Developments in the Built Environment 23 (2025) 100698

Contents lists available at ScienceDirect

Developments in the Built Environment

journal homepage: www.sciencedirect.com/journal/developments-in-the-built-environment

Towards safer educational Facilities: Computational and observational analysis of evacuation processes in primary schools

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ARTICLE INFO

Keywords:
Evacuation time
School design
Evacuation behaviour
Children's safety
Educational facilities

ABSTRACT

Unlike adult or mixed-age studies, this research examines how young children's limited spatial awareness, evolving risk perception, and reliance on adults influence their evacuation choices and timing under varied signage, guidance, layouts, and visibility. Combining RReliefF feature selection with two machine learning frameworks and inferential tests, we used a unique CCTV-based dataset of 742 six-to-seven-year-olds from ten real-world drills to determine the most important predictors. The study reveals that school corridors are the most critical place affecting the children's evacuation process. Teacher presence in both classrooms and corridors significantly accelerates response times, while seating location affects students' exit choices from the classroom, and visibility is crucial in corridor evacuation time and exit selection. By providing practical suggestions, customised training, design modifications, and staff drills to enhance school evacuation safety, the study fills a vital gap in emergency-response literature and lays the groundwork for future research to refine these strategies further.

1. Introduction

The human social system is intrinsically complex: countless interrelated factors shape how people perceive and respond to the world around them, and this complexity becomes even more pronounced under stress. During an emergency, individuals placed in comparable circumstances often react very differently. In addition to personal and cultural traits (Rohli et al., 2018; Y. Yang et al., 2019), people's previous emergency experiences (Ionescu et al., 2021), their interactions with others (Y. Yang et al., 2019; Nogami, 2022), and their emotional states (Mohajeri and Mirbaha, 2021) all influence coping strategies. Moreover, evacuation motivations and intentions further shape behaviour in critical moments (Kakimoto and Yoshida, 2022). Information sources and environmental cues also play decisive roles. The way emergency alerts are communicated—whether through official channels, social media, or word of mouth—can alter response patterns (Zheng et al., 2020; Elzie et al., 2016; Alam et al., 2023). Equally important are the presence of authority figures or guides (Guo et al., 2021; von Schantz and Ehtamo, 2022) and the design of graphical evacuation signage (J. Shi et al., 2022; Ding, 2020a), all of which steer people's actions during emergencies. However, the built environment itself profoundly shapes spatial cognition in emergencies. Exit layouts (Liu et al., 2016; X. Shi et al., 2022; Najmanová and Ronchi, 2017), physical obstacles (Ionescu et al., 2021), visual conditions (Xie et al., 2020; Liu et al., 2019), and even staircase design (Najmanová and Ronchi, 2023) can speed up or slow down escape, depending on how intuitively they guide evacuees.

Risk perception and decision-making mechanisms also critically shape how individuals assess the situation and determine their course of action (Alam et al., 2023; Huang et al., 2012). In this regard, children's risk assessments are significantly distinct from adults' since this vulnerable group remains developing their cognitive and perceptual abilities and frequently underestimates the severity of hazards (Lassa et al., 2025). However, it is crucial to acknowledge the evident gap in research focus, with a predominant concentration on adult emergency behaviour and spatial cognition, whereas children's emergency behaviour receives comparably less attention (Sun et al., 2024). Children's behaviour during evacuations is distinct from that of adults because they often have different cognitive abilities, attention spans, and emotional responses. Due to their immature coping mechanisms and lack of awareness of the hazards, children will continue to depend on adults for help in times of emergency (Save the Children. Foundation for Sustainable Parks and Recreation, 2015; Jin and Zhao, 2021).

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https://doi.org/10.1016/j.dibe.2025.100698
Received 15 February 2025; Received in revised form 12 June 2025; Accepted 23 June 2025
Available online 27 June 2025

These distinct differences and vulnerabilities necessitate a further in-depth evaluation of children's emergency evacuation behaviour. Such studies can also provide realistic data that considers the human social system and provide better-fit data for future evacuation models. Therefore, this study delved into "evacuation choice and time of primary school children at schools". More specifically, the study aims to understand the impact of adults' guidance and evacuation signage systems on both wayfinding and evacuation time and evaluate the differences in evacuation efficiency in good and low visibility situations. This study also assessed the impact of the number of exits and the distance to exits on evacuation time and behaviour. The research team conducted ten evacuation drills, starting from the classrooms and ending once all the students reached the playground. Twelve CCTV cameras installed in the selected classrooms and corridors have recorded the evacuation drills. The data from the recorded drills have been extracted and analysed through various statistical methods to answer the research questions mentioned above. Doing so, this work presents key innovations: (1) a CCTV-based observational dataset of 6–7-year-olds during ten controlled evacuation drills under varying visibility and guidance conditions; (2) dual machine-learning analyses identifying unique predictor sets in classroom and corridor environments; (3) comparing classroom vs. corridor dynamics, revealing how factors contribute differently to evacuation time and choice, and (4) conversion of data-driven insights into practical design and training recommendations for school safety. The remainder of the paper is as follows: Related studies on children's emergency evaluation are given in Section 2. Section 3 describes the experiments' setup and data processing, while empirical results and discussions are provided in Section 4. The paper will end by delving into the main findings and the study's limitations in Section 5.

2. Related research background

In response to rising hazards, schools must rely on a comprehensive, multilayered safety framework to guarantee effective preparedness and response. The Comprehensive School Safety Framework (CSSF) is a globally acknowledged model founded on three pillars: safe learning facilities, school disaster management, and risk reduction and resilience education. Its objective is to protect children, staff, and educational infrastructure from the effects of disasters (United Nations Children's Fund, 2022). Researchers have applied these principles in diverse contexts. For example, J. J. Wang (2020) used the CSSF to guide the immediate reconstruction of Taiwanese schools after the 1999 Chi-Chi earthquake, while Cariño and Garciano (2020) developed the Seismic Evacuation Safety Index (SEI) into a web-based tool now adopted by Philippine schools to bolster earthquake preparedness (J. J. Wang, 2020; Cariño and Garciano, 2020).

To build safer educational institutions, one needs to understand not only institutional frameworks but also children's distinct psychological and physical characteristics. Research on demographics and self-reported emergency behaviours has traditionally relied on survey-based techniques, such as interviews and questionnaires (Shoji et al., 2020; Wei et al., 2021; Xenidis and Georgia, 2022; Gómez, 2013), though they demand careful design and plain, age-appropriate language (Bell, 2014). Simulation and modelling offer powerful means to predict evacuation patterns, but their validity hinges on high-quality, real-world data, which remains scarce in the case of children, given the literature's adult focus. This gap highlights the call by Masten and Osofsky (2010) for evidence-based, child-centred disaster interventions.

Observation, through experimental drills or video analysis, fills some of that gap by capturing actual behaviour in controlled settings illustrating (S. Li et al., 2018; C. Chen et al., 2022; Gu et al., 2016; Q. Wang et al., 2020; Xie et al., 2020). While participants may alter their behaviour when they know they are being watched (Gwynne et al., 2020), observational studies remain the most grounded approach to account for social complexity. Nevertheless, empirical studies on children's evacuation through observation remain scarce (Bahmani et al., 2023), possibly because of ethical and safety considerations during drills. Where present, distinct patterns emerge: gender and BMI impact speed in middle school students (Q. Wang et al., 2020); body diameter influences egress times, corroborating findings by Poulos et al. (2018), and age consistently correlates with both horizontal and vertical movement speeds (Hamilton et al., 2020; Hashempour et al., 2024; Yao and Lu, 2020). Mixed-age groups, conversely, tend to slow overall evacuations (Yao et al., 2023), and although children under 12 generally move more slowly than adults, by age 12, their pace approximates that of grown-ups (Larusdottir, 2014). Larusdottir also revealed that younger kids are more prone to hold hands and take longer to start evacuating; nonetheless, organised training can significantly lower these pre-evacuation delays and enhance general egress timings (Larusdottir, 2014; Hashempour et al., 2024). Children with intellectual disabilities have a greater demand for individualised direction (Zhao et al., 2024), highlighting the significance of maintaining optimal adult-to-child ratios and using suitable guidance techniques (Li et al., 2025).

Finally, the physical layout of school buildings exerts a powerful influence on evacuation efficiency. Structural earthquake damage, as illustrated in simulations of a rural Chinese school accounting for pupils aged 6–12 years, can dramatically slow down egress, highlighting the need for life-saving measures when evacuation windows narrow (Xiao et al., 2017). Children aged 3–7 escape faster in familiar locations (Najmanová and Ronchi, 2023), and proximity to exits, staircase geometry, or various egress options can minimise evacuation time and increase speed (Najmanová and Ronchi, 2017; Hamilton et al., 2020). Studies have also demonstrated that classrooms with two exits and adding additional exits in corridors reduce the time required for evacuation, thereby enhancing overall efficiency (Runjiao Liu, Jiang, and Shi, 2016; Ionescu et al., 2021). Yet retrofitting existing schools to add exits or widen staircases is often impractical due to the large expenditures and operational disruptions they entail. In these situations, real-time adult supervision becomes a reasonably affordable safety strategy through pre-emergency training or direct guidance during an emergency. Guided evacuations significantly enhance results, according to experimental studies including 52 youngsters throughout 12 drills (L. Chen et al., 2018a, 2022).

Taken together, this body of work underscores the need for research that combines rigorous, observational data with practical interventions, especially in primary school settings where children's vulnerabilities and environmental constraints intersect most sharply. Our study builds on these insights to evaluate how visibility, signage, guidance, and facility design jointly shape evacuation choice and timing for 6–7-year-olds in real-world drills.

3. Experiments and research methodology

3.1. Experiment setups and prepration

This research expands upon the experimental framework established in our last research paper (Bahmani et al., 2024), whereby ten evacuation exercises were executed on April 23, 2023, at the Affiliated Primary School of Chengdu University of Technology. A total of 783 pupils from first and second classes, aged 6 to 7 (four groups of students in grade 1 and seven groups of students in grade 2), participated. The exercises were held in two neighbouring classrooms on the school's first level (as shown in Fig. 1) to ensure safety. Students—already aware of the annual evacuation drills and school layout—participated with their families and the school's consent in scheduled experiments. This study investigates the impact of visual evacuation signs and guidance from adults on children's evacuation behaviour and duration in classrooms and corridors. The research team designed a clear step-by-step plan for evacuation drills' setup, execution, data collection and analysis, and validation of findings and insights, as shown in Fig. 1.

To define the objectives and methods of experiments, the research team conducted meetings and training courses for teachers and staff.

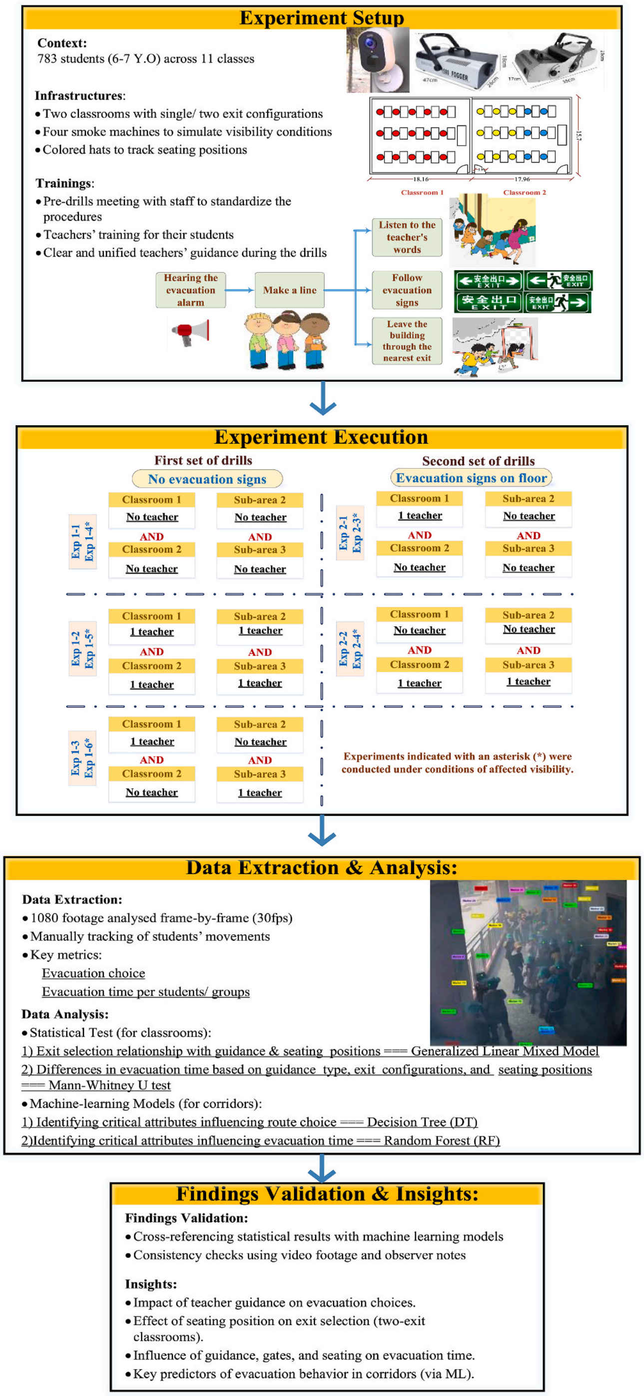

Fig. 1. Study's technical roadmap.

Later, each teacher was in charge of explaining the experiments' procedure to their students. Teachers were requested to stand in designated places behind their desks or at the front of class exits in corridors to guide students during the drills. They all signalled evacuation by raising their right hands and issuing clear orders such as "Leave quickly" and "Go to the playground quickly." Teachers were expressly prevented from guiding pupils to certain exits. In each drill, students were asked to sit randomly at available desks, after which coloured hats were assigned according to the predefined seating-hat scheme. Children sitting in single-gate classrooms wore red hats, and blue/yellow hats were given to those sitting in front/back seats in two-gate classrooms to improve accuracy in data extraction, as shown in Fig. 2.

The experiment was executed in two phases: the initial set of six exercises was performed without graphical signals, while the subsequent set incorporated the signs. The experiments have been conducted in an orderly manner (exp 1-1, 1–2, 1–3) based on their names in Fig. 1 (see "experiment execution") to ensure students have no chance to exchange information. Drills started at 8:30 a.m. and lasted till noon. Except for two groups of students in grade 1 (students' groups 1 and 3) that participated in one distinct experiment, other students' groups participated in two dissimilar drills, with a minimum 1-h gap in between, which minimised the potential learning effect. To guarantee synchrony in the experiments, both classrooms were evacuated simultaneously. The drill finished when every student arrived at the playground. While the team got ready for the following drill and prepared the following group, the first group of students went back to their second-floor classes. 1 walks the readers through the drills' basic information, such as the number of participants, the drills' duration, and the attending groups in each drill.

For the second set of drills, the evacuation signs were placed according to the (National Standard of the People's Republic of China, 2015) and positioned every 9 m along the floor during break time between two sets to ensure that students' awareness would not impact the experiments' consistency. Four smoke machines—two 1500 W and two 3000 W—were positioned at pre-marked locations that affected visibility, as indicated by the flame symbol in the revised Fig. 2. A short predetermined waiting period was applied after activating the smoke machines and before starting the evacuation drills. This allowed sufficient time for the smoke to disperse evenly. Observers then qualitatively verified a constant smoke field at eye and ceiling heights across drills. The settings and positions of all smoke machines were kept constant to ensure the same visibility level across all experiments. New to this experiment, we also aimed to explore the influence of classroom exit configurations by blocking one of the two gates in the classrooms. Twelve full-HD CCTV cameras (1080P) were used for real-time observation and data collection, covering all four sub-areas of the school's corridors (shown by camera symbol in Fig. 2). For more detailed information regarding the experiment setup, including participant training, evacuation procedures, and safety measures, please refer to (Bahmani et al., 2024). Table 1 the readers through the basic information on the drills.

3.2. Data extraction and analysis methodology

According to the video data, the detailed movement characteristics of each child could be extracted. The frame rate of the video was 30 frames per second. We first converted the video into figures to frame by Corel Visio Studio, then manually counted the number of children passing through the classrooms and sub-area gates in each frame. For example, in Experiment 1-1, at the 28th second, six students passed through gate A; therefore, the evacuation time of six pupils equals 28 s.

Afterwards, the cleaned data were analysed to answer the following main questions using statistical tests and supervised learning techniques.

- How does teachers' guidance in the classroom affect the evacuation choice of the students?
- How do primary seating places affect the students' evacuation choice in classrooms with two exits?
- Does teachers' guidance, the number of gates, and the seating place make a difference in classroom evacuation time?
- What are the most critical attributes of evacuation route choice and evacuation time in passages?

The Generalized Linear Mixed Model (GLMM) was employed to determine if there is a relation between evacuation choice and guidance and seating place in the classroom with two gates (Anderson et al., 2009). The Mann–Whitney test, a non-parametric test that is appropriate

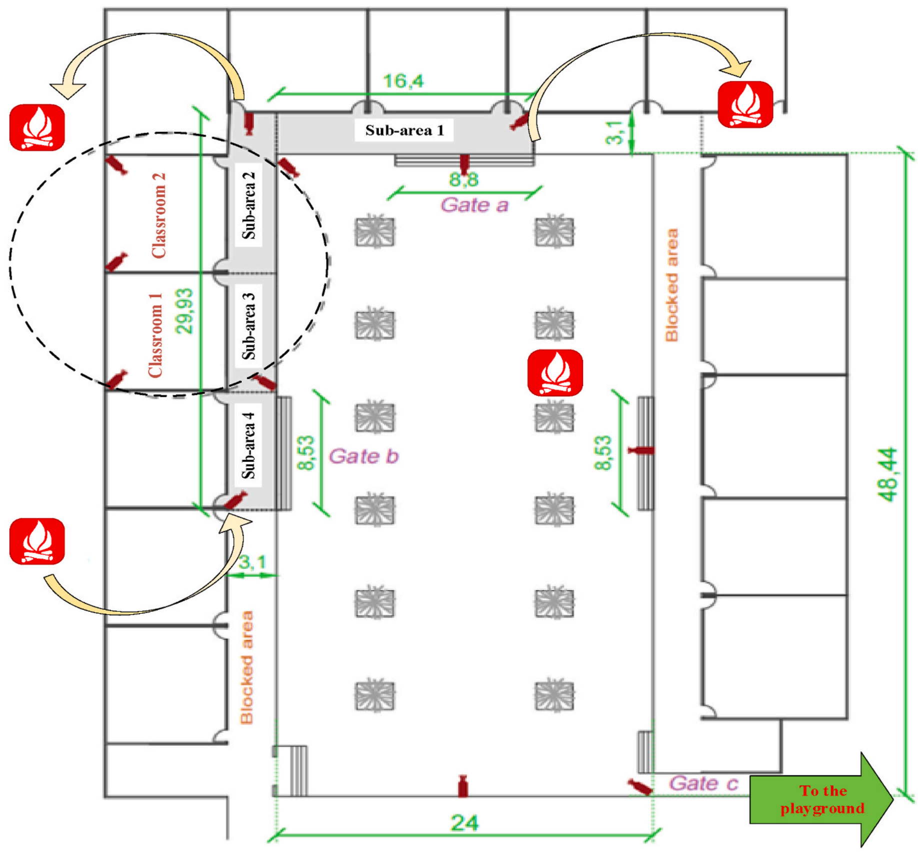

Fig. 2. The school layout.

Table 1
Experiments' basic information.

Experiment	Grade and classes	Number of students	Duration (seconds)
1–1	Grade 1, students' group 4 Grade 2, students' group 1	77	74
1–2	Grade 1, students' group 2 Grade 1, students' group 1	66	46
1–3	Grade 1, students' group 3 Grade 2, students' group 2	62	104
1–4	Grade 2, students' group 4 Grade 2, students' group 6	84	82
1–5	Grade 2, students' group 1 Grade 2, students' group 7	80	37
1–6	Grade 2, students' group 3 Grade 2, students' group 5	86	150
2–1	Grade 1, students' group 2 Grade 2, students' group 2	84	52
2–2	Grade 1, students' group 4 Grade 2, students' group 3	79	55
2–3	Grade 2, students' group 4 Grade 2, students' group 5	86	42
2–4	Grade 2, students' group 6 Grade 2, students' group 7	77	74

for data at an ordinal level that appears to be non-normally distributed, was carried out to determine whether there was a significant difference in evacuation time in corridors considering guidance type, number of gates, and seating place. The last question found an answer using Decision Tree (DT) and Random Forest (RF) algorithms. DT recursively partitions the data into subsets based on the values of the predictor variables to maximise the separation between the classes or minimise the variance of the outcome variable, and they are often used because they are easy to interpret and can handle categorical and continuous predictor variables (Breiman, 2011). On the other hand, RF algorithms combine multiple DTs to improve the accuracy and stability of the model. It works by first randomly selecting a subset of the training data. Then, a subset of features is randomly chosen from the original set of features. A DT is then built using the selected data points and feature subset. This process is repeated multiple times to create a set of DT. Finally, the results of the individual trees are combined to make a final prediction (Breiman, 2001).

4. Results and discussions

4.1. Exit choice in the classroom with two exits and corridors

a) The students' exit choices in the learning space with two gates were subject to being influenced by "their seating place" and "the availability of the teacher's guidance". The study hypothesised that a) seating location and exit gate choice are associated—students seated nearer a particular gate are more likely to exit through that gate, and 2) teacher guidance and exit gate choice are associated—students given guidance choose exits in a pattern that differs from students without guidance. Evacuation behaviour is inherently influenced by complex social interactions and networks, where family, peers, and broader social connections affect individuals' decisions and timing, which may create dependence among observations and violate the strict independence assumption of many classical statistical tests. Such interconnections are an inherent feature of complex social systems and are widely recognized in behavioural science. However, pioneer studies in the field of evacuation behaviour analysis employed statistical tests with the assumption of independence among observations (Feng et al., 2021; L. Chen et al., 2018b; Thakur et al., 2022; Ding, 2020b; Shi et al., 2022; Zhao et al., 2024). This study's observations were independent, as each child's exit choice was recorded independently without duplication in the same drill. However, since the peer effect could possibly impact their evacuation choice, introducing potential non-independence in their decisions, we have employed a GLMM for evacuation decision-making to model clustering effects explicitly. Since the students clustered within 10 evacuation drills, we included random intercepts for each drill, accounting for unmeasured drill-level heterogeneity and ensuring valid statistical inference. The authors additionally monitored the correctness of the model by running assumptions. The plot of residuals versus predicted probabilities for exit choice shows that residuals are generally randomly distributed around zero, with no clear pattern or heteroscedasticity. A few extreme residuals are present at the probability extremes, which is expected in binomial models. The overall pattern indicates a satisfactory model fit and no major violations of GLMM assumptions. Collinearity diagnostics revealed VIF values of 1.006 for both predictors, confirming the absence of problematic multicollinearity between teacher and seat location. Crosstabs showed that all predictor categories included both exit choices, confirming no complete separation in the data. Setting the significance level at 0.05, the model significantly improved fit over the null model ($\chi^2(2) = 68.55$, $p < .001$). As shown in Table 2, seating place had a highly significant effect on exit choice ($\chi^2(1) = 137.08$, $p < .001$), with students seated in the front being approximately 128 times more likely to choose exit 1 compared to those in the back (OR = 128.05, 95 % CI [56.7, 289.18]). Teacher presence did not significantly influence exit choice ($\chi^2(1) = 0.35$, $p = .555$). The random intercept variance for drills was moderate (variance = 3.07, p = .079), indicating some variation in exit choice across drills and supporting the inclusion of drill as a random effect to handle non-independence.[1] These findings confirm the observations by L. Chen et al. (2019). The positive correlation between distance to exit and students' evacuation choice would be due to their daily use of the closest exit, reinforcing it as a habitual exit. Moreover, in emergencies, proximity creates a mental anchor (Tversky and Kahneman, 1975), where closer exits feel safer and more accessible, even if objectively riskier. The lack of observed influence of authority figures on the children's evacuation choice in the classrooms can be further explained by students' perception of teachers as safety controllers rather than exit directors. Moreover, in our experiments, the teachers did not explicitly direct students to specific exits (e.g., saying "Evacuate now!" without specifying a gate), leaving exit choice to student discretion.

b) In the corridors, the students' evacuation choice could be gate A or gate B, and the route choice behaviour was supposed to be predicted by "students' seating place in the classrooms", "visibility", "presence of teachers in the corridors", "teacher's availability in the classroom", and "evacuation graphical signs". The study then applied DT technique to find out the main essential factors affecting children's exit choice in corridors. The original data set was divided into training and test sets to build the DT model using the bootstrapping method to take N samples from the training set. As a result, among 783 instances, 467 sets have been used for training, and the rest used for test sets. Based on the grid search method, the following steps have reached the optimal combination of the three parameters (Claesen and De Moor, 2015). First, we considered at least two instances in leaves, at least five instances in internal nodes, and a maximum depth of 50. The splitting stopped when the majority reached 95 %. Second, the possible combinations were tested, and the model performance was tested by cross-validation by dividing the data into ten folds to show the average over classes and choose the best one. Finally, the DT algorithm found that the model performs best when the tree has 34 nodes and 18 leaves (CA = 0.986, Prec = 0.986).

Next, ReliefF (Urbanowicz et al., 2018) was applied to assess the relevance of features by considering their ability to distinguish instances of different classes and providing the relative importance of predictor variables. The DM model indicates that "seating place", which accounts for 41.0 % of the importance, is the most critical predictor of exit selection in hallways. Evacuation behaviour is also greatly influenced by the "visibility" (17.8 %) and "presence of teachers in the corridors" (17.2 %). Although they have an influence, elements like having "teachers in the classrooms" (11.2 %) and "evacuation graphical signs" (2.8 %) have a smaller role in the students' decision-making process in corridors.

In the next step, the decision rules will be presented in three groups, as shown in Fig. 3, corresponding to the "seating place", which was the most critical variable influencing their exit choice.

- In the first scenario within this category, where ***students are in the classroom with one gate***, visibility emerges as the primary factor influencing their evacuation decisions. When visibility is compromised, all 301 students opt for gate B as their escape route. However, in drills with normal visibility conditions, the presence or absence of a teacher within the classrooms becomes the second critical determinant of route selection for this group. Considering visibility as the most influential indicator for evacuation choice of this group, under good visibility, teachers' instructions confirm the rule of closest gate selection; however, under smoke, cognitive load prevents processing any new cue, including verbal guidance. In low visibility, direct guidance by teachers to physically lead students to the nearest gate in corridors would further optimize the group's suitable exit selection. The DT further illustrates that adult guidance in the hallways and evacuation graphical signage does not significantly contribute to predicting the route choices of those seated in the one-exit classroom. Notably, the DT model effectively predicts all cases within this group.
- For pupils ***seated at the front of the classroom with two exits***, the teacher's presence or absence in the classroom, serving as the initial branch of the decision tree, is the most critical factor in forecasting evacuation behaviour. Exit selection pathways were; a) all the children choose gate A (closest gate to their seating place) when adult guidance is available within the classroom and visibility remains unaffected, b) conversely, in cases involving smoke and having adult's guidance in the classroom, the graphical signage system proves to be a critical predictor of evacuation choices. On the other hand, for those experiments conducted without adult guidance in the classrooms, after the availability of guidance in the passage, graphical evacuation signs is the third substantial factor in predicting evacuation route selection of the children. To wrap up, we observed that for this group, classroom teacher guidance is the primary decision layer (unlike other groups), possibly because of students' closer proximity to the classroom teacher, amplifying their influence. Signs are the least influential factor, while visibility and corridor teachers are equally important. As we reported earlier, this group of students

Table 2
GLMM results.

Model Term	Coefficient (B)	Std. Error	p-value	Exp(B) (Odds Ratio)	95 % CI for Exp (B)
Intercept	−3.103	0.958	0.001	0.045	0.007–0.295
Teacher *(ref. = no)*	0.697	1.179	0.555	2.007	0.198–20.371
Sitting location *(ref. = frontside seats)*	4.852	0.415	<0.001	128.051	56.702–289.181

[1] Notably, the results from the GLMM closely mirrored those obtained from the classical Chi-square test, providing strong evidence that the assumption of independence among observations was upheld. This suggests that potential interconnections among individuals within the social system did not significantly violate the independence assumption in practice.

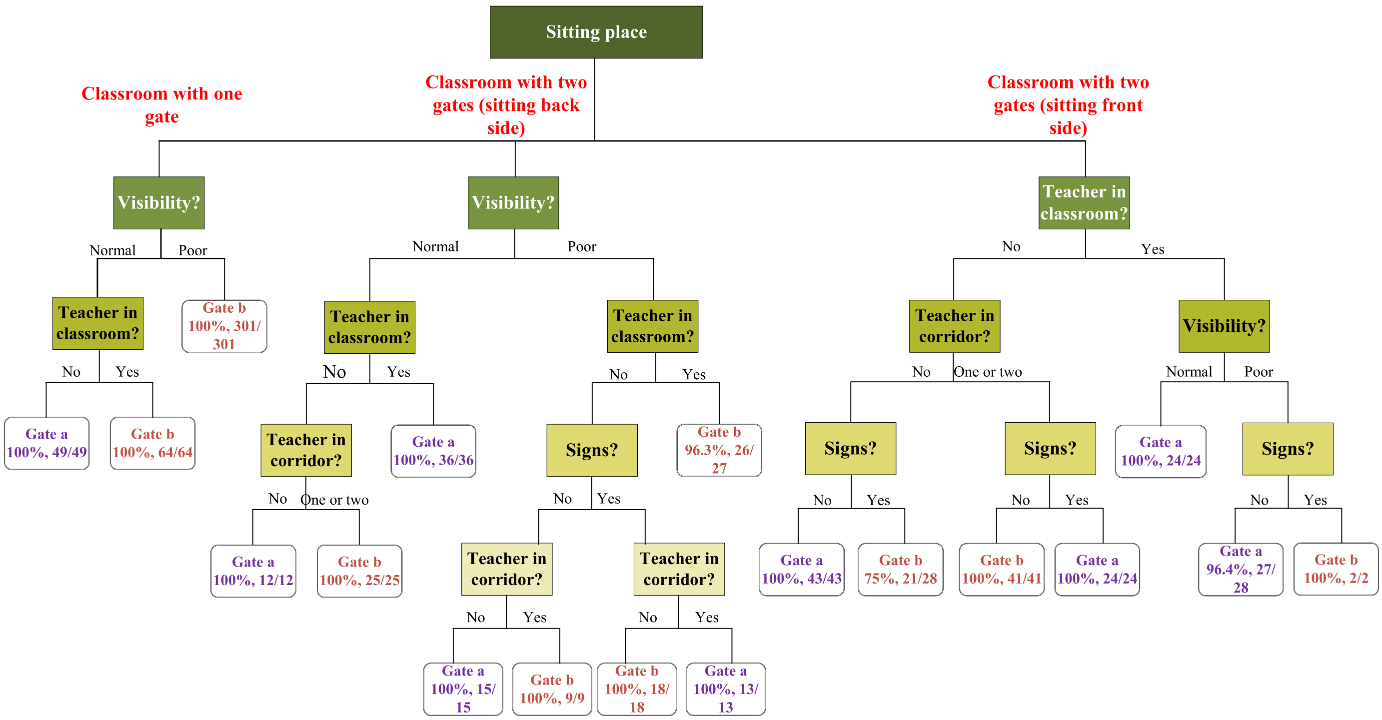

Fig. 3. DT model of exit choice of students.

may distrust signs if they conflict with human guidance in the corridor, necessitating coordination between teachers and signs in the corridors.

- Students ***seated in the back of the classroom with two gates*** formed relatively more complex evacuation decision-making patterns. After visibility, teachers in the classrooms shaped the exit selection of this group; a) Under normal visibility, having adult's guidance in the classroom led all 36 students to uniformly select gate A, the nearest gate to them as their escape route, b) In scenarios without adult guidance in the classroom, all 37 kids picked gate B regardless of having or lacking adult guidance in the hallways. The right section of the decision rule tree of this group illustrated that when visibility was diminished, the presence of a teacher in the classrooms significantly influenced students' route choice selection; a) once teachers were available in the classrooms, 96.3 % of instances selected exit B, b) the absence of adult guidance in the lecture halls then resulted on the dependency of students' exit choice on evacuation signs and teachers' guidance through the corridors: if both visual signs or adult guides in the corridors are absent or when both are present, children reliably select gate A as their escape route. On the other hand, if the DT model reliably predicted that the students would choose gate B as their escape route whenever there were no adult escorts or signs in the passage. Classroom guides seem to have a low impact on selecting the nearest exit for back-seat students, possibly due to their proximity to the students sitting in the back of the classroom. During normal visibility, the exit selection of this group is greatly shaped by the adult guidance in the hallways. In contrast, low visibility disrupts this instinct, forcing reliance on external cues (signs/corridor adults), perhaps due to impaired spatial awareness and stress-induced cognitive narrowing.

4.2. Evacuation time in classrooms and corridors

a) The general perspective of the classrooms' and corridors' evacuation time is provided in Fig. 4. The ***evacuation time in the classroom*** is subject to be influenced by "teacher guidance", "the number of gates", and "the seating place". Except for the last factor, which only applies to the classroom with two exits, the impact of the other first parameters has been evaluated in both classrooms. The normality of the dataset was violated, as skewness and kurtosis were larger than their 1.96 standard errors (ORCAN, 2020). Moreover, the Shapiro–Wilk test also indicated that in some evacuations, the evacuees' evacuation time was not normally distributed (Celik, 2022). We employed the Mann-Whitney test to see if there was any difference between the classroom evacuation times of those groups. The test's statistical significance level (alpha) was set at 0.05, indicating a 95 % confidence level.

Based on the statistical results in Table 3, the classroom evacuation time in the experiments guided by a teacher is significantly higher than those conducted without adults' guidance ($z = -10.981$, p-value $= 0.000$), indicating that the teacher's guidance in the classroom negatively affected the evacuation time. This finding could possibly be due to hesitations from teachers' guidance as they organise, check for stragglers, or give verbal instructions to prioritise ensuring all students exit safely. Secondly, students may also wait for explicit instructions from the teacher instead of acting autonomously, slowing their response time. However, the evacuation time between the other two indexes, the number of gates and seating places, shows no significant difference; therefore, we accept the null hypothesis and conclude that the number of gates and seating places do not make a difference in evacuation time. Lack of statistical association between classroom evacuation time and the number of classroom exits could happen because of students' habit of choosing familiar exits in two-gate classrooms, potentially due to congestion at one gate, negating the benefit of a second exit. Similarly, students' exhibition of herd behaviour during evacuations might override individual proximity advantages. Front-row students may wait for peers or follow the crowd, neutralising their positional benefit.

b) To predict the ***evacuation time in corridors***, we hypothesised that apart from "classrooms' guidance" and "seating place", "visibility", "adults' guidance in the corridors", "exit choice in corridors", and "evacuation signs" also contribute to predicting the evacuation time, which was modelled using RF. First, we used the method of ordinal encoding to convert the categorical data into numerical variables by assigning a numerical value to each category in the categorical variable, such that the categories are ordered meaningfully. The original data set

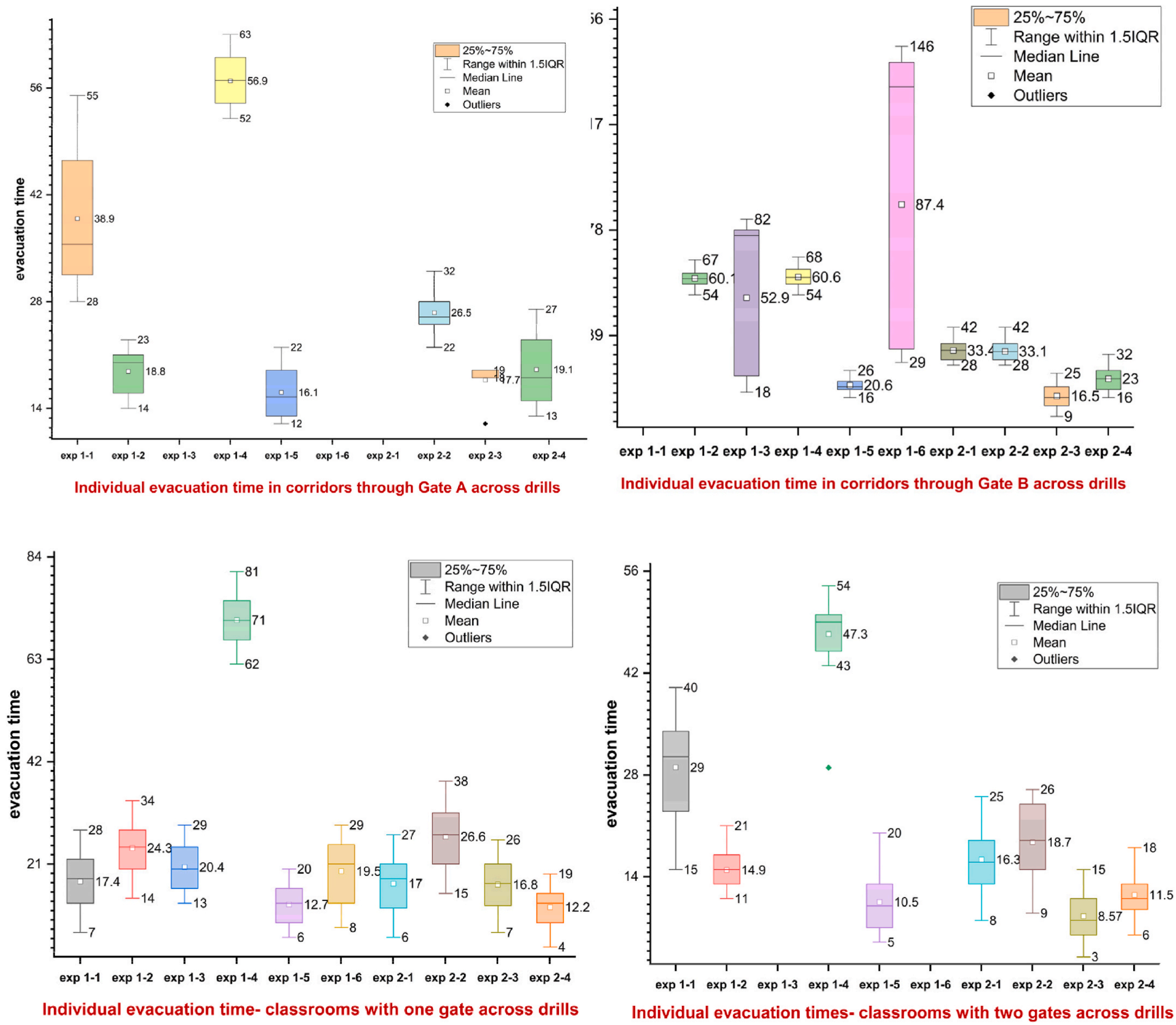

Fig. 4. Boxplots of individual evacuation time in corridors and classrooms across all experiments.

Table 3
Statistical test results for the' evacuation time (classroom with two gates).

Index	Group	Number of observations	Mean rank	U	Z	P-value
Guidance	No guide	416	489.99	44725	−10.981*	<0.001*
	Guided	389	309.97			
Number of gates	One gate	417	394.30	77268.5	−1.101	0.271
	Two gates	388	412.35			
Seating place	Backside classroom	177	195.06	18573.5	−0.091	0.928
	Frontside classroom	211	194.03			

**p < .01; *p < .001.

has been divided into training and test sets using the bootstrapping method to take N samples from the training set. As a result, over 61 % of the instances have been used for training, and the rest have been used for test sets. Based on the grid search method, the following steps have reached the optimal combination of the three parameters (Claesen and De Moor, 2015). First, we considered ten trees and set the maximum number of considered features to five. The training data set was replicable with unlimited maximal tree depth. The node splitting stopped with a maximum number of instances of five. Second, the possible combinations were tested, and the model performance was tested by cross-validation by dividing the data into ten folds to show the average over classes and choose the best one. Finally, the RF algorithm found that the model performs best (RMSE = 3.638, R^2 = 0.984). Using the RReliefF method to identify the importance of scores and ranks of predicting variables, the "adults' guidance in the corridors" is the first critical element in predicting the evacuation time (25.8 %), followed by "visibility" (19.1 %) and "seating place" (16.1 %). "Exit choice in corridors" (14.8 %), "evacuation signs" (14 %), and "classrooms' guidance" (10 %) are other important factors arranged by their relative importance.

Last, while RF models generally outperform traditional linear models in various aspects, they exhibit a drawback in terms of interpretability. Several methods have been developed to address this limitation, among which Partial Dependency Plots (PDP) have gained widespread acceptance due to their user-friendly nature and intuitive visualisation capabilities. PDP plots (Fig. 5) show the relation between the independent variables and the evacuation time (Rahman et al., 2021). In these plots, evacuation time is plotted on the y-axis, and the x-axis is allocated to predictor variables. As depicted in Fig. 5, the influence of having guidance within the classroom on corridors' evacuation time becomes evident. The longest corridor evacuation time recorded in scenarios featuring the presence of a guide was 66 s. In contrast, in experiments conducted without teacher guidance in the learning space, the last students completed their evacuation at the 146th second, signifying a notable difference. However, a similar correlation between the number of adult guides in the corridor and the children's evacuation time cannot be established. In Experiment 1–6, we observed the inactive guidance by the teacher standing in sub-area 2, which could negatively affect the students' evacuation time, even though the adult guidance significantly contributed to reducing the total evacuation time when there were two guides in the corridor. Additionally, PDP shows that the maximum evacuation time in the signed experiments and those run under normal visibility (42 and 82 s, respectively) was shorter than the experiments with no graphical signs and affected visibility (146 s in both cases). Moreover, our study found that individuals seated in the one-exit classroom evacuated the corridors more swiftly than those in the learning space with two gates. Evacuees who chose gate A for their escape route also demonstrated faster evacuation times than those opting for gate B. In the latter group, the longest evacuation time recorded was 146 s, while for gate A, the maximum time observed for the last student to exit was 62 s. These results indicate a conflict among human authority, environmental design, and stress-induced behaviour. Adults in the hallways are essential for minimising evacuation time, but their contribution depends on their commitment to active guidance. Structural deficiencies (such as inadequate exits) and training deficiencies (like passive teachers) intensify evacuation delays, especially in poor visibility situations. Addressing these characteristics through specific interventions can align evacuation behaviour with safety objectives.

4.3. Performance comparison of evacuation choice and time models

The study compared the performance of logistic regression and DT models for evacuation choice prediction and linear regression and RF models for evacuation time prediction using tenfold cross-validation to evaluate the proposed models' accuracy (L. Yang et al., 2021). The main parameters for comparison of logistic regression and RF models are accuracy, precision, recall, and F-score, which are calculated using Equations. (1)–(5): Where N is the number of samples in the validation set, TPi is true positive (the observed chosen gate is gate A, and the predicted gate to exit is also gate A), TNi is true negative (the observed walking selected gate is gate B, and the expected gate to exit is also gate B), FPi is false positive (the observed chosen gate is gate A, but the expected gate to go is gate B), FNi is false negative (the observed selected gate is gate B, but the predicted gate to exit is gate A).

$$\text{Area Under Curve} = \sum_{i=1}^{N-1} \frac{(TP_{i+1} - TP_i) - (FP_{i+1} - FP_i)}{2} \qquad \text{Equation.1}$$

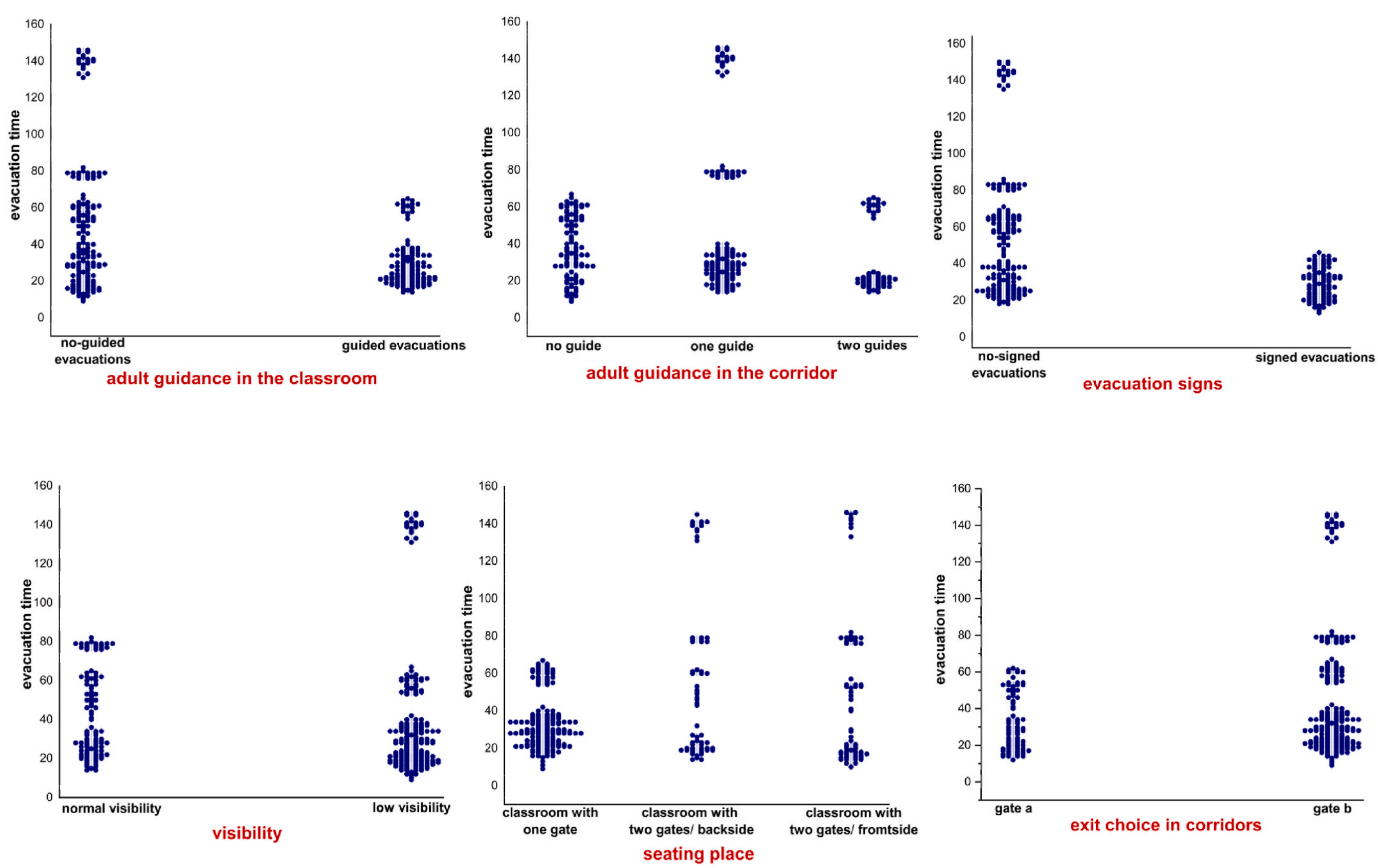

Fig. 5. Partial Dependent Plots of dependent variables.

$$\text{Accuracy} = \frac{\sum_{i=1}^{N} TP_i + TN_i}{\sum_{i}^{N} TP_i + TN_i + FP_i + FN_i} \quad \text{Equation.2}$$

$$\text{Precision} = \frac{\sum_{i=1}^{N} TP_i}{\sum_{i}^{N} TP_i + FP_i} \quad \text{Equation.3}$$

$$\text{Recall} = \frac{\sum_{i=1}^{N} TP_i}{\sum_{i}^{N} TP_i + FN_i} \quad \text{Equation.4}$$

$$\text{F} - \text{score} = \frac{2{*}\text{precision}{*}\text{recall}}{\text{precision} + \text{recall}} \quad \text{Equation.5}$$

For comparing the performance of models by linear regression and RF, Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and Coefficient of Determination (R^2), and their formulas are the widely used primary metrics and their formulas are shown in Equations. (6)–(9); Where n is the number of data points, y_i is the actual value of the dependent variable, $\bar{y}$ is the predicted value of the dependent variable, SS_e is the sum of squares of residuals (errors), SS_t is the total sum of squares (variation of the dependent variable).

$$\text{MSE} = \left(\frac{1}{n}\right) {*}\, \Sigma(y_i - \bar{y})^2 \quad \text{Equation.6}$$

$$\text{RMSE} = \sqrt{\text{MSE}} \quad \text{Equation.7}$$

$$\text{MAE} = \left(\frac{1}{n}\right) {*}\, \Sigma|y_i - \bar{y}|^2 \quad \text{Equation.8}$$

$$R^2 = 1 - (SS_e \ / \ SS_t) \quad \text{Equation.9}$$

Based on Table 4, Decision Tree modelling evacuation choice performs better than the traditional logistic regression for all metrics. Moreover, while the regression model predicting evacuation time is significant for predicting evacuation time (F-value = 85.736, df = 5, p-value = 0.000), the Random Forest model's performance stands higher than the traditional logistic regression model for all the metrics. These findings demonstrate the robustness and efficiency of decision tree and random forest models in processing the data, showing them to perform better than typical regression models in their respective domains (evacuation choice and time).

5. Concluding remarks and limitations

Given the necessity of gaining a more detailed understanding of children's evacuation behaviour and addressing the challenges of existing educational facilities, where major structural changes are often impractical, this study investigated the factors influencing primary school children's evacuation choices and times escaping from classrooms and corridors by conducting evacuation drills in a primary school. In contrast to earlier studies that examine route selection or movement speed independently, our dual-model approach simultaneously analyses exit choice through decision trees and evacuation time using random forests, uncovering concurrent prediction hierarchies. Moreover, to our knowledge, no prior study has integrated CCTV observation with dual machine learning modelling and filter-based feature selection under manipulated visibility to derive evidence-based evacuation guidelines for children.

Looking at the classroom evacuations, the study found that when teachers were present, children's evacuation time was relatively longer, but their route choice was unaffected. However, children naturally chose the nearest gate to their desks to escape to the hallways. Interestingly, there was no significant difference in evacuation time between classrooms with one or two exits, contradicting the findings by Runjiao Liu, Jiang, and Shi (2016). As mentioned in section 4.1, this observation, although new, can still give us clues on authority roles in guiding young children and their perception of these authority figures during emergencies. Primary schools not only need to focus on classroom facility designs such as exit placement and furniture arrangement, but also teachers' capabilities to actively and promptly guide the students without affecting the evacuation speed of children are also crucial. In line with our first suggestion, earlier studies showcased successful classroom evacuations using collaborative desk layouts (Delcea et al., 2020), which further echoes the need for well-designed classroom layouts and seating arrangements for effective evacuations. In this regard, it is recommended that less mobile or younger children be placed in front-row seats nearest exits to leverage the "nearest-gate" bias. Moreover, we would like to emphasise further the importance of preparing the teachers and staff about emergency and safe evacuation and their critical role in saving lives and accompanying young age children to prevent accidents like the fire accident at Jiangxi Radio and Television Art, June 5, 2021, China, which caused the death of 13 children (China News 2001). Because corridors present different sight-lines and social dynamics than classrooms, evacuation choice and time are driven by overlapping but distinct factors. The top three predictors for exit choice are "primary seating location" (accounting for 41 % of decision variance), "visibility", and "adult guidance in corridors", contributing 70 % of the RReliefF cumulative importance.[2] "Adult guidance in hallways", "visibility", "seat placement", and "exit decisions" best-predicted corridor evacuation time; these factors also total approximately 70 % of importance. This divergence suggests that while classroom drills should focus on seating arrangements to guide choice behaviour, corridor drills would benefit most from emphasizing adult leadership and visibility enhancements. On the other hand, adult guidance has the best influence on evacuation time, and visibility holds a consistently high rank for both evacuation choice and time. Therefore, one of the key contributions of this study is the direct comparison of classroom versus corridor evacuation dynamics, demonstrating that seating proximity dominates exit choice in classrooms while adult guidance governs corridor egress time.

Because most of the decision variance in exit choice is influenced by the primary seating area, schools should consider designing classroom layouts to ensure that exit paths are obvious and unobstructed. Direct access to multiple exits can be enhanced by implementing arrangements that alleviate congestion. In practice, schools can leverage these insights by reconfiguring the design of seating areas so people naturally start closer to exits, which would make the exit choice quicker and safer (Abulhassan et al., 2018). As mentioned earlier, it is best to arrange for the students who may require more assistance to sit closest to primary exits—a strategy that reduces evacuation times and decision errors under stress. Second, use bright, glowing signs and clear floor arrows, and keep pathways clutter-free. Good visibility helps children decide faster and keeps them moving smoothly. In this regard, the use of photoluminescent materials and electrically powered systems like LED at

Table 4
Performance comparison of evacuation choice and time models.

Modelling evacuation choice in corridors	AUC	CA	F1	Prec	Recall
DT	0.996	0.986	0.985	0.986	0.986
Logistic Regression	0.878	0.749	0.738	0.739	0.749
Modelling evacuation time in corridors	**MSE**	**RMSE**	**MAE**	**R2**	
RF	13.240	3.638	2.827	0.984	
Linear Regression	417.891	20.442	14.817	0.495	

[2] All potential factors were provided in the results section, however our summary and briefing focus on the subset with 70 % cumulative RReliefF significance. By this cutoff, we emphasise the top-ranked factors that account for most of the model's discriminative power, providing a succinct but informative overview of evacuation-choice and time drivers.

low heights paired with directional signage can help maintain wayfinding visibility even in dim conditions, accelerating sign recognition and preserving clear sight lines during corridor egress (Tonikian et al., 2006). Next, as the study illustrated the need for facility management techniques involving trained personnel and regular exercises, school staff evacuation training, whether they are teachers, event staff, or security teams, can promote active guidance (like shouting directions or using loudspeakers) and potentially speed up evacuation times more than anything else. Finally, embedding scenario-based drills that vary which exit is designated "primary" and follow up with brief debriefings—where students articulate why they chose particular routes—reinforces their understanding of seating proximity, visibility cues, and guidance strategies, improving exit choice. Furthermore, we proved that machine learning approaches to predict evacuation behaviour and timing offer a fresh approach to optimising evacuation plans and improving educational facility design.

While this study's results provide essential information for building professionals, architects, and facility managers looking to make school evacuations safer and more efficient, it has some limitations. The drills were conducted in a controlled environment, which may not accurately reflect real-world emergency conditions. Furthermore, the study concentrated on a particular institution, limiting the generalizability of the findings. Future research should examine the long-term effects of safety precautions on children's evacuation behaviour. Longitudinal studies to evaluate the long-term impact of safety precautions and evacuation exercises could be part of future studies. Examining the interaction of human characteristics, guiding tactics, and environmental details can reveal crucial new insights. Technological alternatives, such as smart evacuation systems coupled with BIM platforms, should be researched to improve evacuation protocols in elementary school corridors. Ultimately, this research contributes to safety science by offering suggestions for better educational facility management, design, and construction based on evidence. By integrating these findings into architectural practices and facility management strategies, stakeholders can enhance the safety and resilience of school buildings and ensure sustainable and disaster-resilient infrastructure.

CRediT authorship contribution statement

Homa Bahmani: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Resources. **Yibin Ao:** Supervision, Resources, Project administration, Funding acquisition. **Dujuan Yang:** Writing – review & editing, Conceptualization. **Qiang Xu:** Project administration, Funding acquisition. **Jianjun Zhao:** Resources, Funding acquisition.

Informed consent

All subjects engaged in the study provided informed consent. Parents received comprehensive information on the nature and purpose of the evacuation exercises, and their signed agreement was acquired before their children's involvement.

Ethical statement

The Office of Humanities of Social Sciences, Chengdu University of Technology, reviewed and approved this research proposal under the project title "Implications for Improving Evacuation Safety in Primary School Corridors." All participant-related data have been deidentified, and anonymity has been preserved.

Funding source

This work was supported by a grant from the National Social Science Foundation of China (Grant No. 24&ZD164).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We would like to thank the National Social Science Foundation of China (Grant No. 24&ZD164) and the 2023 Integrated Research on Disaster Risk Young Scientists Program for supporting this research. Any opinions, findings, and conclusions expressed in this material are those of the authors and do not necessarily reflect the foundations' views. Finally, we are very grateful to the Affiliated Primary School of Chengdu University of Technology and Chengdu Yingcai School for their valuable advice and support during the research process.

Data availability

Data will be made available on request.

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