Evacuation from Cramped Interiors with Aisle Seats: Uncertainty Induced by the Random Choice of Initial Positions

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Abstract Considering evacuation from cramped interiors with aisle seats, the initial seating positions of pedestrians represent a non-negligible source of variance in total evacuation time. By means of Pathfinder simulations, this uncertainty is quantitatively investigated for a train and lecture hall geometry with homogeneous and heterogeneous groups of agents. Furthermore, an energy-inspired description of the occupation configuration is introduced that enables a proper numerical representation of the configuration space of the initial seating positions.

Keywords Uncertainty analysis · evacuation · simulation · agent heterogeneity · initial seating positions · energy-based description

1. Introduction

Microscopic simulations of evacuation from cramped interiors consisting of seats and narrow aisles, such as lecture theatres [1] or various means of transport [2, 3], represent a current challenge that becomes even more complex when the crowd heterogeneity is to be appropriately mimicked. As recent studies indicated [4, 5], the heterogeneity of the crowd is an essential aspect that affects the evacuation process. Special attention was paid to different types of heterogeneity in movement abilities [6, 7], interaction processes [8, 9], and social relationships and groups in the crowd [10, 11]. It was also shown that crowd heterogeneity can lead to various seating preferences and configurations [12, 13].

As described in [14], the variation in the initial positions of the individual occupants in a cramped interior layout may represent a significant source of randomness in their evacuation processes. This study aims to quantify the uncertainty caused by such variation in the initial seating positions of the occupants, considering two main aspects: distribution of unoccupied seats and positions occupied by pedestrians of different types in a heterogeneous crowd. It explores how to describe a configuration of initial positions in a way that enables a proper representation of the initial configuration space and thus allows quantification of the impact of initial seating positions on total evacuation time (TET) by means of sensitivity analysis [15, 16]. Inspired by the social force model [17, 18], we introduce two macroscopic measures that describe the properties of a given configuration of initial positions determined by the values of artificial potential and interaction energy.

2. Simulation Setting

The simulation study presented was performed using the Pathfinder simulator [19] and focused on two different cramped layouts: a train and a lecture hall (Fig. 1). The train geometry is related to an experiment conducted in June 2018 that is further described in [2] and represents one-half of a double-deck rail car with a capacity of 67 seats. The model of the lecture hall corresponds to an experiment in a university auditorium with a capacity of 73 seats carried out in June 2023.

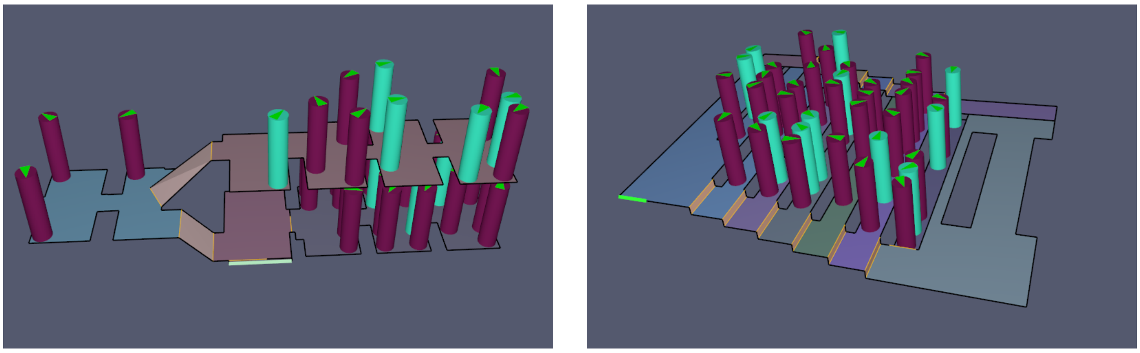

Figure 1 Pathfinder model of the investigated train (left) and lecture hall (right) geometry.

To filter out the effect of randomness in agent parameters and thus increase the readability and interpretability of the results, two types of agents with fixed movement parameters were considered in a simplified set of agent parameters. The *Able-bodied* (AB) agents represented pedestrians without movement limitations using Pathfinder default settings, that is, a maximum velocity of 1.2 m/s, an acceleration time of 1.0 s, and a diameter of 0.45 m. The agents *With-limitations* (WL) mimicked pedestrians with any movement disabilities simulated by a lower maximum velocity of 0.8 m/s, a longer acceleration time of 1.5 s, and a diameter of 0.55 m reflecting the larger space requirement induced by balancing, *Homogeneous* (HOM) group of agents means that the simulated crowd consists only of AB agents. *Heterogeneous* crowd consists of a mixture of AB agents and WL agents.

To test the effects of initial seating positions under different facility loads, several occupancy levels were considered. In the HOM scenarios, the occupancy level was represented by a ratio of seats occupied to full seating capacity (70%, 80%, 90%). In the HET scenarios, the level was given by a ratio of WL agents to AB agents in a fully occupied facility (20%, 30%, 40%). For comparison, a *control* (CTRL) scenario represented by a facility fully occupied by AB agents only (100% HOM and 0% HET simultaneously). Altogether, each simulation scenario in this study is defined by a triplet: Geometry (train/lecture hall), Group (HOM/HET/CTRL), and Ratio as described in the previous paragraphs.

3. Uncertainty in Total Evacuation Time

Due to the simplified simulation settings described above, the uncertainty in TET for each scenario is induced by two factors: 1) the *inherent randomness* of the model represented by random parameters intrinsic in Pathfinder simulator (like initial orientation of agents or internal priority level), 2) the *occupation configuration* represented by positions initially occupied by AB agents in HOM scenarios and by WL agents in HET scenarios. Although the effects of inherent randomness can be filtered out by averaging multiple runs, it is important to know how much information may be lost and whether the effect of initial positions is actually more significant than the inherent randomness of the model.

Quantitative comparison of these two sources of uncertainty in TET can be performed by means of the Law of Total Variance. Given fixed agent parameters, a part of the total variance in TET can be attributed to the variation of occupation configuration (referred to as explained variance – VE). The remaining can be attributed to the inherent randomness (referred to as unexplained variance – VU). The Law of Total Variance reads

$$\underbrace{\mathrm{Var}(\mathrm{TET})}_{\text{Total variance}} = \underbrace{\mathrm{Var}\left(\mathbb{E}[\mathrm{TET} \mid C]\right)}_{\text{Explained variance}} + \underbrace{\mathbb{E}\left[\mathrm{Var}(\mathrm{TET} \mid C)\right]}_{\text{Unexplained variance}}, \tag{1}$$

where C is a random variable with range in the possible occupation configurations space.

The explained and unexplained variances were estimated using Pathfinder simulations. For each scenario, 92 occupation configurations were randomly sampled. The simulation for each configuration was performed 10 times with randomly generated internal random seeds to address the inherent randomness. These numbers were chosen as a compromise between computational time and accuracy. A short convergence analysis is given in the supplementary material [20]. More details on the random generation of occupation configurations and internal random seeds can be found in [14] and [21]. The results of the simulations are shown in Tab. 1. The following observations can be drawn from the estimated values of the explained and unexplained variances.

The total variance of the control scenario (CTRL) was the lowest of all scenarios in both geometries. Therefore, the presence of empty seats (HOM scenarios) or WL agents (HET scenarios) was an important source of variance. The variance explained by the occupation configuration was non-negligible in all non-CTRL scenarios. Moreover, in HET lecture hall scenarios and HOM train scenarios, the explained variance even prevailed the unexplained variance attributed to inherent randomness.

In lecture hall scenarios, the variation of the positions of AB agents in HOM scenarios did not cause a significant increase in the total variance of the TET, while the variation of the initial positions of WL agents in HET scenarios contributed significantly to the increase of the total variance in the TET. On the contrary, in train scenarios, the variance explained by the initial positions of AB agents in HOM scenarios was significant compared to the low uncertainty attributed to the positions of WL agents in the fully occupied HET scenario.

Table 1 Uncertainty study (Sec. 3): $\overline{\mathrm{TET}}$ – estimated mean TET; $\sigma_{\mathrm{TET}} = \sqrt{\mathrm{Var(TET)}}$ – estimated standard deviation of TET; VU, VE – explained and unexplained variance, respectively (in percent of Var(TET)). Estimated standardized coefficients of the TET-energy linear model described in Eq. 4 from Sec. 4.

Scenario			Uncertainty			Energy		
Geom.	Group	Ratio	$\overline{\mathrm{TET}} \pm \sigma_{\mathrm{TET}}$ [s]	VE [%]	VU [%]	R^2	α_U^*	α_I^*
L. hall	HOM	0.7	48.36 ± 1.84	56.91	43.09	0.63	0.67	0.45
L. hall	HOM	0.8	54.42 ± 1.68	36.46	63.54	0.44	0.59	0.29
L. hall	HOM	0.9	61.47 ± 1.59	15.78	84.22	0.10	0.28	0.16
L. hall	CTRL	–	67.78 ± 1.45	0.00	100.00	–	–	–
L. hall	HET	0.2	79.13 ± 2.77	52.36	47.64	0.94	0.94	0.11
L. hall	HET	0.3	83.90 ± 3.22	64.96	35.04	0.90	0.92	0.13
L. hall	HET	0.4	89.75 ± 3.52	63.79	36.21	0.76	0.82	0.13
Train	HOM	0.7	40.95 ± 3.97	85.94	14.06	0.84	0.90	0.06
Train	HOM	0.8	46.35 ± 3.25	73.72	26.28	0.88	0.93	0.05
Train	HOM	0.9	51.47 ± 2.41	48.57	51.43	0.89	0.93	0.05
Train	CTRL	–	57.30 ± 2.08	0.00	100.00	–	–	–
Train	HET	0.2	68.39 ± 3.30	45.14	54.86	0.59	0.84	–0.29
Train	HET	0.3	73.71 ± 3.35	36.44	63.56	0.54	0.81	–0.33
Train	HET	0.4	78.84 ± 3.60	31.68	68.32	0.57	0.80	–0.38

4. Energy of Occupation Configuration

As mentioned above, occupation configurations had a significant impact on TET in some scenarios. It may be therefore desirable to quantitatively compare such an impact with the influence of other investigated quantities/parameters (e.g. door width or agent velocity) by means of sensitivity analysis. Most common tools of sensitivity analysis require a numerical representation of the investigated quantities that allows a proper sampling of the parametric space. This section introduces a physics-inspired approach of numerical representation of occupation configuration.

For a given occupation configuration C, a tuple of potential energy $U(C)$ and interaction energy $I(C)$ is defined. Let us denote by $r(C)$ the set of positions occupied by AB agents in the HOM scenarios and the set of positions occupied by WL agents in the HET scenarios, respectively. The potential energy is then defined by

$$U(C) = \sum_{\boldsymbol{x} \in r(C)} u(\boldsymbol{x}), \quad \text{with} \quad u(\boldsymbol{x}) = d(\boldsymbol{x}, \text{exit})^2, \tag{2}$$

where d is some distance metric and exit is the location of the exit point. The interaction energy is defined by

$$I(C) = \sum_{\boldsymbol{x} \in r(C)} i(\boldsymbol{x}), \quad \text{with} \quad i(\boldsymbol{x}) = \sum_{\boldsymbol{y} \in \text{kNN}(C, \boldsymbol{x})} \exp\{-2d(\boldsymbol{x}, \boldsymbol{y})\}, \tag{3}$$

where $\text{kNN}(C, \boldsymbol{x})$ are the k nearest neighbors of $\boldsymbol{x}$ in $r(C)$ ($k = 8$ was used in our analysis). Thus, low potential energy U means that the relevant agents (all in HOM and WL in HET) are close to the exit and high energy U means that they are far from the exit. Similarly, high interaction energy I means that the relevant agents are somehow clustered and low interaction energy means that they are spread uniformly in the facility. It is important to note that the two energies are not independent. A uniform spread of agents (low I) prevents the potential energy U from extreme values. Similarly, low U (all agents close to exit) is accompanied by high interaction energy I. A situation with strong non-linear dependence between U and I is depicted in Potential-Interaction energy diagram in Fig. 2.

An important factor in both definitions is the choice of the distance metric, which should reflect the cramped interior with aisle seats. In this paper, we used an ad-hoc distance corresponding to the real-life walking distance in a given geometry.

To estimate the relative influence of the individual energies on the TET, the simulated data were fitted by a linear model of the form

$$\text{TET} = \alpha_U \cdot U + \alpha_I \cdot I + \varepsilon, \tag{4}$$

where ε is the noise term with $\mathbb{E}[\varepsilon] = 0$. Since we focused solely on the effects of initial seating positions, the inherent randomness of the model was averaged out before the fitting. The resulting values of standardized coefficients α_U^* and α_I^*, as well as the overall R^2 of the fit, are presented in Tab. 1. Based on these values, the following observations can be drawn.

From the R^2 values we may conclude that the train and lecture hall scenarios are essentially different regarding the predictability of the TET by means of the introduced energies. Whereas in lecture hall scenarios, the model Eq. 4 seems to predict the TET well in the HET scenarios ($R^2 \approx 0.9$) and poorly in the HOM scenarios ($R^2 \leq 0.63$), in train scenarios it is exactly opposite: R^2 is above 0.8 in the HOM and below 0.6 in the HET scenarios. This may be interpreted in the way that in the train environment a higher impact on the TET can be attributed to the agent positions (upper, middle, or lower deck) rather than to their type, whereas in lecture hall scenarios the positions of WL agents were more important than the distribution of empty positions.

We can further notice in Tab. 1 that the low R^2 values are accompanied by low percentages of explained variance VE (e.g. in the lecture hall HOM 0.9 scenario), which can indicate that the poor performance of model in Eq. 4 was caused by a low impact of the occupation configuration on TET rather than an improper description of the configuration by means of the energies. This conclusion is supported by the Predicted TET - Actual TET diagrams in the supplementary material [20].

In all scenarios simulated in this study, the potential energy outperformed the interaction energy as $|\bar{\alpha}_U| > |\bar{\alpha}_I|$ and is deemed to be the dominant predictor of the two presented energies. This finding is also illustrated by Potential Energy–TET diagram in Fig. 2 and other diagrams provided in the supplementary material [20]. Additionally, except for the train HET scenarios, the interaction energy contributed with a positive coefficient α_I, indicating that the TET increased as the occupants were closer together. In the train HET scenarios, negative α_I indicated that tighter clustering of WL agents lead to lower TET. However, due to the above discussed dependence of energies U and I, this interpretation must be handled carefully.

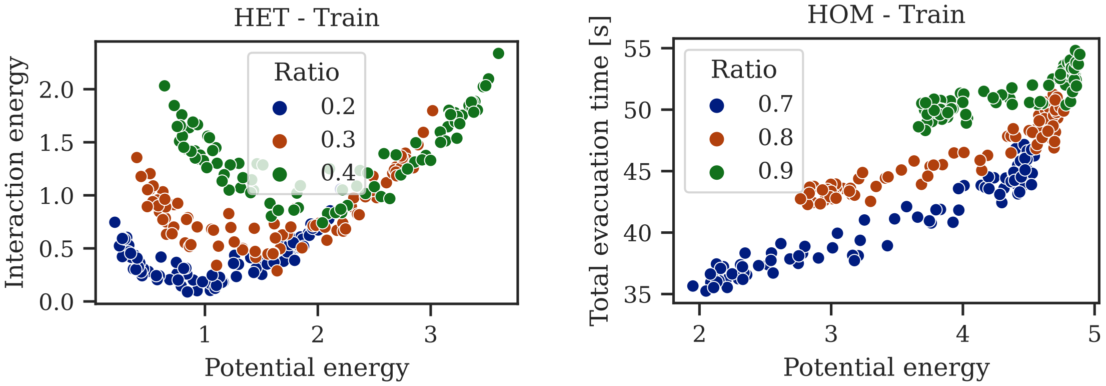

Figure 2 Potential-Interaction energy diagram (left) and Potential Energy–TET diagram (right).

5. Conclusion

This study aimed to quantify the influence of initial seating positions on evacuation from cramped interior layouts by means of Pathfinder simulations. The uncertainty in TET was explored with the conclusion that the variance in initial seating positions contributed significantly to the variance in TET. Furthermore, the artificial potential and interaction energies of the initial seating positions were introduced as numerical descriptors of the occupation configuration. The simulation study showed that the concept presented is reasonable, as these energies are strong predictors of TET in scenarios with high variance induced by initial seating positions.

However, a broader interpretation of the results must be considered limited to the simplified agent parameter settings used in the simulations. The significance of initial seating positions and energies indicated in the presented analysis needs to be further studied in the full context of crowd heterogeneity, and the relevance of this phenomenon outside cramped interior layouts should be deemed worth of further investigations.

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A. Supplementary material

Supplementary material [20] are available on the Collective Dynamics website and include:

- `supplementary.pdf` (Comments on number of simulation runs leading to Tab. 1 and additional graphs completing the graphs in Fig. 2),
- `data_content.csv` (Data necessary for reproduction of the graphs),
- `data_description.txt` (Description of the provided data).