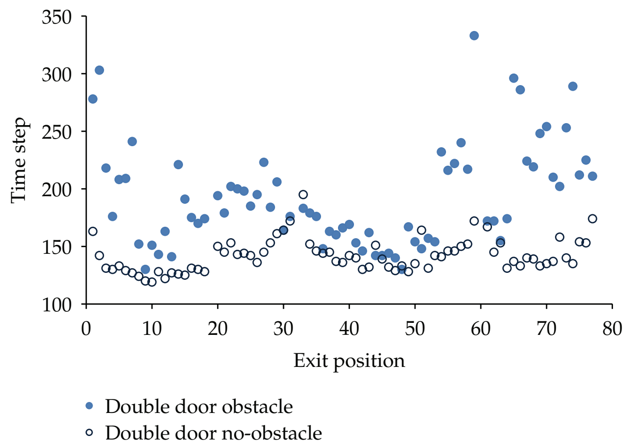

Figure 17: Evacuation time (in time steps) for different locations of one double-door exit in the restaurant shown in Figure 12, with (filled circles) and without (open circles) obstacles.

However, for quadruple doors, the worst exit location is cells 5–8, while the optimal location is cells 11–14. The exit is optimally positioned when it is around the center of the side of the room, which is the shortest overall distance to the exit for all occupants.

The optimal evacuation times for a double-door and a quadruple-door exit are, respectively, $130 \pm 35\Delta t$ and $97 \pm 32\Delta t$ (error estimated from the average deviation of data from the mean value), while for the single-door exit, it is $158 \pm 39\Delta t$. This corresponds approximately to 20 s or less, which is a reasonable evacuation time, according to [27].

Next, we replace the double door with two single doors, and the quadruple door with two double doors. Figure 19 shows the optimal locations of both the two single doors (D1 and D2) and two double doors (D3) that minimize evacuation time. Therefore, the best results are obtained when the doors are located next to the walkway and at the side of the room. Figure 20 compares the static, dynamic, and proposed models in terms of evacuation time

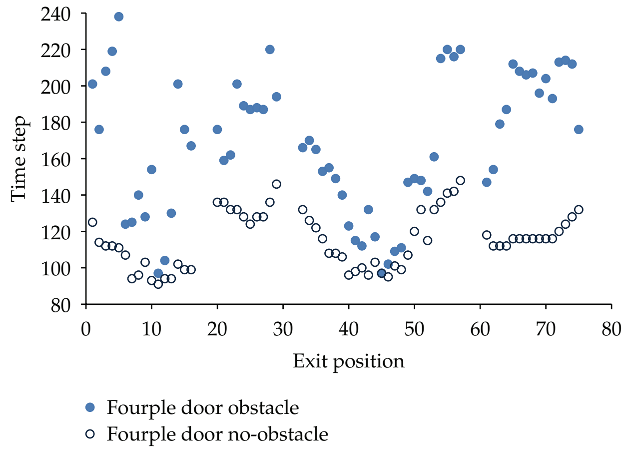

Figure 18: Evacuation time (in time steps) for different locations of one quadruple-door exit in the restaurant shown in Figure 12, with (filled circles) and without (open circles) obstacles.

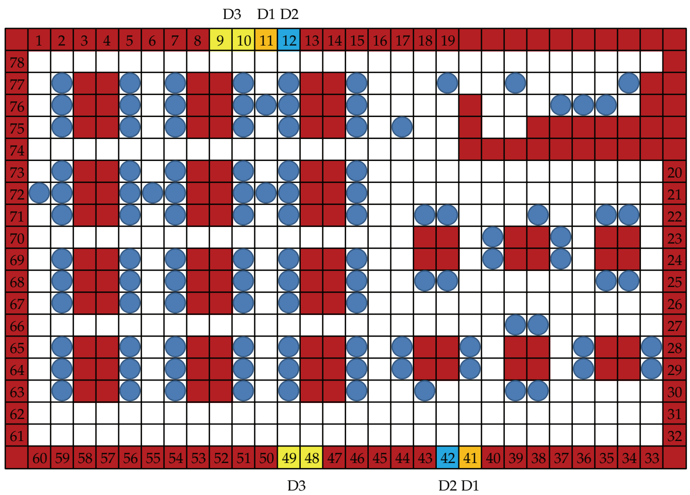

Figure 19: The restaurant from Figure 12 having two single-door and two double-door exits, with the best locations for the pair of doors labeled as D1 and D2 (two single doors) and D3 (two double doors).

for different types of exits. The figure shows that the shortest evacuation time achievable is $83 \pm 32\Delta t$. In addition, having two double doors is preferable to having two single doors or one quadruple door. Figure 21 shows a snapshot of the simulation with the floor field in Figure 12 after 85 time steps.

5. Conclusion

In this paper, we use a modified dynamic CA model to simulate the evacuation process in the presence of obstacles. The design of the model takes into account the distribution of the crowd, the location of exits, and the position of obstacles at each time step in order to make an optimal decision in selecting the best evacuation exit. Simulations using the proposed model

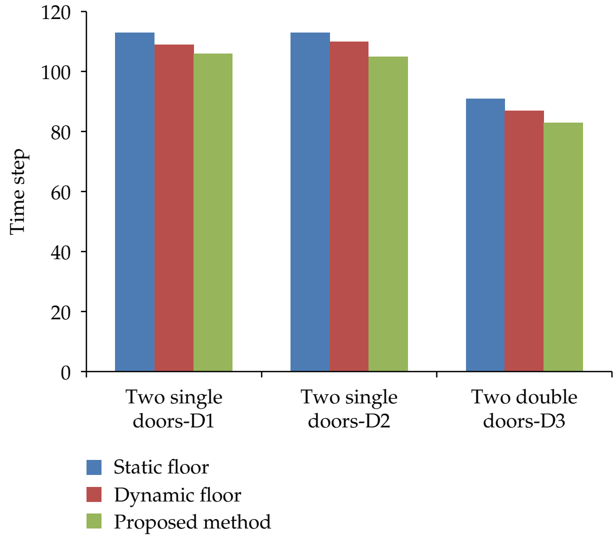

Figure 20: Comparing evacuation time (in time steps) for the static, dynamic, and proposed models for different types of doors.

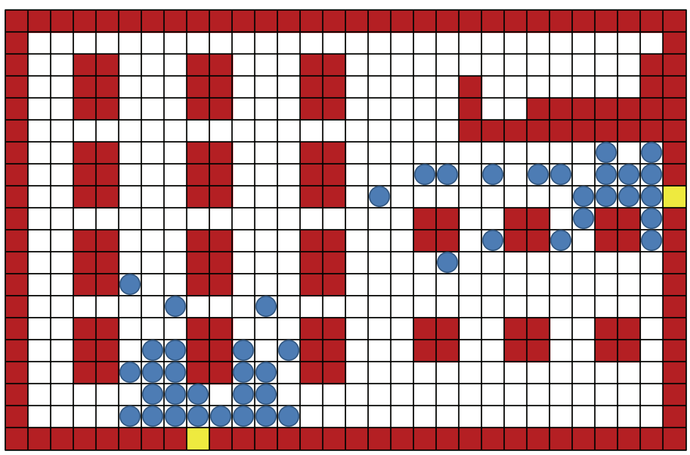

Figure 21: Snapshot of a simulation with 112 persons in the floor field from Figure 12 after 85 time steps.

produce the following results. First, evacuation time is effectively reduced in the proposed model compared with existing static and dynamic models. Second, the optimal positions for exit doors that minimize evacuation time are at the center of both sides of the restaurant. Third, compared with both static and dynamic models, evacuation time in the proposed model is lower in all simulations that we performed in this study. Finally, when there is only one exit (whether single door, double door, or quadruple door), increasing the exit width only contributes to a minor reduction in evacuation time for the three models studied, which is consistent with most of the existing findings.

The proposed model can be improved further by considering obstacles such as tables as movable, since during an evacuation some people may move the tables to create a new walkway, which may lead to a smoother flow. For more realistic simulations, factors such as age, physical ability, psychological factors (e.g., emotions), and group formation should also be considered. For future work, some of these factors will be integrated into our model and applied to other types of spaces, such as halls, stadiums, and movie theaters.

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