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Impact of Leader-Follower Behavior on Evacuation Performance: An Exploratory Modeling Approach

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Abstract Different leader-follower behaviors may be observed in models, such as group gathering, backtracking, and changing between groups. However, a comparison of these behaviors resulting in possible substantially different estimates of optimal evacuation procedures is lacking. Hence, we developed an agent-based model in combination with exploratory modeling to compare backtracking, group gathering, and followers changing leaders and investigate their influence on the evacuation and response time. The simulation results showed that backtracking and changing of groups increased the evacuation time. Whereby group gathering increase the response time. In addition, the combination of behaviors increases the influence on evacuation and response time. Further research needs to test these results with empirical studies and investigate the impact of other leader-follower behavior. The found insights may be utilized in evacuation research for modeling this behavior and they provide a valuable basis for designing policies in buildings with a high distribution of leader-follower groups.

Keywords Leader-following behaviour · Evacuation · Agent-based modelling · Uncertainty · EMA workbench

1 Introduction

In general, leadership can be seen as a core attribute of social groups [1]. Haghani et al. found that leadership was one of the most influencing decision-making processes during an evacuation [2]. In addition, real-life observations of evacuations revealed

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that leaders play an essential role in the evacuation process [3, 4]. The leader drives the group's movement and thus influences the follower in his decisions towards the exit [5]. Various researchers have already explored leader-follower behavior with the help of empirical studies [6, 7]. For instance, Jones and Hewitt [3] realized that a leader might be imposed through hierarchical structures or emerge spontaneously. In addition, the group may split in case of different opinions, resulting in a new group with another leader. In line with observations in empirical studies, researchers implemented leader-follower behavior in models. For instance, Li et al. [8] developed a social force model, including leader-follower behavior. Other authors incorporated that the group is gathering before the evacuation [9]. Yet, leader-follower behavior implemented in evacuation models differ substantially. These differences in model implementation potentially result in different estimates of the optimal evacuation procedure. A thorough comparison of different model implementations is essential to better understand the impact of leader-follower behaviour models on the evacuation performance. This research aims to determine how three different leader-follower behaviours influence the evacuation and response time in buildings, namely backtracking, group gathering and followers changing leaders.

The remainder of this paper first presents the methodology in Chap. 2. Chapter 3 introduces an innovative Agent-based model and provides verification and validation. After the model presentation, the results are shown in Chap. 4. Finally, the article ends with a discussion of the results and conclusion in Chap. 5.

2 Methodology

In order to identify the effects of the three leader-follower behaviors, we first need to develop a suitable model and then establish experiments to receive a robust result for the influence. We used 2 distinct methodologies, namely Agent-based (ABM) and exploratory modeling. Below, both methods are briefly outlined.

2.1 Agent-Based Modeling

Various methodologies exist to model evacuations, such as social force models, fluid dynamics, and ABM [10]. Each methodology may be utilized for unique research goals. As the research investigates different behaviors and their influence on the emergent pattern in a complex environment, ABM is a suitable methodology for this study. Due to its bottom-up approach and ability to incorporate flexible and autonomous actions of agents in an environment [11], ABMs enable the integration of evacuee relationships and building interactions during an evacuation. Especially these attributes lead to choosing an ABM.

2.2 Exploratory Modeling

Ronchi et al. [12] identified four different uncertainties, which are predominant in evacuation research: Input, measurement, behavioral and intrinsic uncertainty. In an exploratory analysis, different parameter combinations in the parameter space will be chosen in order to investigate how the model behaves under the influence of uncertainties. Exploratory models do not predict or find precise answers to specific questions [13]. However, it develops insights regarding the behaviour of the model and helps discover extreme model behaviors [13]. For instance, feature scoring, explores the influence of uncertainties of the model. Higher confidence in results and thus a more robust solution may be achieved [14]. For leader-follower behaviors in evacuations, exploratory modeling may accomplish robust results about the influence on evacuations, independent of one particular scenario, increasing the overall value of this study for the evacuation research community.

2.3 Simulation Procedure

The difference between traditional and exploratory modeling is the absence of a base case but the utilization of a base ensemble [15]. A base ensemble represents a sample over the uncertainty space. In our model, we used a Latin hypercube sampling with 1000 scenarios. In addition, feature scoring may help identify the relevance of uncertainties on the KPIs [16] and is thus applied. Finally, we performed a multivariant behavior testing on the base ensemble. The key performance indicators of interest are total evacuation, and the mean response time. Whereby the total evacuation time is defined by the time between the start of the evacuation and the last agent leaving the building and the response time is determined by the time period between the recognition time of the agent and the first movement towards the exit. Furthermore, to study the behavior inside the groups and how this varies with additional policies, we monitored as a secondary outcome the mean intragroup distance between the groups. We conducted all experiments with the Exploratory Modelling and Analysis (EMA) Workbench. A detailed description of the EMA Workbench may be found in [14].

3 Model Representation

We developed an ABM, including different leader-follower behavior. A detailed description of the model is found on request at https://github.com/JIRnic. First, the purpose of the model is explained, then the state variables and states are shown [17]. The next part describes the process, the leader-follower behavior and the uncertainties. Finally, the chapter finishes with a short explanation of verification and validation.

3.1 Purpose of the Model

The purpose of the model is to investigate how specific leader-follower behavior may influence the evacuation and response time inside buildings. In particular, we examined three behaviors in more detail: backtracking, group gathering before the evacuation, and followers to change to another leader. Our goal is to receive a robust result regarding these three “policies” in buildings with the help of exploring the uncertainty space in an evacuation process.

3.2 State Variables and States

Overall, our agent-based model consists of three hierarchical levels: the individual level of each agent, the spatial level and the environment [18].

Agents: Our model contains three different agents: the leaders, followers, and individual evacuees. Leaders and followers are members of a group. Whereby the leader searches the path, and the follower follows the leader. Individual agents evacuate on their own.

Layout: We designed the layout of the model to mimic a museum or municipality hall. It contains five exits, whereby the main exits are located on the left and right sides of the main hall. The three other emergency exits are positioned at the top and bottom. The width of each exit is set to two meters. Black cells represent walls and obstacles, which must be avoided by agents. The building is illustrated in Fig. 1. A symmetrical layout was utilized to minimize the influence on the evacuation performance of where groups and individuals are placed.

Operationalization layout: The environment includes the scale and time dimension of the model. The software Netlogo represents the environment as a grid, in which one patch represents an area of 1×1 m in real-life. In addition, time is epitomized by ticks. For each tick, an agent is following specific rules. In the model, one tick symbolizes one second in the real time.

3.3 Process Overview and Scheduling

We divided the model into three phases, namely the pre-movement, movement and queuing [19]. The pre-movement step may further be subdivided into the recognition and response time [19]. After the pre-movement process, agents move towards the exit. Before leaving the building, the agent needs to queue as the door may be blocked by other agents. The three different Leader-follower behavior may be additionally added to the pre-movement and movement phase. The overall high-level process is shown in Fig. 2.

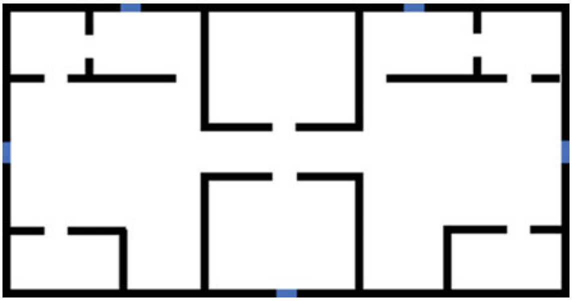

Fig. 1 Building layout

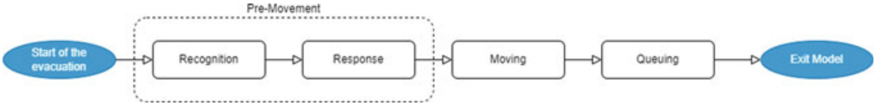

Fig. 2 The overall process for each agent in the model

3.4 Leader-Follower Behavior

We included and explored three different kinds of leader-follower behaviors: Backtracking, Group gathering before the evacuation, as well as Flexibility of the group.

Backtracking: Backtracking is a behavior that has been observed by leaders in social groups, for instance, close friends and family [20]. The group members evacuate and try to stay together throughout the whole evacuation process [20]. However, a group member may depart from the group in the rush of the evacuation and interaction with other evacuees [21]. In order to reestablish the connection, the leader reduces its speed and delays its evacuation until the lost member has caught up [21].

Group gathering: Group members may perform different actions during the recognition and response phase. After every group member finishes their task, social groups gather before evacuating together [3]. In our model, every group member moves towards the leader. Only if all group members are within a range defined by a threshold the leader starts evacuating. Here, we operationalized the threshold using the work of Moussaïd et al. [5]. As Group gathering may be allocated to the pre-movement process, it is added to the total response time.

Followers changing leaders: Groups may not only exist before, but may also arise during the evacuation [22]. Hereby, leaders with specific properties, such as authority [3] or due to the spatial position [23], may emerge. These emergent groups can be distinguished from social groups with high intragroup social relations, by their steadiness and the attachment among group members and leaders [24]. Phenomenons such as backtracking may be found in social groups [21]. Whereby emergent groups may only last temporarily, and spatial distances may split group members from the leader [24]. In a dynamic group, a follower may change to a new leader if another leader is closer to the follower [25] and in its visibility [26].

3.5 Uncertainty in the Model

Various uncertainties may be encountered in the model and are analyzed in order to receive a robust result regarding the three behaviours. All uncertainties are summarized in Table 1. Encountered values in literature determine the range for the base case. An exact overview may be found at https://github.com/JIRnic.

3.6 Verification, Validation and Sensitivity Analysis

Ronchi et al. [27] proposed various verification tests, to verify evacuation models. We applied all verification tests with a positive result.

In order to validate the model, we performed macro and micro validation. Whereby, the micro behavior may be defined as individual behavior of agents [28]. In contrast, macro behavior relates to the overall outcome of the model due to the interaction of agents [28]. For macro validation, we compared the evacuation time to empirical data from Haghani et al. [2]. For Micro validation we contrasted each core behavior to empirical data found in literature or due to face validation [27].

Finally, a higher trust in the built model and increased validity of the model may be achieved with the help of a sensitivity analysis [29]. If the model is sensitive to parameters that also occur in the real world, the trust in the model increases [29]. Sobol sensitivity analysis provides the possibility of conducting a global sensitivity analysis [30]. Further explanation of the Sobol methods can be encountered in [30]. The results indicate that the influence of parameters on the main KPIs is logical and, thus, increases the trust that the suitable model for its purpose was built. All results of tests and the sensitivity analysis can be found on https://github.com/JIRnic.

4 Results

Here we represent the model results. We first analyzed the uncertainty space, then we present and discuss the effects of different behaviors.

Table 1 Uncertainties in the agent-based model

Uncertainty	Location of uncertainty	Explanation	Value range in the model
Familiarity	Input data uncertainty	The familiarity may change, depending on the time and location of the building	0–30
Population	Input data uncertainty	Depending on the building use and time, the population inside the building may change	100–1200
Percentage groups	Input data uncertainty	Depending on the building and time, the group percentage may differ	55–70
Group distribution	Input data uncertainty	Different means for a Poisson distribution could be found in the literature	0.83–1.4
Max crowd density	Input data uncertainty	Different maximum crowd densities can be found in literature	5–8
Max distance group members	Input data uncertainty	The max distance between group members may vary	1–6
Min_age	Input data uncertainty	In some areas, no children may be present	10–20
Max_age	Input data uncertainty	In some areas, no elderly may be available	65–85
Recognition time distribution	Structural uncertainty	Different recognition time distributions may be found depending on the location and source	Department Store, Restaurant, Office
Determination of group leader	Structural uncertainty	In literature, various methods to determine the group leader were encountered	Random, Closest to the exit

4.1 Uncertainty Analysis

In order to investigate how uncertainties in the model influence the overall behavior of the model, we conducted an uncertainty analysis. First we describe the overall behavior in more detail, then feature scoring is utilized.

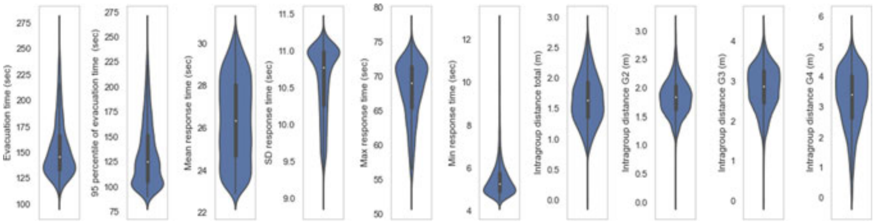

Fig. 3 The overall behavior of the base ensemble on the KPIs

Overall behavior The overall behavior of the model is summarized in Fig. 3. The plot illuminates the spread of results for each KPI. First, it illustrates that the mean evacuation time for each scenario ranges from 105.72 s until 271.70 s. Whereby the median lies at around 145.58 s. The same emergent behavior may be observed for the 95% percentile of the evacuation time (Fig. 3: left). In contrast, regarding the uncertainties, the mean response time may not be as sensitive as the evacuation times (Fig. 3: middle). However, it shows that the model's max and min response time is highly variable. Finally, we studied intragroup behavior of the model. The mean intragroup distance illustrates a large difference between the scenarios. With an increasing number of group members, the distance between group members grows.

Feature scoring The above results demonstrate that uncertainties highly impact the outcome of an evacuation. We utilized feature scoring to identify the relevant influence of uncertainties on the KPIs. A higher score in Fig. 4 indicates a greater influence on the KPI. It shows that the evacuation time is mostly influenced by the population, the familiarity and only minimal from the recognition time distribution. A higher recognition time distribution may lead to longer recognition times and thus impacts the total evacuation time. The same phenomena may be observed for the 95 percentile of the evacuation time. The response time is affected by "the percentage of groups". Whereby the population mainly influences the maximum of the response time.

4.2 Leader-Follower Behavior

Fig. 5 compares the three different leader-follower behaviors with the base case without additional leader-follower behaviors. The plot already indicates that backtracking demonstrates a higher evacuation time compared to the base case. In addition, the results from a Mann-Whitney U test confirm this result. Furthermore, the difference between the medians (150.77 for the base case and 202.31 for backtracking) indicates the negative influence on the evacuation time. To conclude, the backtracking of the leader may reduce the speed of groups leading to a higher evacuation time.

The statistical test indicates a difference in the response time between the base case and group gathering. However, the gap between the medians shows only a

0	evacuation100	evacuation95	mean response time	SD response time	Max response time	Min response time	Mean intragroup distance total	Mean intragroup distance G2	Mean intragroup distance G3	Mean intragroup distance G4
Mean_Poisson_distribution	0.018	0.014	0.031	0.034	0.019	0.022	0.1	0.019	0.016	0.046
Recognition_distribution_location	0.14	0.12	0.0098	0.011	0.013	0.021	0.02	0.034	0.03	0.025
determination_of_leader	0.0095	0.009	0.0064	0.0077	0.0088	0.012	0.014	0.015	0.012	0.015
distance_group_members_setup	0.016	0.015	0.013	0.014	0.016	0.022	0.43	0.42	0.59	0.39
familiarity_percentage	0.23	0.22	0.014	0.015	0.017	0.024	0.038	0.18	0.1	0.061
max_age	0.018	0.015	0.014	0.016	0.018	0.023	0.019	0.021	0.016	0.02
max_congestion	0.016	0.014	0.011	0.015	0.016	0.023	0.047	0.046	0.028	0.025
min_age	0.015	0.015	0.013	0.015	0.018	0.023	0.02	0.02	0.015	0.019
percentage_groups	0.018	0.016	0.87	0.86	0.031	0.62	0.04	0.032	0.052	0.2
population	0.52	0.56	0.013	0.016	0.84	0.21	0.27	0.21	0.14	0.2

Fig. 4 Feature scoring for the uncertainties. A higher number indicates a greater influence of uncertainties (left side of the figure) on the KPI (bottom of the figure)

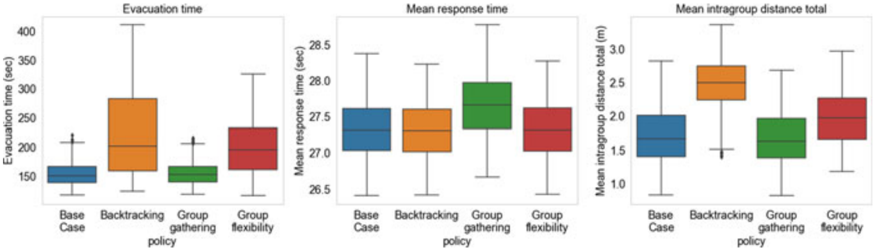

Fig. 5 The evacuation times and response times for each leader-follower behavior compared to the base case

slight divergence. The reason behind the small gap lies in the distribution of the agents. Group members are already located close to each other before the evacuation. This gap increases if the group member is situated further apart. No impact in the evacuation time could be observed by this behavior.

The flexibility of the group increases the evacuation time. Mann-Whitney U test verifies this trend. However, the overall intragroup distance increases. When implementing flexible groups in the model, bigger groups emerge. Overall, these groups demonstrate a higher intragroup distance and lower walking speed, leading to higher evacuation times and increasing the mean distance. All results are summarized in Table 2.

Table 2 Results for each leader-follower behavior

Behavior	KPIs	Mann-Whitney U test: P-value	Median base case	Median behavior
Backtracking	Evacuation time	< 0.01	150.77	202.31
	Response time	0.82	27.32	27.31
	Mean intragroup distance	< 0.01	1.67	2.50*
	Evacuation time	0.25	150.77	152.21
Group gathering	Response time	<0.01	27.32	27.66*
	Mean intragroup distance	0.10	1.67	1.63
	Evacuation time	< 0.01	150.77	195.56*
Flexibility of the group	Response time	0.97	27.32	27.31
	Mean intragroup distance	< 0.01	1.67	1.97*

Significant differences at the p-value lower than 0.05 are marked with a *

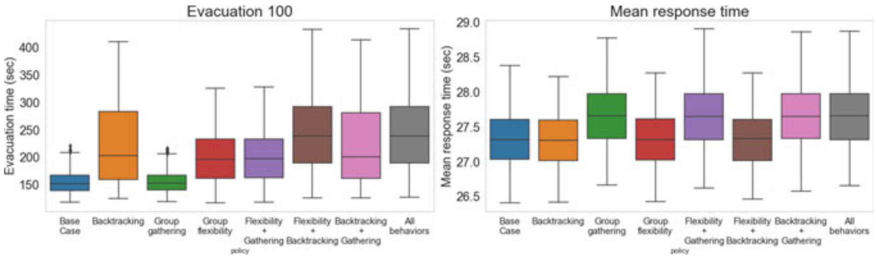

Fig. 6 Results for the multi variant behavior testing. The evacuation times (left) and response time (right) for each combination

4.3 *Multivariant Behavior Testing*

Also, we studied the impact of combinations of leader-follower behaviors. Figure 6 indicates that certain combinations of the behaviors increase the evacuation time compared to the implementation of one leader-follower strategy and the base case. In particular, the combination of group flexibility and backtracking results in the highest increase. An explanation is the higher number of agents per group due to the possibility of changing to another leader. This leads to longer waiting times for the leader as group members may get lost in congestion. Only combinations featuring group gathering have a increased response time. This is logical, as only the group gathering strategy adds to the response time.

5 Discussion and Conclusion

Our research question was how do different leader-follower behaviors in groups (backtracking, group gathering, and followers changing leaders) influence the evacuation and response time inside buildings. Therefore, we developed an agent-based model, and utilized an exploratory modeling approach. The main simulation results demonstrated that the group's flexibility and backtracking increased the evacuation time. Whereby group gathering impacts the response time. Additionally, the group distance was monitored and indicated that group gathering reduces the distance between group members during the evacuation. However, backtracking and flexibility of the group displayed diverse results regarding this KPI. It reduced the intragroup distance only for groups with fewer members. However, the reason behind it may be the implementation in the model as evacuees attempt to avoid the patch of other group members and step aside, leading to a higher distance between the group members. For the flexibility of the group, the reason lies in the creation of bigger groups, which generally have a greater intragroup distance [5]. Furthermore, with the help of sampling over the uncertainty space, higher confidence in the results could be achieved. Overall, the results may aid researchers who apply this behavior to understand how different leadership behavior influence the overall evacuation process. Of course, it is essential to remember that a model may never represent the real world, and the outcome is related to the implementation of the behavior in the model. In addition, uncertainties in the model about the input, measurement of the results, agent behavior, and model formalization are present. Furthermore, the model only compared different kinds of leader-follower behavior. Nevertheless, various groups may be observed in an evacuation, with varying decision-making structures [2]. Lastly, no empirical data about different leader-follower behavior are currently available, which increases the difficulties in comparing the model with real-life experiments.

Overall, the results in this study indicated that all additional leader-follower behaviors impact the evacuation performance. Thus, modelers and researchers must include backtracking and group gathering for social groups and flexibility of the group for emergent groups in evacuation models due to their impact on the evacuation performance found in this study. Currently, many models only implement the core leader-follower behavior and neglect the additional behaviors of leader and follower. However, only implementing the core leader-follower behavior in models may lead to wrong conclusions. Policymakers and fire safety engineers may then utilize the models with the included behaviors to prepare buildings for these critical situations and save people's lives.

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