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Modelling Context Effects in Exit Choice for Building Evacuations

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Abstract: Understanding exit choice behaviour is essential for optimising safety management strategies in building evacuations. Previous research focused on contextual attributes, such as spatial information, influencing exit choice, often using utility models based on monotonic functions of attributes. However, during emergencies, evacuees typically make rapid, less calculated decisions. The choice of context can significantly impact the evaluation of attributes, leading to preference reversals within the same choice set but under varying context conditions. This cognitive psychological phenomenon, known as context effects, encompasses the compromise effect, the similarity effect, and the attraction effect. While researchers have long recognised the pivotal role of context effects in human decision making, their incorporation into computer-aided evacuation management remains limited. To address this gap, we introduce context effects (CE) in a social force (SF) model, CE-SF. Evaluating CE-SF's performance against the UF-SF model, which considers only the utility function (UF), we find that CE-SF better replicates exit choice behaviour across urgency levels, highlighting its potential to enhance evacuation strategies. Notably, our study identifies three distinct context effects during evacuations, emphasising their importance in advancing safety measures.

Keywords: building evacuations; exit choice behaviour; social force model; context effects

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1. Introduction

Understanding how crowds can safely and efficiently evacuate in emergencies is crucial for public safety. The urban population is growing faster than ever before, and mass gatherings are becoming more regular [1], thus making the probability of overcrowding, crowd surges, crowd collapses, and stampedes much higher [2]. The South Korean Halloween night tragedy on 29 October 2022, the worst stampede disaster in the recent year, which caused 156 deaths and 170 injuries [2], highlights the significance of crowd management and evacuation optimisation strategies.

Optimisation via behavioural modification in route/exit choice is one of the important approaches to improve evacuation efficiency [3]. Various numerical and experimental studies have investigated how to optimise evacuation by modifying the route/exit choice strategies. For instance, Wang and Cao [4] used a revised social force model to investigate the efficacy of diverse evacuation strategies, including walking along walls and following the average moving direction or positional cues, across differing visibility levels, densities, and exit widths. Observations revealed the varying effectiveness of these strategies across different conditions; for instance, following the average movement direction or position proved more efficient under high densities, while wall walking exhibited greater efficacy under low densities. Similarly, Zhou et al. [5] utilised the social force model to compare five evacuation strategies incorporating distance, density, and capacity considerations. Optimal performance across these strategies diverged under different conditions, as evaluated from the perspectives of evacuation time, the channel utilisation rate, and evacuation efficiency. For instance, strategies integrating density and capacity factors excelled in minimising evacuation time, whereas distance-based strategies exhibited a superior evacuation efficiency. Additionally, Ma et al. [6] proposed a dynamic exit choice model to assess the evacuation efficiency of varied multiple exit layouts, establishing alterations in exit locations and the implementation of two parallel exits as the most efficient layout for optimising evacuation time. Furthermore, Feng et al. [7] conducted virtual reality experiments to evaluate the impact of additional evacuation information—namely exit signs, directional signage, and cues provided by fellow evacuees—on exit choice performance, noting significant influences and observing asymmetrical exit choices, particularly in interactions with other evacuees. Moreover, Zhang et al. [8] highlighted the substantial influence of crowd flow on human wayfinding decisions and performance, emphasising the importance of comprehending how individuals navigate route and exit choices in optimising evacuation strategies. Real-world observations by Helbing and Molnár [9] underscored the frequent oversight or inefficient utilisation of exits during emergency situations, further emphasising the criticality of understanding decision-making processes in route and exit selection to optimise evacuation strategies.

In the context of exit choice, decision makers engage in a multifaceted evaluation of various choice attributes, encompassing factors such as the distance to exits, fire conditions, and the presence of emergency illumination [10]. Consequently, their decisions hinge upon a convergence of factors, incorporating external considerations like the architectural configuration of the structure [11] and the information available to them during evacuation [7,12]. Additionally, internal factors, such as individual risk attitude [13] and demographic characteristics [14,15], play a pivotal role in shaping exit choices. Moreover, the dynamics of social interaction, as evidenced by leader–follower behaviour [16,17], introduce an additional stratum of complexity to this decision-making process.

Despite potential evacuee familiarity with a building's layout, presuming exhaustive knowledge of factors influencing exit choice is unrealistic [18]. In reality, individuals often grapple with integrating information across multiple attributes to make strategic decisions accurately. This challenge in attribute weighting can lead to conflicting preferences among decision makers. Additionally, the seminal contributions of Daniel Kahneman, a renowned psychologist awarded the Nobel Prize in 2002 for his insights into the psychology of judgment and decision making, have shed light on the prevalence of heuristics and biases in human decision processes [19,20]. His research underscores the non-uniform rationality of human decisions. Furthermore, Klüpfel et al. [21] have highlighted the inherent difficulty evacuees face in making meticulously calculated strategic decisions during emergencies. Moreover, Gao et al. [13] have demonstrated that exit choice decision making is subject to rank-dependent and reference-dependent preferences, further elucidating the intricate nature of this process in evacuation contexts.

The selection of context holds significant sway over attribute evaluation, thereby profoundly influencing decision makers' preferences [22]. Notably, the occurrence of preference reversals can arise within the same choice set under varying contextual conditions, including distinct framing or representations of identical choice sets [23]. Empirical investigations across a range of decision tasks consistently revealed the profound impact of context effects on the decision-making processes [24]. This phenomenon manifests across diverse domains, including, but not limited to: (a) decision making within game scenarios with penalties for incorrect responses [25], (b) assessments of suitable candidates for scholarship awards [26], (c) product-selection processes and subsequent in-store purchasing decisions by consumers [27], and (d) resolutions of perceptual dilemmas [28]. Moreover, our prior investigation [29] furnishes compelling evidence that context effects play a pivotal role in exit choice behaviour during evacuations.

Numerous scholars specialising in evacuation modelling have conducted extensive inquiries into the impact of contextual variables, such as exit proximity and prevailing fire conditions, on exit choice [30,31]. Nonetheless, it is worth noting that, to the best of our knowledge, relatively few modelling simulations have accounted for the psychological responses of evacuees to visual cues and available information during building evacuations. This study seeks to address this gap by integrating context effects into the development of a social force model. By incorporating psychological reactions into the visual context, our model aims to provide a more comprehensive representation of the complex decision-making dynamics inherent to evacuation scenarios.

The subsequent sections of this paper are structured as follows. Section 2 provides an overview of context effects, a brief explanation of utility function, and a general introduction to the social force model. In Section 3, a comprehensive account of the experiment and simulation methodologies is delineated. Section 4 is dedicated to presenting simulation results, followed by a comparative analysis with empirical data. Section 5 engages in a thorough discussion of the findings. Lastly, Section 6 offers a summary of the discoveries and provides concluding remarks, encapsulating the core insights derived from this study.

2. Related Works

2.1. Context Effects

Human decision making frequently diverges from strategic and rational principles, primarily due to the human brain's struggle to provide accurate and precise measurements for available options. As Kahneman [19] observed: people are lazy controllers who avoid effortful thinking when possible. This phenomenon aligns with the principle of least effort, whereby individuals inherently seek paths of minimal cognitive exertion. Numerous studies [19,32–35] have observed that people make a decision based on cognition, heuristics, and biases. The phenomenon of context effects constitutes a notable aspect of cognitive psychology, elucidating systematic alterations in decision-making behaviour stemming from individuals' perception of choice sets [35]. The context effects include the compromise effect, similarity effect, and attraction effect [24,35].

The compromise effect [36] posits that individuals tend to perceive a particular option more favourably when they view it as a compromise among available choices, rather than considering it as an extreme or outlier selection [37]. For example, Figure 1a shows the distances and congestion of two exits in front of an evacuee. Exit A is located in close proximity to the evacuee but is heavily congested, while Exit C is farther away but less crowded. In general, the probabilities of the evacuee choosing either Exit A or Exit C as their target are similar. Then, we introduce a third option, Exit B, which differs significantly from both Exit A and Exit C. In accordance with the compromise effect, the presence of Exit B results in a reduction in the probability of the evacuee choosing either Exit A or Exit C as their preferred exit, while the likelihood of choosing Exit B increases. This shift in behaviour reflects a preference for Exit B as the compromise option, akin to a customer rating a restaurant's service from a range of five options: very poor, poor, fair, good, and very good. In such cases, most customers tend to avoid extreme ratings (i.e., very poor and very good) in favour of selecting a compromise option, a behaviour elucidated in previous literature [36].

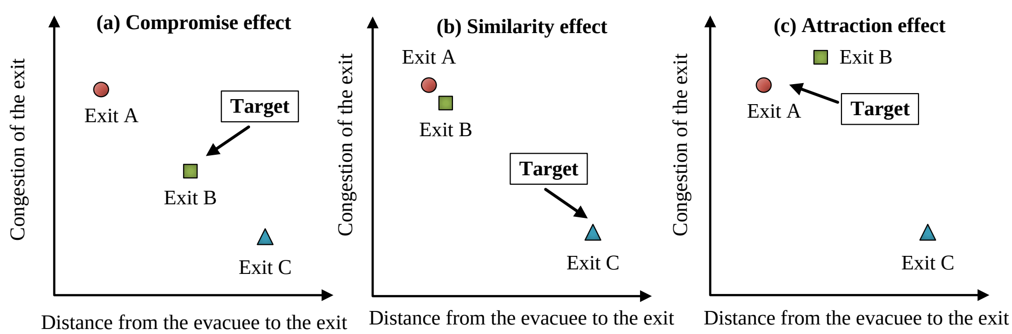

Figure 1. Illustration of (**a**) compromise effect; (**b**) similarity effect; and (**c**) attraction effect in the context of exit choice during evacuations. The arrow points to the exit more likely to be selected under three distinct context effects, with varying Exit B conditions, while the choice set {Exit A, Exit C} remains constant.

The similarity effect [38] denotes a phenomenon where decision makers tend to change their choices away from options that closely resemble existing alternatives and lean toward options that exhibit dissimilarity, particularly when the similar option is neither clearly superior nor inferior [39]. This effect can manifest in exit choice scenarios, as shown in Figure 1b. In the absence of Exit B, the probabilities of evacuees choosing Exit A and Exit C as their preferred exits are comparable. However, with the introduction of Exit B, which closely resembles Exit A, the probability of evacuees choosing Exit A and Exit B diminish, while the probability of choosing Exit C, which significantly differs from both Exit A and Exit B, increases. This change in choice behaviour illustrates the presence of the similarity effect, wherein decision makers are inclined to opt for options that are dissimilar to those already under consideration. A parallel example in a shopping context reinforces this concept: consider encountering three apples in a fruit shop, two of which closely resemble each other in terms of size, smell, and colour, and both are smaller but cheaper than the third apple. Due to the similarity effect, customers are more likely to choose the third apple due to its uniqueness and dissimilarity to the other two, even though it is comparatively larger and more expensive.

The attraction effect [40] describes a phenomenon where the likelihood of choosing a superior option is heightened when an option that is similar but inferior is introduced into the choice set [24,37]. This effect is illustrated in Figure 1c within the context of exit choice during an evacuation. Exit A, while in close proximity to an evacuee, is congested, whereas Exit C, though farther away, offers less congestion. When Exit A and Exit C are the sole exit options, the probabilities of choosing either exit are comparable. However, with the introduction of Exit B, which is marginally less favourable than Exit A, evacuees tend to be drawn toward similar exit alternatives. As a result, a majority of evacuees opt for the superior exit, Exit A. This effect can also be demonstrated by a shopping scenario. Consider three toaster options: a USD 3 toaster (toaster A) with two slots wide enough for standard white bread, a USD 9 toaster (toaster C) with six slots of the same size, and a USD 3 toaster (toaster B) with two slots that are too narrow for standard white bread. In this scenario, customers tend to evaluate the two similar toasters (A and B) and often choose toaster A due to its superior attributes. Consequently, toaster C becomes less attractive to customers due to the presence of the attraction effect.

Decades of research have observed these effects and explored how context influences preferences in decision making involving multiple attributes and alternatives, spanning from traveller choice dynamics [41] to consumer decision-making processes [42], from the intricacies of risky decision making [43] to the complexities of market behaviour [44], and from the discernment of preferences by human decision makers [45] to the remarkable decision-making abilities exhibited by non-human entities such as honeybees [46] and even slime mould [47]. These findings highlight the necessity for any serious theoretical model to capture the context effects in the decision-making process [48,49].

2.2. Utility Function

Modelling exit choice behaviour is generally based on the framework of utility function [50–53], which depends on the linear weighting attributes of available exits [15,30]. The exit with the maximum utility is chosen as the target exit. To account for the evacuees' behavioural uncertainty, the utility U_{ik}^t of option k for evacuee i at time t is expressed as [14,15,31]:

$$U_{ik}^t = V_{ik}^t + \varepsilon_{ik}^t \tag{1}$$

where V_{ik}^t denotes a deterministic component given by Equation (2) and ε_{ik}^t is a random residual parameter:

$$V_{ik}^t = \sum_{m=0}^{M} \beta_{mk} X_{imk}^t \tag{2}$$

Here, there are M factors influencing exit choice. X^t_{imk} is the expected value of the mth factor affecting the choice for option k perceived by evacuee i at time t. β_{mk} is the weight parameter representing the evacuees' preferences related to the factor m.

2.3. Social Force Model

Social Force (SF) model is one of the most widely used evacuation simulation models with the significant merits of simulating continuous movement [9,54] and describing the realistic self-organisation phenomena of crowd behaviour, e.g., arching and clogging [9], lane formation [55], "faster is slower" [56], and stop-and-go waves [57]. The SF model can be used to describe the diversity of pedestrians, e.g., disabilities [58] and wicked pedestrians [59]. The SF model is based on Newton's Second Law, which describes the force generated by evacuees and their surroundings observed in crowd evacuations [54,57]. The force expression is given by Equation (3), which can be divided into three parts: the self-driving force of evacuee i, f_i^0 (Unit: N); interaction force between evacuee i and j, f_{ij} (Unit: N); and interaction force between evacuee i and walls W, f_{iW} (Unit: N):

$$m_i \frac{dv_i(t)}{dt} = f_i^0 + \sum_{j(\neq i)} f_{ij} + \sum_W f_{iW} \tag{3}$$

where evacuee i of mass m_i (Unit: kg) changes his or her position with the velocity $v_i(t) = \frac{dr_i}{d_t}$ (Unit: m/s). The expression of self-driving force is as follows:

$$f_i^0 = m_i \frac{v_i^0(t)e_i^0(t) - v_i(t)}{\tau_i} \tag{4}$$

where evacuee i likes to move with a desired velocity $v_i^0(t)$ (Unit: m/s) in the expected direction $e_i^0(t)$ at time t, and τ_i is the acceleration time from the current velocity to the desired velocity.

In rooms with multiple exits, evacuees need to make a decision on their direction of movement, i.e., $e_i^0(t)$. Several studies have explored exit choice strategies within the SF model framework. Xie et al. [60], Hou et al. [61], and Song et al. [62] delineated exit choice strategies for evacuees, categorising them based on their roles. Xie et al. [60] and Hou et al. [61] distinguished between leaders and followers, while Song et al. [62] classified them as authority figures and normal evacuees. Leaders and authority figures were typically directed towards either the nearest exit or the exit with lower pedestrian density, while followers or normal evacuees tended to follow the guidance of their leaders or authority figures. Zheng et al. [63] proposed an improved SF model to determine the exit direction by probability with consideration of spatial distance and occupant density. They defined transition rules to address the issue of unrealistic evacuee trajectories in previous methods. Fu et al. [64] proposed a static and dynamic exit choice model to calculate the probability of exits being selected, and evacuees either choose the exit with the highest probability or keep the original direction. In this study, the proposed CE-SF model is used to determine the desired moving direction, i.e., $e_i^0(t)$. This approach upgrades the SF model from pre-defining an exit for each occupant to evacuees autonomously choosing an exit based on their visual context.

3. Methodology

3.1. Experimental Data

We use the experimental data collected from a field observation reported by Haghani et al. [16] for model calibration and validation. The controlled experiment was conducted in a rectangular room equipped with two entrances (each 1 m wide) and three exits (each 0.5 m wide), as depicted in Figure 2. Participants entered the room through Entrance I and II and made decisions on exiting through Exit A, B, or C. Two types of scenarios were implemented: low- and high-urgency scenarios. In the low-urgency scenarios, 33 participants waited at Entrance I and 27 participants waited at Entrance II, instructed to leave the room without competition. Conversely, in the high-urgency scenario, 27 participants waited at Entrance I and 25 participants waited at Entrance II, tasked with escaping from the room as fast as possible. The experiment was recorded using a camera to capture participant's trajectories and evacuation times. Additional details of the experimental setup can be found in the reference [16]. We used PeTrack [65,66] software (version v0.9) to extract participants' trajectories, enabling us to analyse their exit choice. Trajectories were computed at a 25 frames per second rate, i.e., 0.04 s/frame. At each frame, the coordinates of the participants' position were recorded and then used to calculate the distance to exits by comparing their coordinates with those of each available exit.

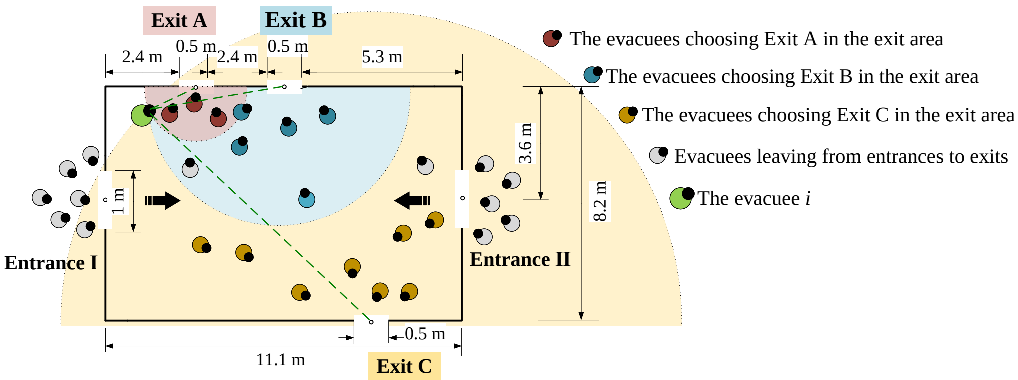

Figure 2. Schematic of the experimental and modelling setup. To estimate the number of people in proximity to each exit, we use the *exit area* [63,67], which is defined as a semi-circular region centred on the exit and having a radius equal to the distance between the evacuee and the exit. For Exit A, B, and C, the exit areas are indicated by red, blue, and yellow semi-circular regions, respectively.

The distance d_{ik}^t (Unit: m) from evacuee i to exit k at time t is represented by the dashed straight line in Figure 2. The decision on exit choice at each time step is determined by the change in distance from $t-1$ to t. The choice is made based on the exit with the shorter distance and the maximum absolute distance. A semi-circular area centred on the exit position, with a radius from the evacuee, is defined as the *exit area* [63,67], illustrated by the red, blue, and yellow area in Figure 2. Evacuee i competes with those in the exit area who choose that exit, so the number n_{ik}^t of evacuees choosing exit k within the exit area is considered as a factor in making the exit choice, calculated at each time step.

3.2. Model Description

In this section, we introduce the 'UF-SF model', integrating the previously discussed utility function (UF) with the social force (SF) model, to consider the impact of specific attributes on exit choice in the experiment. Additionally, building upon this original model, we propose the context-effects-implemented social force (CE-SF) model in this study to simulate real exit choice behaviour. Both the UF-SF and CE-SF models are employed to determine the desired moving direction, with subsequent movement being driven by the SF model.

3.2.1. UF-SF Model

Li et al. [68] determined three factors governing exit choice through a VR experiment and a field study, namely: (i) distance to exits, (ii) density in front of exits, and (iii) moving speed at exits. Lovreglio et al. [69] also determined three factors contributing to exit choice: (i) the number of people using exits, (ii) the distance of an evacuee to exits, and (iii) the presence of smoke. Cai et al. [50] developed an exit choice model in which they defined the total utility of each exit, which is the linear combination of the exit's defined static and dynamic utilities, and found that the exit with the largest total utility is chosen. The static utility is determined by the width of the exits. The dynamic utility is defined as the linear combination of two terms: (i) the distance of an evacuee to exits and (ii) the evacuees' density at exits. The path distance and the level of congestion at exits markedly influence exit choice [64]. Based on the above factors and Equations (1) and (2), utility U is given by

$$U_{ik}^{t} = \beta_d \frac{d_{ik}^{t}}{d_{i,\max}^{t}} + \beta_n \frac{n_{ik}^{t}}{n_{i,\max}^{t}} \tag{5}$$

where d_{ik}^{t} (Unit: m) is the Euclidean distance of evacuee i from exit k at time t, see the straight dashed line in Figure 2; n_{ik}^{t} (Unit: ped) refers to the number of evacuees in proximity to the exit k, see people at the semi-circular region in Figure 2; and $d_{i,\max}$ (Unit: m) is the distance of evacuee i from the farthest exit, i.e., $d_{i,\max} = \max_{k=A,B,C}(d_{ik}^{t})$. Similarly, $n_{i,\max} = \max_{k=A,B,C}(n_{ik}^{t})$ (Unit: ped), and β_d and β_n are coefficient parameters of the weighting distance and exit efficiency, respectively. As the distance from the exit increases and the number of people selecting that exit rises, the utility of that exit should decrease, and thus both β_d and β_n are negative.

3.2.2. CE-SF Model

When a room has only one exit, no exit choice needs to be made. If there are two exits, the exit with the higher U is chosen. When there are three or more exits, the exits with the three highest U are chosen, and the final exit choice is made after accounting for context effects. According to the references [49,70,71], the coexistence of the three context effects is very rare. Therefore, a demarcation system was proposed in this study to identify the most dominant context effects for a given exit-choice scenario.

The compromise effect requires the three exits to be dissimilar to each other; the similarity effect requires two exits to be similar and the third exit to be dissimilar to the other two; and the attraction effect requires two exits to be dissimilar to each other, while the third exit should exhibit similarity but be inferior to one of the others. Therefore, the measurement of option similarity and inferiority is our primary cue for identifying the three context effects.

Two attributes, i.e., distance to exit k, d_k (Unit: m) and the number of evacuees near exit k, n_k (Unit: ped), are considered separately in our study as the different units and ranges. Two threshold values d_{sim} (Unit: m) and n_{sim} (Unit: ped) are defined to demarcate similarity and dissimilarity. That is, Exit k_1 and k_2 are similar if Equation (6) is satisfied; otherwise, they are dissimilar. Similarly, two threshold values d_{inf} (Unit: m) and n_{inf} (Unit: ped) are defined to demarcate inferiority and non-inferiority. Exit k_2 is inferior to Exit k_1 if Equation (7) is satisfied; otherwise, it is non-inferior. Here, $\begin{cases} 0 < d_{\text{inf}} < d_{\text{sim}} \\ 0 < n_{\text{inf}} < n_{\text{sim}} \end{cases}$.

$$\begin{cases} |d_{k_2} - d_{k_1}| \le d_{\text{sim}} \\ |n_{k_2} - n_{k_1}| \le n_{\text{sim}} \end{cases} \tag{6}$$

$$\begin{cases} d_{k_2} - d_{k_1} \ge d_{\text{inf}} \\ n_{k_2} - n_{k_1} \ge n_{\text{inf}} \end{cases} \tag{7}$$

Figure 3 illustrates how context effects influence exit choice. The size marking on the rectangular area of the left of Figure 3 is determined by Equations (6) and (7). An option within the light-coloured area is similar to the centre reference point, an option within the darker area at the bottom left corner is superior to the reference point, and an option within the darkest area at the top right is inferior to the reference point. The compromise effect occurs when the three exits are dissimilar from each other, and the compromise option, Exit B in Figure 3a, where the size of each attribute is the middle, i.e., Exit B in Equation (8), is chosen. The similarity effect occurs when the two exits are similar to each other, and the dissimilar option, see Exit C in Figure 3b, where the size of one attribute is small, and the other is large, i.e., Exit C in Equation (9), is chosen. The attraction effect occurs when the two exits are similar to each other, and one of the similar options, which is superior to the other, such as Exit A being superior to Exit B in Figure 3c, is chosen:

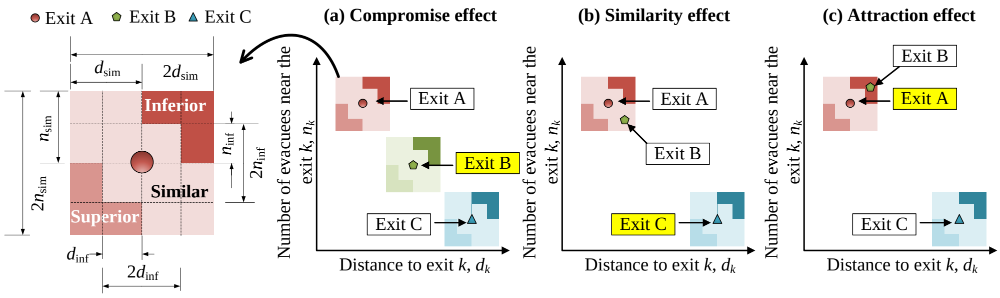

Figure 3. Demonstration of the (**a**) compromise effect for choosing the compromise option, i.e., Exit B; (**b**) similarity effect for choosing the dissimilar option, i.e., Exit C; and (**c**) attractive effect for choosing the superior option, i.e., Exit A. The target exit is highlighted in yellow. For each rectangular area, the light-coloured area around the exit point is the similar range; the darker area at the bottom left corner is the superior range; the darkest-coloured area at the top right corner is the inferior range.

$$\begin{cases} d_A < d_B < d_C \\ n_A > n_B > n_C \end{cases} \tag{8}$$

$$\begin{cases} d_A < d_B < d_C \\ n_A > n_B > n_C \end{cases} \text{or} \begin{cases} d_A > d_B > d_C \\ n_A < n_B < n_C \end{cases} \tag{9}$$

3.2.3. Model Framework

In the CE-SF model, context effects are integrated as a new module to improve the traditional UF-SF model. The simulation process of these two models is illustrated in Figure 4 through a flow chart. First, all attributes are computed, and the U values for all available exits are determined using Equation (5). Next, the three exits with the three highest U are selected. In the UF-SF model, the target direction is oriented towards the exit with the maximum U, while in the CE-SF model, the evacuees' visual context on exits determines the target direction. The context module is highlighted in the yellow rectangle in Figure 4. After identifying the three exits with the highest U, Equation (6) is employed to assess the similarity between the two exits. If all three exits are similar to each other, evacuees follow the moving direction of their last step. Conversely, if all three exits are dissimilar to each other and there exists a compromised exit (determined by Equation (8)), the compromise effect is applied, and the compromised exit becomes the desired target. If the dissimilar exit is not significantly superior to the two similar exits (determined by Equation (9)), and if an exit is superior to its similar exit (determined by Equation (6)), then the attraction effect is applied, and the superior exit is chosen. Otherwise, the similarity effect is applied, and the dissimilar exit is chosen. Lastly, in both UF-SF and CE-SF models, the position of evacuees is updated by the SF model after making a decision on exit choice. The simulation continues until all evacuees leave the room. The SF model parameters in this study adhere to those originally proposed by Helbing et al. [54]: $k = 1.2 \times 10^5\,\text{kg/s}^2$, $\kappa = 2.4 \times 10^5\,\text{kg/(m}\cdot\text{s)}$, $\tau_i = 0.5\,\text{s}$, $A_i = 2 \times 10^3\,\text{N}$, $B_i = 0.08\,\text{N}$. All evacuees are assumed to have a body radius of 0.2 m and a weight of 80 kg. The desired moving velocity is set as 1.2 m/s for low urgency and 2.5 m/s for high urgency [16,54].

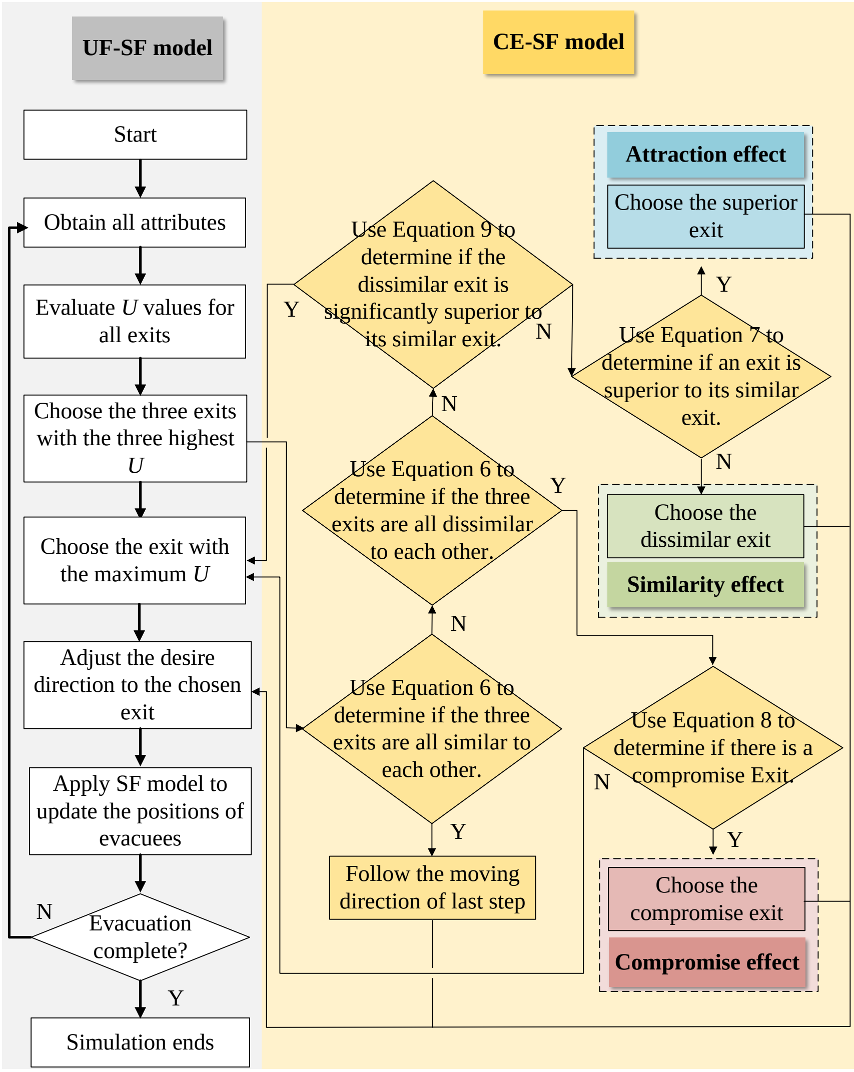

Figure 4. Flow chart of the simulation process.

4. Results

4.1. Sensitivity Analysis of the UF-SF Model

Two sensitivity parameters, namely β_d and β_n , are used to control evacuees' preference for exit choice. β_d and β_n weight the influence of path distance and exit congestion, respectively. In this study, β_d and β_n vary from -0.3 to -10, and the combination for simulation scenarios is shown in Table 1. In scenarios U1 and U2, the effect of exit congestion is greater, while in scenarios U4 and U5, the effect of path distance is greater; in the middle scenario U3, the effect is the same for both. To compare the simulation results with the corresponding experiment results, the difference in the total evacuation time between the simulated T_{SIM} (Unit: s) and the corresponding experimental T_{EXP} (Unit: s) is termed the $error(T)$, given by Equation (10):

$$error(T) = \frac{|T_{\text{SIM}} - T_{\text{EXP}}|}{T_{\text{EXP}}} \tag{10}$$

Table 1 shows that all the $error(T)$ of UF-SF simulations are under 15%. However, the simulated moving trajectories significantly disagreed with the experiment, see Figure 5. Figure 5a,g show that at least three individuals entered the room through Entrance I and chose Exit C to leave in the experiment, as indicated by the arrow of the moving direction depicted in Figure 5a,g. In contrast, there was no one from Entrance I leaving from Exit C in the UF-SF simulations. Moreover, the number of evacuees leaving from exits over time is shown in Figure 6. The flow of people leaving from Exit A and C in the UF-SF simulation is faster than that in the experiment (see the slopes of lines in Figure 6a,c,d,f), while it is reversed for the flow of people leaving from Exit B (see Figure 6b,e).

Table 1. Simulation scenarios and parameters used in the UF-SF model and the simulation error of total evacuation time $error(T)$. The bolded line is the UF-SF parameters used for further study in the next section.

No.	UF-SF Model		$error(T)$	
	β_d	β_n	Low Urgency	High Urgency
U1	−0.3	−10	1.6%	3.8%
U2	**−0.3**	**−1**	**9.4%**	**3.8%**
U3	−1	−1	11.1%	10.0%
U4	−10	−0.3	2.2%	2.2%
U5	−1	−0.3	9.6%	13.2%

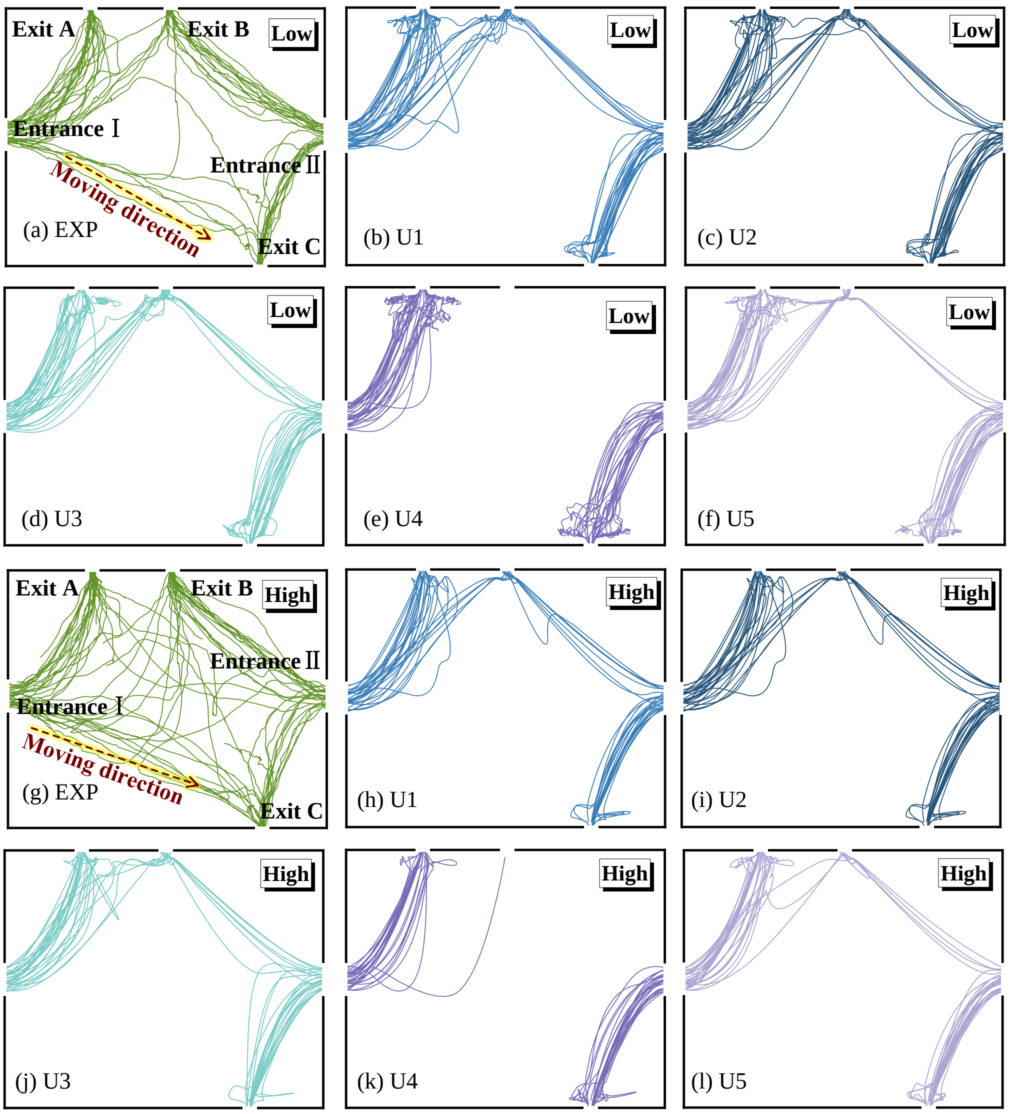

Figure 5. Evacuees' movement trajectories in the experiment (EXP) under low urgency (**a**) and high urgency (**g**), and simulated in UF-SF model by different parameters (see U1–U5 in Table 1 under low urgency (**b**–**f**) and high urgency (**h**–**l**)).

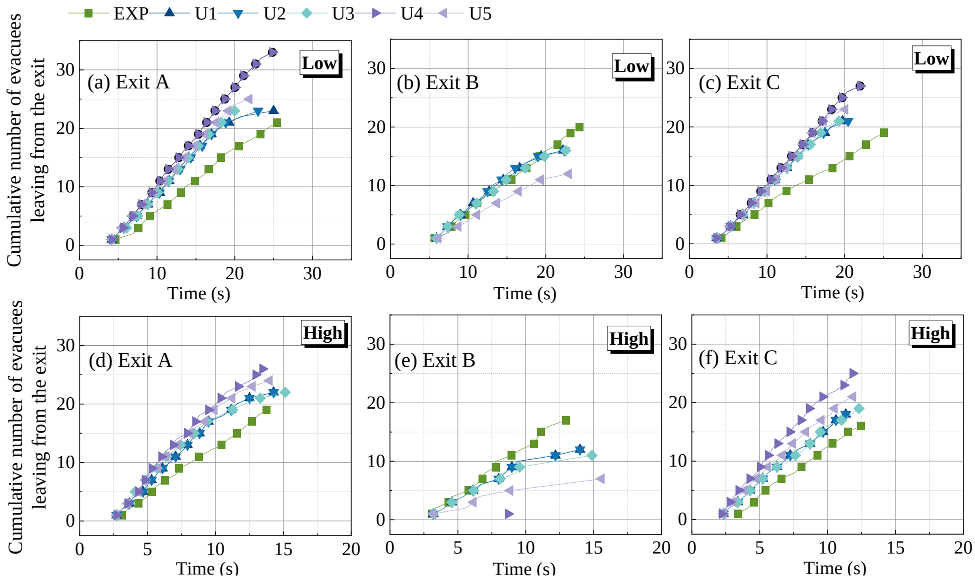

Figure 6. The number of evacuees leaving from Exit A, i.e., (**a**,**d**); Exit B, i.e., (**b**,**e**); and Exit C, i.e., (**c**,**f**) under low urgency (**a**–**c**) and high urgency (**d**–**f**) in the different scenarios of UF-SF model, i.e., U1–U5.

Although the evacuation time of the UF-SF simulation is consistent with the experiment, the moving trajectories and the exit choice are significantly different from the experiment. Therefore, to simulate the real exit choice behaviour, in this study, the context effects are implemented into an SF model, i.e., the CE-SF model. Considering the relatively good performance of $error(T)$, moving trajectories, and the flow of people leaving exits in the UF-SF simulations, the parameters in scenario U2, i.e., $\beta_d = -0.3$, $\beta_n = -1$, are adopted in the CE-SF model.

4.2. Simulation Performance of the CE-SF Model

4.2.1. Sensitivity Analysis of the CE-SF Model

Two pairs of threshold parameters d_{sim}, n_{sim} and d_{inf}, n_{inf} are used to determine the similarity and the inferiority of two available exits, which further determine whether the context effects can be applied. Specifically, d_{sim} and n_{sim} are the smallest detectable difference of d_k and n_k between two exits. The Just Noticeable Difference (JND), which signifies the visibility threshold, refers to the smallest detectable difference between two stimuli [72]. According to Weber's Law, the JND is directly proportional to the magnitude of the stimulus (ϕ), expressed mathematically as $\Delta\phi = k\phi$, where k is Weber fraction, a constant [73]. Research indicates that Weber fractions for perceived 3D lengths vary between 25 and 30% [74], and the median Weber fraction for the visual ratio was found to be 32.6% [75]. Therefore, in this study, the range of d_{sim} and n_{sim} is derived from the JND and Weber fraction k and is estimated as 30%. Given that the maximum distance to an exit is 11.8 m and the number of evacuees near the exit does not exceed 20 ped, consequently, $d_{\text{sim}} \leq 3.5$ m , $n_{\text{sim}} \leq 6$ ped. d_{sim} ranges from 2 to 3 m, and n_{sim} ranges from 3 to 6 ped during simulations. Additionally, d_{inf} and n_{inf} are introduced to delineate inferiority and non-inferiority, as shown in Figure 3; that is, $\begin{cases} 0 < d_{\text{inf}} < d_{\text{sim}} \\ 0 < n_{\text{inf}} < n_{\text{sim}} \end{cases}$. Thus, the range of d_{inf} is set from 1 to 1.5 m, and n_{inf} is 2 ped. Table 2 shows the value of these parameters adopted in this study and the nine simulation scenarios, i.e., C1–C9 in the CE-SF model.

The percentage of evacuees entering the room from Entrance I and II and leaving from Exit A, B, and C is presented in Figure 7. Whether under low urgency (Figure 7a) or high urgency (Figure 7b), around 10% of evacuees entered from Entrance I and left from Exit B or C in the experiment (EXP). In contrast, in the UF-SF model, no evacuees who entered the room from Entrance I left from Exit C under low or high urgency. In the CE-SF model, the percentages of evacuees entering from Entrance I and leaving from Exit B and C fluctuate around 10%, except for scenario C9. To further compare the simulation and experimental results, the difference in the percentage of evacuees leaving the exit between the simulated P_{SIM} and experimental P_{EXP} is determined by Equation (11):

$$error(P) = \sum_{i=\mathrm{A,\,B,\,C}} \sum_{j=\mathrm{I,\,II}} |P_{\mathrm{SIM}_{i,j}} - P_{\mathrm{EXP}_{i,j}}| \quad (11)$$

Table 2. Simulation scenarios and parameters used in the CE-SF model.

No.	d_{sim} (m)	n_{sim} (ped)	d_{inf} (m)	n_{inf} (ped)
C1	2	3	1.5	2
C2	2	4	1.5	2
C3	2	6	1.5	2
C4	2	3	1	2
C5	2	4	1	2
C6	2	6	1	2
C7	3	3	1.5	2
C8	3	4	1.5	2
C9	3	6	1.5	2

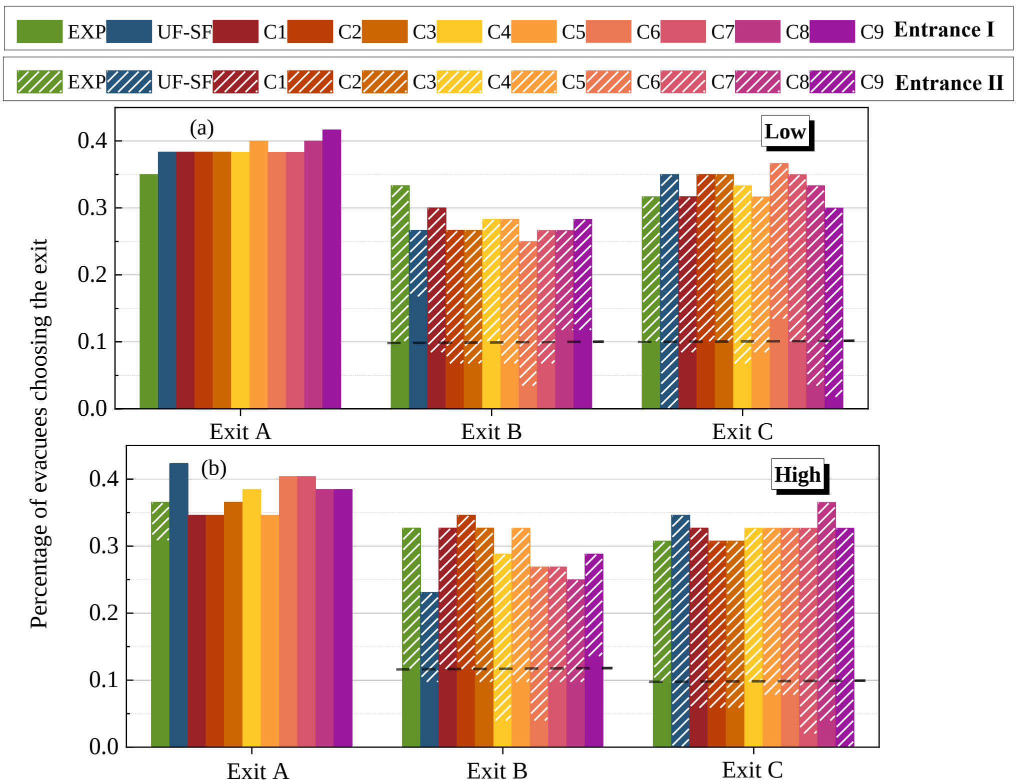

Figure 7. Percentage of evacuees choosing the exit is depicted for (**a**) low-urgency and (**b**) high-urgency scenarios. The columns without and with white diagonal lines represent the percentage of evacuees entering the room from Entrance I and II, respectively. The black dashed line indicates the dividing line between the percentage of evacuees entering from Entrance I and II in the experiment.

Figure 8 illustrates the simulation error of evacuation time, $error(T)$, and the percentage of evacuees leaving from exits, $error(P)$. The $error(T)$ under low urgency, as shown in Figure 8a, in the CE-SF model, except for C7, fluctuates at the $error(T)$ of the UF-SF model, i.e., 0.1. The $error(T)$ under high urgency in the CE-SF model is larger than that in the UF-SF model. However, under both levels of urgency, the $error(P)$ (see Figure 8b) of the

CE-SF model is significantly smaller than that of the UF-SF model. To further investigate the differences between the UF-SF and CE-SF models, the scenario of C1 is selected for additional analysis, due to its commendable performance in both $error(T)$ and $error(P)$.

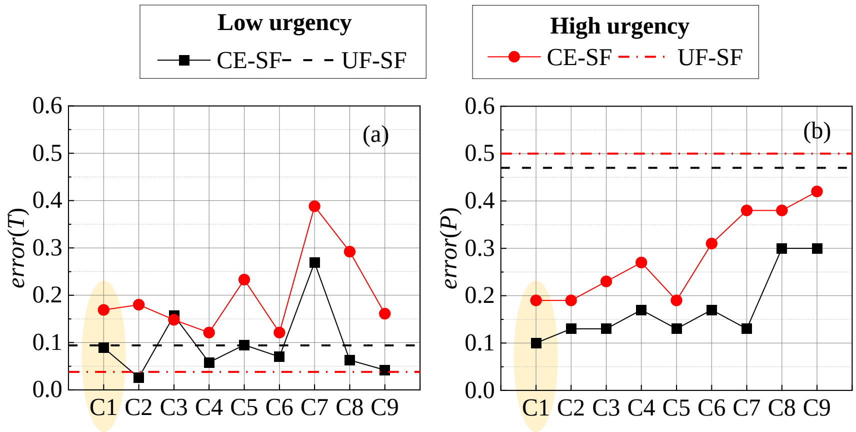

Figure 8. The simulation error of (**a**) total evacuation time $error(T)$ and (**b**) percentage of evacuees leaving from exits $error(P)$ in the different scenarios of CE-SF model, i.e., C1–C9. The scenario of C1 in the yellow oval is selected for further study.

4.2.2. Different Percentages of Evacuees Affected by Context Effect

To further investigate the influence of context effects on our proposed exit choice model, some evacuees were designated to adhere to the CE-SF model while others followed the UF-SF model. Three simulation scenarios were conducted, where different percentages of evacuees (i.e., 100%, 80%, and 60%) adhered to the CE-SF model, denoted as CE-SF_100%, CE-SF_80%, and CE-SF_60%, respectively, while the remaining evacuees followed the UF-SF model, which adopted the parameters of C1.

Figure 9 presents a comparison of movement trajectories between the experimental data and simulations. In both low- and high-urgency scenarios of the experiment, evacuees were observed entering the room from Entrance I and exiting from Exit C, as depicted by the arrow of the moving direction in Figure 9a,g. Notably, this phenomenon was effectively simulated by the CE-SF model across various scenarios, irrespective of the percentage of evacuees influenced by the context effects (see Figure 9d–f for low urgency and Figure 9j–l for high urgency). However, this observed behaviour was notably absent in simulations conducted using the SF model with the shortest path (Shortest) or the UF-SF model, as evidenced in Figure 9b,c,h,i. Additionally, the experimental observations revealed instances of exit choice-changing behaviour, particularly notable in scenarios characterised by high urgency (see Figure 9g). In contrast, simulations utilising the Shortest or UF-SF models exhibited rare instances of exit choice alteration (see Figure 9b,c,h,i). Impressively, our proposed CE-SF model successfully replicated this observed decision-changing behaviour across various scenarios, regardless of the percentage of evacuees influenced by the context effects. Notably, the scenario where 80% of evacuees adhered to the CE-SF model demonstrated the highest fidelity in simulating exit choice-changing behaviour. The CE-SF model exhibits remarkable flexibility in modelling both exit choice behaviour and exit choice-changing behaviour, which has been observed in numerous empirical studies [76–79].

Moreover, Figure 10 shows that the number of evacuees leaving from exits over time in the three scenarios of the CE-SF model is much more consistent with the experimental data compared to that from the Shortest and UF-SF models. Although the errors in evacuation time for the UF-SF and Shortest are smaller than those in the CE-SF model (still less than 0.3), as shown in Figure 11a, the errors in the percentage of evacuees leaving from exits in the UF-SF and Shortest models are much larger than those in the CE-SF model, as depicted in Figure 11b.

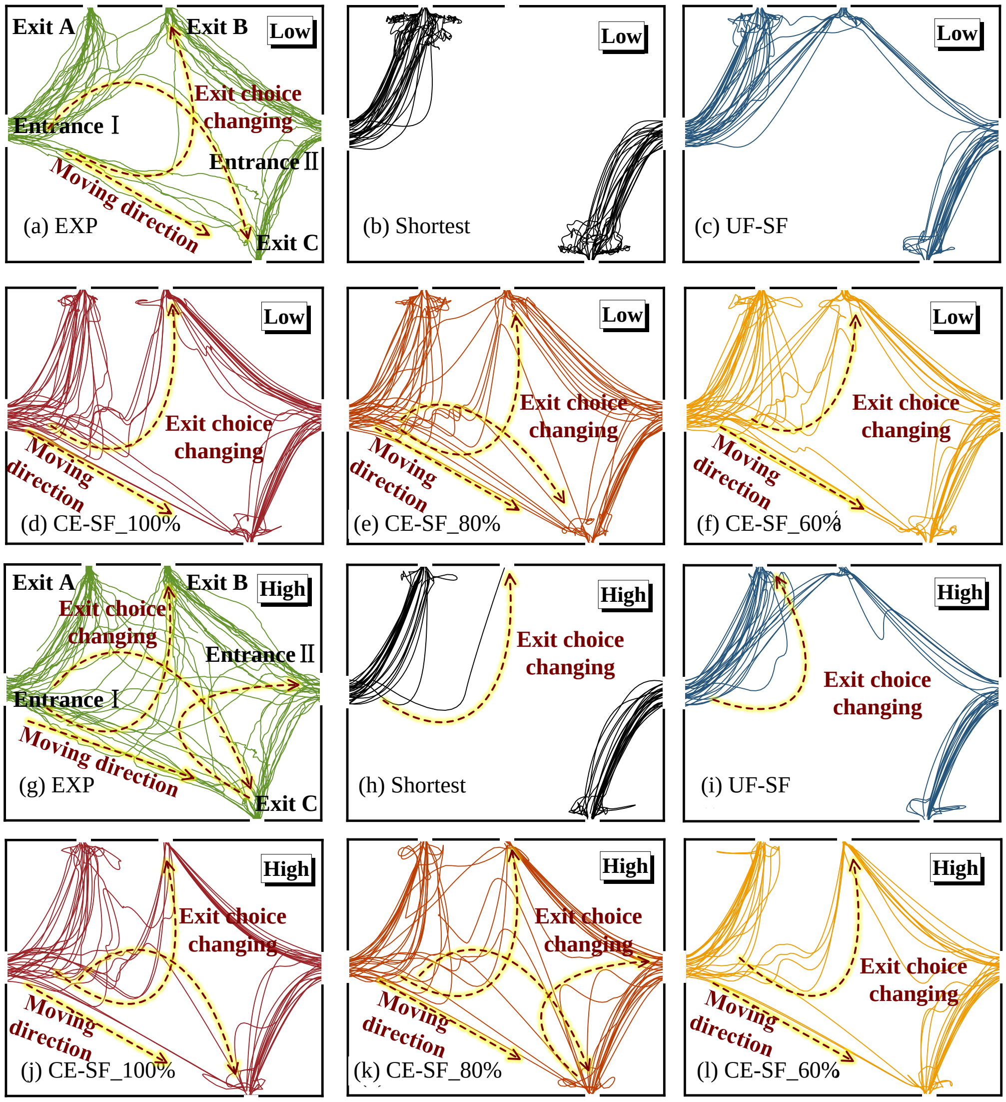

Figure 9. The movement trajectories of evacuees are depicted in the following scenarios: (**a**,**g**) experiment (EXP); (**b**,**h**) SF model using the shortest path (Shortest); (**c**,**i**) UF-SF model; and (**d**–**f**,**j**–**l**) CE-SF model with varying percentages of context effect under low urgency (**a**–**f**) and high urgency (**g**–**l**).

4.3. Evidenceof Context Effects in Experimental Data

The coordinates of each participant in the room for each frame were obtained using PeTrack software (version v0.9) from the experimental video (see Section 3.1 for more details), facilitating the extraction of exit k attributes, i.e., d_k and n_k. Subsequently, Equations (6) and (7) were employed to determine whether exit choice is influenced by the context effects or not. The parameter pairs in Equations (6) and (7) are given by the scenario of C1: $d_{\text{sim}} = 2$ m, $n_{\text{sim}} = 3$ ped, $d_{\text{inf}} = 1.5$ m, and $n_{\text{inf}} = 2$ ped. Finally, the cumulative occurrences of occurrences in the context effects are computed and shown in Figure 12. All three context effects—the compromise effect, similarity effect, and attraction effect—were observed in the experiment under both low and high urgency levels. Notably, the similarity effect occurred more frequently than the compromise and attraction effects.

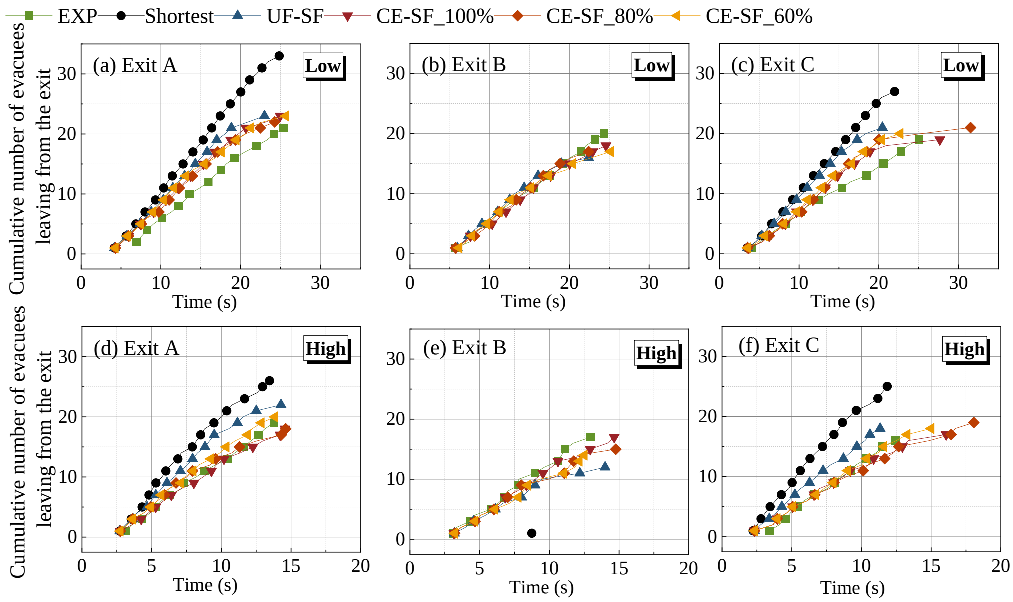

Figure 10. The number of evacuees leaving from Exit A, i.e., (**a**,**d**); Exit B, i.e., (**b**,**e**); and Exit C, i.e., (**c**,**f**) under low urgency (**a**–**c**) and high urgency (**d**–**f**) in the CE-SF model with different percentages of context effects.

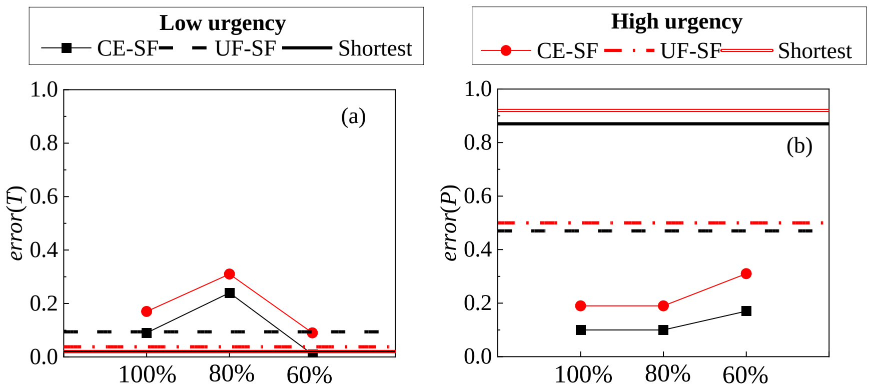

Figure 11. The simulation error of (**a**) total evacuation time $error(T)$ and (**b**) percentage of evacuees leaving from exits $error(P)$ in the different scenarios of the CE-SF model, i.e., 100%–60%.

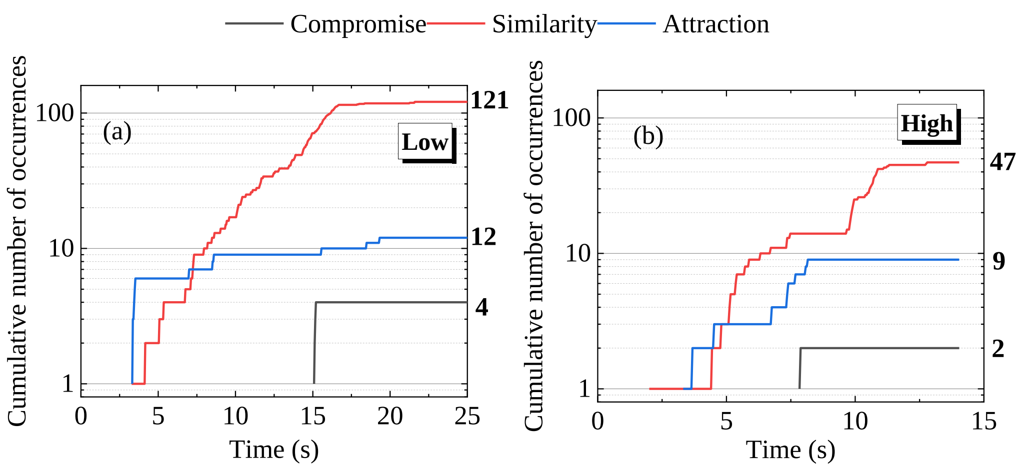

Figure 12. Cumulative number of evacuees affected by context effects in experimental data [16] under (**a**) low urgency and (**b**) high urgency.

5. Discussion

The simulation results in the UF-SF model (see Section 4.1) reveal that the traditional utility function model, relying solely on a monotonic function of the attribute value, fails to accurately mimic real exit choice behaviour. Previous studies [24,37,80] have demonstrated that the simple scalability property, fundamental to most utility models, inadequately accounts for the three context effects commonly observed in multialternative and multiattribute decision-making tasks. Moreover, significant evidence of context effects emerged in evacuation experiments under varying urgency levels (see Section 4.3). This evidence elucidates why our CE-SF model outperforms the original exit choice model, i.e., the UF-SF model, in replicating exit choice behaviour. However, errors persist in movement trajectories and evacuation time during CE-SF simulations. These errors can be mitigated by reducing the percentage of evacuees affected by context effects to 80% (see Section 4.2.2). As illustrated in the previous studies [80,81], the context effects change the probabilities of the same option across different choice sets. Nonetheless, the maximum or an increase in the probability of an option does not guarantee the final choice. Thus, it is reasonable to assume that not all individuals adhere to context effects when making decisions.

6. Conclusions and Limitations

Exit choice behaviour under varying levels of urgency was investigated by integrating context effects into a social force model (CE-SF). The capability of the CE-SF model was validated by comparing evacuation time, exit utilities, and movement trajectories with those of a utility-function-based SF model (UF-SF). A sensitivity analysis of the UF-SF model revealed that while the simulated evacuation time aligned well with experimental data across urgency levels, the trajectories and exit utilities exhibited significant discrepancies from the experiment, irrespective of variations in the exit attribute parameters. Despite CE-SF displaying a slightly inferior performance in evacuation time compared to UF-SF, it surpassed UF-SF in terms of trajectory accuracy and exit utilities regardless of the parameter values. The simulation results of CE-SF with different percentages of evacuees influenced by context effects indicated that adjusting the percentage to 80% could enhance trajectory accuracy, albeit leading to a slight increase in the evacuation time error. Furthermore, we provided substantial evidence of three context effects during real evacuation decision making, irrespective of urgency levels.

However, our study has limitations that need addressing in future research. Firstly, we solely explore variations in participant urgency within the same experimental layout. Despite each evacuee facing the same choice set of exits A, B, and C, the properties of each exit (e.g., distance and congestion) differ at each time step. In other words, in the continuous simulations, the evacuees are faced with a different choice set due to the different exit properties at each time step.

Secondly, our study only considers three exits. The definition of context effects necessitates a choice set with three or more options. While most studies [24,35,37,49] on context effects examined a choice set of three options, some researchers [82,83] have observed context effects in choice sets with more than three options. Additionally, a recent study [84] suggested that comparisons between multiple options could be made in pairs before finally being considered together. Another approach to addressing the issue of having more than three exits could involve considering only the three most preferred exits for each evacuee, as it is unlikely for an evacuee to choose exits with low preference levels. Therefore, our findings can be applicable to evacuation scenarios with more than three exits.

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