UNDERSTANDING GROUP BEHAVIOUR DURING EVACUATIONS INSIDE BUILDINGS

AN EXPLORATORY AGENT-BASED MODELLING APPROACH

Master thesis

To obtain the degree of Master of Science at Delft University of Technology.
To be defended publicly on Thursday 26th of August 2021 at 14:00.

Written by

Kylian KNETEMANN

Faculty of Technology, Policy, and Management,
Delft University of Technology, The Hague and Delft, Netherlands,
Born in Zoetermeer, the Netherlands

Composition of the board:

Prof. dr. F.M. Brazier,	Chair, Faculty of Technology, Policy and Management
Dr. C.N. van der Wal,	First supervisor, Faculty of Technology, Policy and Management
Dr. ir. W.L. Auping,	Second supervisor, Faculty of Technology, Policy and Management

Keywords: Agent-based modelling, Exploratory modelling, Evacuations, Group behaviour, Group decision-making, Evacuation time

Printed by: Kylian Knetemann

Model and related notebooks are available on request at
https://github.com/KylianKnetemann

An electronic version of this master thesis is available at
http://repository.tudelft.nl/.

Executive Summary

Over the last decades, the world population has grown vastly and the percentage of people living in cities has increased. This process of urbanization has had a lot of implications for both safety management and research on evacuations. Due to this growth in urbanization, more high density gatherings are taking place, potentially resulting in more casualties during emergencies.

A common method used to conduct research on evacuations is simulation models. Simulation models have already improved our understanding of human behaviour during evacuations, but researchers argue that most current models are still not able to accurately describe human behaviour during evacuations since they do not take into account the effect of groups. Empirical research has shown that social groups in crowds influence the dynamics of evacuations. For instance, when an emergency happens and groups have to decide where to go, groups sometimes just follow other groups. However, accurately modelling such notions is often complex and contains uncertainty. One of the ways to deal with uncertainty systematically is by applying exploratory modelling. This, however, has yet to be applied to evacuations.

This study aims to address the need for models which include the notion of groups by analysing the effect of two decision-making schemes on the evacuation time; leader-follower decision-making and consensus decision-making. Furthermore, this study aims to provide a stepping stone for exploratory modelling in the realm of evacuation modelling. In order to do so, this study uses three methods; a literature study, agent-based modelling, and exploratory modelling. The literature study was conducted to lay the foundation of the agent based model, while exploratory modelling was used to explore the uncertainty space of the agent-based model. After the development of the model, it was verified and validated using multiple tests, and data from a previous study.

Through extensive validation and verification, it was concluded that this model is fit for purpose. It is both able to generate behaviour in the same magnitude as previous empirical research, and show valid behaviour on the lower abstraction levels of the model. Results show that groups have a significant impact on evacuation time. The more groups are present, and the bigger they are, the higher the evacuation time will be. Furthermore, results show that there is almost no difference in leader-follower decision-making and consensus decision-making. These two only differ when no one is familiar in a building. When there is 0% familiarity, leader-follower behaviour will lead to lower evacuations times compared to consensus decision-making. Lastly, results show that the combination of groups being present and all people being familiar with a building may actually have adverse effects on the evacuation time in crowd densities between 0.07 and 0.36. In case of crowd densities up to 0.36, a high percentage of familiarity may actually lead to higher evacuation times.

All in all, this study provides a stepping stone for modelling group behaviour using an exploratory agent-based modelling approach. This study was the first to lay focus on the effect of group decision-making schemes by incorporating it in an agent-based model and exploring its behaviour by running it numerous times under different parameter settings. Furthermore, this research has important implications. First, evacuations inside buildings should not only be evaluated by crowd density or familiarity, but also by exit capacity. Secondly, different crowd compositions have different effects on the evacuations time. Policymakers should, therefore, take into account what types of groups will most likely be present. As regards future research, future research should mainly focus on the effect of modelling leader-follower behaviour in different ways, modelling consensus groups in general, analysing the effect of groups on different segments of evacuation time, and adding more (social) factors to the model which influence evacuation behaviour.

List of Figures

List of Tables

Contents

1

INTRODUCTION

Over the last decades, the world population has increased vastly and the percentage of people living in cities has grown, and continues to grow (Ritchie and Roser, 2018; Antrop, 2004). This increase in urbanization has had important implications for safety management, but also for doing research on evacuations. With respect to the former, research has shown that due to this increase in urbanization, more high density gatherings are taking place inside buildings (Zhou *et al.*, 2019). In other words, disasters which occur inside buildings with a higher crowd density could potentially lead to more casualties. As regards the latter, when disasters do happen inside buildings, many deaths could be prevented if people were to react appropriately (Grosshandler *et al.*, 2005; McConnell *et al.*, 2010).

To clarify, research has shown that when people are faced with adverse conditions, they tend to want to stay in the proximity of familiar people (Sime, 1983). As a consequence, groups can cause delays during emergency situations, since they may try to gather first before evacuating (Bode *et al.*, 2015). It is unsafe human behaviour like this in the early stages of an emergency that mainly determines the severity of the disaster, as this is one of the most critical stages in terms of survival (Pires, 2005). The early stages are important because in these stages, people typically have to rely on themselves and others in their direct surroundings, since professional emergency services can only be provided at a later stage (Rubadiri *et al.*, 1997). Therefore, it is important to analyse the effect of groups in case of evacuations.

In the body of literature regarding the effect of groups on evacuations, there are different, and sometimes contradicting, findings. On the one hand, there are researchers who argue that the presence of groups is disadvantageous for evacuations. For instance, Conradt and List (2009) and Sumpter and Pratt (2009) found that initial movement of groups may be slower since deciding where to go often takes longer in groups as groups first have to communicate with each other and have to reach consensus on certain important decisions with regard to evacuating. On the other hand, there are researchers who argue that the presence of groups is advantageous. For instance, groups are often considered to be more effective at evacuating because in groups incomplete information can be pooled, eventually leading to more accurate decisions than individuals would make in the same situation (Bode *et al.*, 2015; J. Krause, G. D. Ruxton, and S. Krause, 2010). As regards group decision-making during evacuations, decisions in groups are made in different shapes and forms; some groups may tend to follow the crowd (also known as herding behaviour) (Haghani and Sarvi, 2019a; Haghani, Cristiani, *et al.*, 2019), while others may decide to assign the role of leader to one of the members and follow his or her decisions (Moussaïd, Perozo, *et al.*, 2010). These different types of decision-making are often referred to as decision-making schemes (J. Davis, 1969). Interestingly, studying the effect of different decision-making schemes on evacuations using a simulation model has yet to be done.

Modelling crowds during evacuations has been done using different approaches (Zheng *et al.*, 2009). Two of the advantages of simulations models over empirical research are that they allow researchers to do experiments that are generally considered to be impractical or too expensive, and that they allow researchers to model systems which are deemed too complex to analyse mentally (Maria, 1997; J. D. Sterman, 1994). There are different kinds of simulation models with respect to evacuations. The Traditional evacuation models see people as moving particles who will all respond exactly the same in a given situation. For instance, the panic model made by Sime (1983) assumes that people in an evacuation can be considered homogeneous and will become overwhelmed, confused, disoriented, and will have a lack of coordination. However, most of these traditional models are criticized heavily as they do not include elements such as, for instance, the influence of groups in crowds (Drury, 2004; Duives *et al.*, 2013; Santos and Aguirre, 2004). Many (modelling) studies consider crowds as a collection of individuals who each have their characteristics such as desired speed, and direction Antonini *et al.* (2006), Helbing and Molnar (1995), Johansson *et al.* (2007), and Moussaïd, Helbing, *et al.* (2009). However, research has shown that pedestrians do walk in groups (Aveni, 1977; Coleman and James, 1961; James, 1953).

A suitable modelling approach for studying groups during evacuations is agent-based modelling (Cuesta, Abreu, and Alvear, 2015). Agent-based models have had different applications for a while now. They have, amongst others, been used to do research on evacuation from a building in case of a fire (Kasereka *et al.*, 2018), trying to understand behavioural patterns and path choice in case of earthquakes (D'Orazio *et al.*, 2014), evacuation traffic management (Madireddy *et al.*, 2011), and decision-making in case of tsunami evacuation (Wang *et al.*, 2016). Nevertheless, an agent-based model which focuses on the effect of different types of decision-making of groups on evacuation time inside buildings has yet to be developed.

Additionally, when it comes to developing models, not coming across uncertainties is inevitable. A current state-of-the-art approach for dealing with uncertainties is exploratory modelling. Exploratory modelling has emerged over the last two decades and has already had its implications in many fields and on various topics (e.g. Exploring the dynamics of farming practices in the Philippines (Olabisi *et al.*, 2015), or to test business models for electricity storage (Mir Mohammadi Kooshknow *et al.*, 2020)). However, an exploratory model on evacuations has yet to be developed.

Therefore, the aim of this research is to develop an agent-based model on the effect of different decision-making schemes on the evacuation time, to provide a stepping stone for developing exploratory models with respect to evacuations, and to address the need for more simulation models which include the notion of group behaviour. To do so, I will be answering the following research question: *"What is the effect of two different group decision-making schemes (consensus and leader-follower) compared to individual decision-making on the evacuation time inside buildings?"* and relative sub questions:

1. What can be considered groups during evacuations from buildings?
2. Which group-decision making schemes do groups use during evacuations?
3. How can different group decision-making schemes be modelled in evacuation models using an exploratory agent-based modelling approach?
4. What is the effect of two different group decision-making schemes (consensus and leader-follower) on the evacuation time, compared to individual decision-making?

To answer the sub questions, three methods will be used. The first three sub questions will be answered by doing a literature study while the fourth will be answered by doing experiments using an agent-based model, the Exploratory Modelling and Analysis (EMA) Workbench and Netlogo's behaviour space.

The structure of this thesis is as follows. First, in chapter 2, I will discuss the current background literature and will answer the first three sub-questions (section 2.3). Then, in chapter 3, I will discuss the methodology and the setup of the validation and verification of the model. In chapter 4, the setup of the agent-based model, and the verification and validation will be discussed. In chapter 5, I discuss the experimental setup, show the results, and give the answer to the last sub question. Finally, in chapter 6, conclusions will be drawn, and the results will be discussed.

2

LITERATURE STUDY

In this chapter, insight will be provided on the literature available with regard to; group decision-making during evacuations (section 2.1), and modelling decision-making schemes during evacuations (section 2.2). In section 2.3, a summary of the literature found will be given, along with its implications.

2.1. GROUP DECISION-MAKING DURING EVACUATIONS

For a long time, crowds were considered merely as an aggregate of people in the same location (Templeton *et al.*, 2015). However, research has shown that crowds are not only an aggregate of people without any connection in the same location, but are also agglomerates of people who feel unity and show coordinated behaviour which is not planned or expected by design (S. Reicher and Drury, 2010; Turner *et al.*, 1987; S. D. Reicher, 1984), e.g. a Mexican wave during a football match, or a group of people lifting a vehicle together when a person is stuck underneath the vehicle. In psychology, this is referred to as physical versus psychological crowd (Neville and S. Reicher, 2011). In simple terms, a physical crowd is a large group of people in the same place, while a psychological crowd is a group of people which feel like they share a social identity. It is important to keep in mind that in one physical crowd, multiple psychological crowds can be present (Templeton *et al.*, 2015). For instance, the fans of two basketball teams make up for two psychological crowds within one large physical crowd in a stadium. In addition to this, crowds are again made up of multiple social groups (Oberhagemann *et al.*, 2014). To clarify, many people who attend large scale events, such as baseball matches or concerts, do not go there by alone. People who attend these events are usually accompanied by friends or family, and thereby creating a social group.

Collective behaviour by groups used to be explained by one of two ways; a mass of people with one collective mind, or a mass of people who were not connected in any way, but would facilitate each other's hidden behaviour (Le Bon, 1960; Allport, 1924). The former states that when an entity enters a mass of people, it will lose its personality and ability to reason and will eventually become part of a big crowd with one collective mind (Le Bon, 1960). The latter argues that crowds do not actually have a collective mind, but are merely an aggregate of individuals whose mutual presence stimulates behaviour which is already present in each individual (Allport, 1924). However, researchers have argued that these explanations are incorrect since these theories insinuate that crowds show violent behaviour, which is not always the case (Fogelson, 1971; S. D. Reicher, 1996; Thompson, 1971).

Nowadays, collective behaviour is often described through the notion of contagion. Contagion in this context means that seeing or hearing the behaviour of others group influences people to behave way in the same way (see for instance; Mann *et al.* (2013) and Gallup *et al.* (2012)). However, this is also considered an incorrect explanation as this is not able to explain group boundaries (Van Der Schalk *et al.*, 2011; Milgram *et al.*, 1969). One of the most accepted ways to describe collective behaviour of groups is through the self-categorization theory (Tajfel, 2010; Turner *et al.*, 1987). The self-categorization theory states that individuals can either perceive themselves as unique individuals or part of something bigger (e.g., or a group or social category) through the process of depersonalisation (Turner, 2010). Depersonalisation means that individuals see themselves connected to a social category and interchangeable with others in that same category. This results in individuals shifting from being a unique identity to being a group member of a social group (Turner *et al.*, 1987).

Table 2.1: Overview of Most used definitions of a social group, the used definition in this research, and their respective author(s)

Definition	Author(s)
A social group is an aggregate of people who are brought into social relationships with each other.	MacIver
A social group emerges when two or more people gather and influence one another	Ogburn and Nimkoff
A social group is an aggregate of people who see themselves as a member of a group. They expect certain behaviour from other members that they do not expect from non-group members.	Merton
A section of a crowd who share specific properties which create group-specific interactions.	Müller, Wohak, and Schadschneider

In the literature, there are different definitions of what a social group is. Three of the most used definitions are by MacIver (1952), Ogburn and Nimkoff (1947), and Merton (1968) (see table 2.1). However, for this research, a different definition will be used. The definition used in this research, is the definition by Müller *et al.* (2014). They define a group as a section of a crowd who share specific properties which create group-specific interactions; these specific properties can vary between groups. They also refer to these groups as distinctive groups to differentiate between groups that purposely stay together and groups that form spontaneously through phenomenon such as herding behaviour. This definition is an appropriate definition for this study since this study will focus on leader-follower and consensus.

One of the most important characteristic of this definition is that distinctive groups can be denoted by spatial coherence; this spatial coherence is caused by attraction between members of a group (Müller *et al.*, 2014). Furthermore, Distinctive groups come in different forms. For instance, a mother and a child have a different spatial coherence compared than a group of friends. A mother guides her child and will retain a very close connection during evacuations, while a group of friends may have a more loose connection. That is to say, they will walk closely when the situation allows, but will also split if needed (e.g., an emergency).

When it comes to the effect of groups on evacuations, there is only so much known about the exact effect of groups (Van der Wal *et al.*, 2017; Moussaïd, Perozo, *et al.*, 2010). Similarly, studies that have been done are primarily empirical studies (e.g. Bode *et al.* (2015) and Von Krüchten and Schadschneider (2017)). Haghani, Sarvi, *et al.* (2019) did a lab-in-the-field experiment where they analysed the behaviour of groups under different levels of stress. They found that (1) group size had a significant effect on pre-movement time and decision time, (2) the exit-choice mechanism of groups is familiar to that of individuals, (3) groups were more prone to switch their exit decisions when exposed to higher levels of stress, and (4) that as regards group decision-making; leadership was the dominant style. Von Krüchten and Schadschneider (2017) had similar findings; they found that groups have a significant impact on the evacuation time, but they found also that bigger groups are more efficient at evacuating than smaller groups. This last finding is also supported by Cuesta, Abreu, Balboa, *et al.* (2021). Furthermore, research has shown that pre-existing social structures influence evacuation decision-making (Jones and Hewitt, 1986; Aguirre, Wenger, *et al.*, 1998). For instance, Jones and Hewitt (1986) showed that in case of companies, the form of decision-making which is adopted during evacuations is close to the organizational structure of the organization. That is to say, if a disaster were to happen at a certain company which would require the building to be evacuated, managers will often (naturally) take on the role of a leader and lead their colleagues to the exits of the building.

Group decision-making is often studied from different perspectives. Many important theories are based on literature by Arrow (2012), Black (1948), Black *et al.* (1958), and J. H. Davis (1973). Even though group decision-making is studied from different perspectives, they do overlap in the sense that they address the same fundamental issue; aggregating individual preferences into a single group preference. Group decision-making is considered to be a social process and comes in different shapes and forms (J. Davis, 1969). In general, the following schemes are observed in the literature when groups try to come to a decision; (1) leader-follower, (2) majority, two-thirds-majority (3), unanimity, (4) truth wins, (5) truth supported, and (6) first shift (Kerr and Tindale, 2004; J. H. Davis, 1973; Hollenbeck *et al.*, 1995; Tindale *et al.*, 2012). The major types (or so-called social decision schemes) which are observed in general, and have been studied, are majority and unanimity (Kerr and Tindale, 2004; Laughlin, 2011). In short, majority means that more than half of the people have to agree, and unanimity means that everyone has to agree.

To the best of my knowledge, the following four schemes have been observed during evacuations; leader-follower, majority, consensus, and herding (Cuesta, Abreu, Balboa, *et al.*, 2021; Haghani, Sarvi, *et al.*, 2019; Haghani and Sarvi, 2019a). The two schemes which will be analysed in this study are leader-follower and unanimity (also known as consensus), since these two fit right into the definition of social group used in this research and different findings were found with respect to which scheme is dominant during evacuations. On the one hand, in the experiments conducted by Cuesta, Abreu, Balboa, *et al.* (2021), they found that in groups of 5 members, consensus was the most perceived decision-making mechanism (64%). In groups of 12, they found that some groups used unanimity (48%), while others used majority (48%) or leader-follower (4%). In the smaller groups, leader-follower behaviour was not perceived. On the other, Haghani, Sarvi, *et al.* (2019) observed a different distribution of decision-making schemes in their experiment. They found that leader-follower was by far the most dominant scheme. Approximately 60% of the groups used leader-follower as their decision-making mechanism. Leader-follower behaviour is often observed in case of evacuations and is described as one individual being the leader of a group, while the remaining members of the group are merely followers which follow the leader in their decisions (Moussaïd, Perozo, *et al.*, 2010). The leader of a group varies per situation; in some situations it is determined by social structure, while in others it is determined by the level of training which individuals have had (Aguirre, El-Tawil, *et al.*, 2015).

Consensus decisions is a phenomenon which is often observed in both groups of animals and humans. Groups of animals often have to make important decisions which require consensus (e.g. their direction, which activities they have to perform, and the duration of said activities) (Conradt and Roper, 2003). These decision often have to be taken because there are conflicting interests present in the group (Couzin *et al.*, 2005). However, if these conflicts cannot be resolved, i.e. consensus cannot not be reached, a group will often split, and the respective members will not be able to benefit of being part of a big group (J. Krause, G. D. Ruxton, G. Ruxton, *et al.*, 2002).

As regards humans, a lot of research has been done on the decision-making process of individuals or groups, but also on the differences between the decision-making process of individuals and groups under varying circumstances (e.g. Cuesta, Abreu, Balboa, *et al.* (2021), Lovreglio, Ronchi, *et al.* (2015), Haghani and Sarvi (2016), Haghani, Sarvi, *et al.* (2019), and Kocher and Sutter (2005)). An important finding in this body of literature and related to the field of this research is that individuals still agree with the majority of groups even though they know the others are in the wrong (Asch, 1956). That is to say, they found that the influence of the majority of a group plays a significant role in group decision-making (Asch, 1956). Similarly, Dyer *et al.* (2008) found that in group decision-making, a minority of informed people is able to guide a group of uninformed people, and the time to reach a destination or the deviation from the target is reduced by the presence of informed individuals. They also found that whenever there is an imbalance in the number of people with conflicting information, the majority directed the direction of the group. With respect to modelling consensus decision-making during evacuations, no models have been developed yet. Based on the aforementioned notions, this study will be the first to model consensus based decision-making in groups during evacuations.

Both of these schemes are conscious decisions. However, evacuees also make decisions subconsciously during evacuations. To clarify, during evacuations, evacuees often subconsciously are influenced by others with respect to decisions. research has shown that when it comes to exit choice, people are often influenced by other's exit choice (Haghani and Sarvi, 2019a; Lovreglio, Fonzone, *et al.*, 2014). That is to say, during evacuations, evacuees often change their exit choice when others in their proximity change their exit choice; this is commonly known as herding behaviour. Table 2.2 provides an overview of all the mentioned decision-making schemes, their definition, their layer of decision, and the context in which they appear.

Table 2.2: Group decision-making schemes

Scheme	Definition	Layer of decision	Context of scheme
Leader-follower	One person takes the lead in a decision and other members follow	Conscious	Everyday lives, and evacuations
Majority	Single decision by a group when more than half of the group agrees	Conscious	Everyday lives, and evacuations
Two-thirds-majority	Single decision by a group when two third of the members agree	Conscious	Everyday lives
Unanimity	Group comes to a decision when everybody in the group agrees	Conscious	Everyday lives, and evacuations
Truth wins	One member who is informed is enough to make a decision	Conscious, and subconscious	Everyday lives
Truth supported	Two members who are informed is enough for a group to make a decision	Conscious, and subconscious	Everyday lives
First shift	When in a deadlock, if one person changes their mind, others will often follow that person	Conscious, and subconscious	Everyday lives
Herding behaviour	Evacuees unconsciously follow other people in a crowd	Subconscious	Evacuations

2.2. MODELLING DECISION-MAKING SCHEMES DURING EVACUATIONS

In the previous section, evacuations were discussed from a more empirical perspective. However, evacuations can also be studied by using models. There are different approaches to model crowd behaviour during evacuations. Zheng *et al.* (2009) have discussed seven approaches which are often used in modelling evacuations; (1) cellular automata (Wolfram, 1983), (2) lattice gas models (Fredkin and Toffoli, 1982; Wolfram, 1983), (3) social force models (Helbing and Molnar, 1995), (4) fluid dynamic models (Hughes, 2002), (5) agent-based models (Goldstone and Janssen, 2005), (6) game theoretic models (Lo *et al.*, 2006), and (7) approaches based on experiments with animals (Saloma *et al.*, 2003)[1]. Cellular automata is a method where at discrete time

[1]This method will not be considered as it is not a real simulation model method.

steps a grid evolves over time; cells in a grid change in value based on values of neighbouring cells and the values of the previous time step (Wolfram, 1983). Lattice gas models are a specific type of cellular automata. In lattice gas models, individuals are seen as particles which move over a grid. Social force models are models where the speed and direction of an individual is determined by four factors; the desire to reach a destination, the need to keep a certain distance from others, tries to avoid bumping into objects such as walls, but is sometimes attracted by other individual or friends. This type of method is often combined with other methods (e.g. Lin *et al.* (2006) and Guo and Huang (2008)). Compared to the previously explained models, fluid-dynamics models explain pedestrian crowds by assuming crowds have fluid-like properties (Henderson, 1971; Bradley, 1993; Helbing, Farkas, *et al.*, 2002). The core of these models is partial differential equations. That is to say, fluid-dynamics models use these types of equations to describe the changes in density and velocity of a crowd. As regards game theoretic models, these types of models are ideal for situations where the decision process of an evacuee is the focal point (Lo *et al.*, 2006). Contrary to the other approaches, which have a more top-down structure, ABM builds structures bottom-up by simulating individuals as agents with unique characteristics which could create emergent behaviour through the rules that dictate the interactions amongst agents (Wilensky and Rand, 2015). Agent-based modelling has been used for evacuation studies and is regarded a suitable method. Bonabeau (2002) and Zheng *et al.* (2009) argue that collective panic behaviour emerges from complex individual behaviour and interactions between people, agent-based models capture emergent phenomena, give a natural description of a system, are flexible, and have successfully described pedestrian behaviours (see Braun *et al.* (2005) and Bandini *et al.* (2005)). Similarly, Templeton *et al.* (2015) argue that agent-based models are able to simulate psychological crowds and self-categorization in crowds, since they can capture varying levels of perceptual and cognitive processes. However, an agent based model which captures the notion of different group decision-making schemes has yet to be developed. Table 2.3 gives an overview of the methods, their description, and whether the time and space are continuous or discrete.

Table 2.3: Overview of approaches used to model evacuations

Modelling approach	Description	Time step and Space	Examples
1. Cellular Automata	A uniform grid with cells where values of cells are determined at each time step by the value of variables of neighboring cells	Discrete	-L. Yang *et al.* (2005) -Daoliang *et al.* (2006)
2. Lattice gas models	Special form of cellular automata where participants are particles moving on the grid	Discrete	-Tajima and Nagatani (2001) -Nagai *et al.* (2005)
3. Social force models	A model where pedestrians move based on desires to avoid or go to certain objects	Continuous and discrete	-Lin *et al.* (2006) -Guo and Huang (2008)
4. Fluid dynamic models	Approach where crowds behave as gases or fluids	Continuous	-Hughes (2002) -Colombo and Rosini (2005)
5. Agent-based models	Approach where structures are build bottom up and heterogeneity of agents causes emergent behaviour	Continuous and discrete	-Zarboutis and Marmaras (2004) -Toyama *et al.* (2006)
6. Game theoretic models	Models which focus on decision-making based on utility	Discrete	-Lo *et al.* (2006)

As noted before, groups may use different schemes to come to a decision during evacuations. In section 2.1, it was observed that the four schemes which are during evacuations are; (1) leader-follower, (2) unanimity or consensus, (3) majority of vote, and (4) herding behaviour. Nevertheless, only consensus and leader-follower will be considered in this study. As regards modelling leader-follower behaviour, there are different nuances. However, in general, in all the models of publications found which include modelling leader-follower behaviour, the followers move towards the leader, and the leader determines the exit and path towards the exit. When looking at the nuances, it can first be observed that there are different ways to determine the leader of a group. Some of the studies which include leader-follower behaviour determine the leader of the group randomly (e.g. Mao, Fan, *et al.* (2019)), while others assign it to the one closest to the exit (e.g. K. Li *et al.* (2019) and Xie *et al.* (2021)). Secondly, different models have different rules on whether group members were allowed to switch groups. In some models, group members were able to switch groups (e.g. Mao, Fan, *et al.* (2019), and in others the size of the group stayed fixed (e.g. Zhang *et al.* (2018)). Finally, in some models, leaders of the groups were susceptible to influence from either external or internal factors (Mao, Fan, *et al.*, 2019; Mao, S. Yang, *et al.*, 2020; Qin *et al.*, 2018). With respect to modelling consensus (or unanimity), to the best of my knowledge, no model is available which touches on the notion of consensus in human groups. However, one study was found which modelled consensus making with respect to groups of animals on the move. Couzin *et al.* (2005) performed a simulation study on collective behaviour and decision-making via consensus. They concluded that if a small portion of a group (of animals) which is on the move is informed, this same small portion of the group is able to move the rest of the naïve individuals towards a location. They also concluded that consensus can be reached even when informed individuals in the group don't know anything about the information other individuals may potentially have. A small overview of these findings can be found in table 2.4. Interestingly, from this literature study, it was observed that none of the studies found used agent-based modelling. This indicates that there is a lack of agent-based models which address the notion of group decision-making schemes.

Table 2.4: Overview of unique traits of modelling decision-making schemes

Author(s)	Unique model trait	Type of model	Decision-making Scheme	Humans or animals
Zhang et al., 2018	-Members have the possibility to switch groups -Leader of the group is the one in the middle	Social force	Leader-follower	Humans
Qin et al., 2018	Groups are fixed, no one can switch	Social force	Leader-follower	Humans
Wang et al., 2016	Groups gather first before evacuating	Social force	Leader-follower	Humans
K. Li et al., 2019	Assign role of leader to the one closest to the exit	Social force	Leader-follower	Humans
Mao et al., 2019	Leaders are influenced by others both in- and outside the group	Social force	Leader-follower	Humans
Mao et al., 2020	Leaders are influenced by others and have impact on other group members	Social force	Leader-follower	Humans
Y. Li et al., 2021	Leader backtracks	Social force	Leader-follower	Humans
Xie et al., 2021	Included variable which indicates the desirability of followers to follow leader	Cellular automata	Leader-follower	Humans
Couzin et al., 2005	Within groups, members transfer information without signalling	Mathematical model	Consensus	Animals

2.3. SUMMARY: THEORY AND MODELLING APPLIED TO THE CURRENT RESEARCH

As stated in the previous sections, there is a lack of models which include the notion of group behaviour. As regards groups, research walk in groups, either consciously or subconsciously, and that groups use different decision-making schemes in order to make a decision. Two of these conscious decision-making schemes will be the focal point of this study, namely consensus and leader-follower. These two fit right within the definition which is used; a group as a section of a crowd who share specific properties which create group-specific interactions, which can also vary between groups. As regards the modelling method, agent-based modelling is considered to be a suitable method to analyse the effect of group decision-making schemes on the evacuation time and will, therefore, be used. Multiple researchers argue that agent-based modelling is able to capture emergent behaviour and multiple levels of perceptual and cognitive processes. See section 3.1 for a more detailed explanation on agent based modelling.

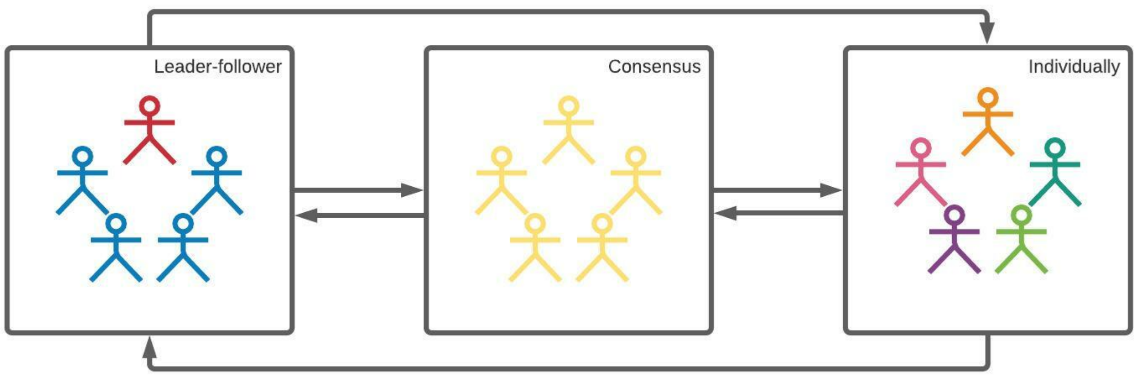


Figure 2.1: Conceptual model

figure 2.1 gives an overview of the essence of the model. Three types of groups will be interacting with one another; groups which use the leader-follower decision-making scheme, groups which use consensus decision-making, and groups of which the members will evacuate individually. This last group will serve as a reference in order to analyse the effect of groups on the evacuation time compared to evacuating individually. It is, however, important to keep in mind that in this research, groups will be modelled in a more abstract way. The stick figures in figure 2.1 could be seen as groups of children, or groups of friends, but this is not the case. This research considers groups on a more abstract level.

As regards modelling the different types of groups, a few key concepts found in the literature will be used. First, both the consensus and leader-follower groups will gather first before evacuating. Secondly, the leader of leader-follower groups solely determines the exit and path towards the exit, all the other members will simply follow the leader. Thirdly, with respect to consensus decision-making, the most important finding will be implemented in this model; minorities who are informed are able to convince majorities who are uninformed. That is to say, if one of the group members of a consensus groups if familiar with the building and knows where the nearest exit is, the group will eventually move towards that exit. However, since there are different ways to model leader-follower behaviour and consensus decision-making in light of evacuations has not been done yet, uncertainty is present. One of the state-of-the-art methods to deal with uncertainty in a structured way is exploratory modelling. Exploratory modelling is a method which aims to explore the uncertainty space of a system by running the model numerous times under different parameter settings (Kwakkel, 2017). This study will do exactly so by using Netlogo's behaviour space and the EMA Workbench (Kwakkel, 2017).

3

METHODOLOGY

In this chapter, the methodology will be discussed. In section 3.1, it will be discussed why an exploratory agent-based modelling approach was chosen for this research, and what software package will be used. In section 3.2 and 3.3, the setup of the verification and validation of the model will be discussed.

3.1. AGENT-BASED MODELLING AND EXPLORATORY MODELLING

As shown in chapter 2, there are different ways to modelling evacuations inside buildings. For this research, agent-based modelling was chosen.

Agent-based modelling is a modelling simulation approach which allows users to analyse and simulate the effects of interactions between individuals (so-called agents) and their environment in a system over time (Wilensky and Rand, 2015; Crooks and Heppenstall, 2012). An agent can represent anything from a company to a human or bird; the key point is that agents in agent-based modelling are autonomous, heterogeneous, and active (Wooldridge and Jennings, 1995). That is to say, they are able to make independent decisions, have different attributes, and exert influence on other agents and their environment.

There are many advantages to using agent-based modelling. The main advantage of using agent-based modelling in contrast to other approaches is that within agent-based models, agents are modelled as unique beings which each have their own set of characteristics. As a result of these different sets, emergent behaviour can occur (Wilensky and Rand, 2015). Emergent behaviour is observed often during evacuations. For instance, Aguirre, Wenger, *et al.* (1998) have shown that based on pre-existing social relations, sometimes norms can emerge during evacuations which would normally not occur. Similarly, Bonabeau (2002) argue that panic behaviour emerges from interactions between individuals. Another advantage of agent-based modelling is that it allows a modeller to give a more natural description of a system (Bazghandi, 2012). For instance, it is easier to describe how an individual walks through a corridor than describe to describe the dynamics of a whole crowd through a set of equations. However, there are also disadvantages to using agent-based modelling.

The first disadvantage of this modelling method, and all modelling methods in general, is that the right level of abstraction has to be used for a model to serve its intended purpose (Couclelis, 2002). If the level of abstraction is too detailed, there is a chance that the model quickly becomes too complicated and difficult to understand. However, if the model is too simply, key aspects may be missed. Another downside of agent-based modelling is that often complex natures of agents has to be modelled. Quantifying, calibrating, or even justifying these complex natures is difficult and a trade of its own (Crooks and Heppenstall, 2012). Finally, One of the main downsides of agent-based modelling is that it's a rather computationally expensive method to use (Zheng *et al.*, 2009). Agent-based models look at a system at a very detailed level. As a consequence, developing agent based models often requires modelling many attributes, behaviours, and their interaction with their respective environment. These factors are often uncertain and require an agent-based model to be run multiple times under different initial conditions and parameter settings (Axtell, 2000). A suitable way to deal with this uncertainty is by using exploratory modelling.

Traditionally, models were developed in a consolidative manner. That is to say, based on unified knowledge and potential information available, an attempt would be made at developing the 'perfect' model. However, when it is observed that the system under study is characterized by a lot of uncertainty, then the use of consolidative models does not see fit any more. When this is the case, a novel approach to thinking about and developing models has to be taken, namely exploratory modelling (Auping, 2018). Exploratory modelling was first introduced by S. Bankes (1993) and is used to understand the uncertainty space of a system (Kwakkel, 2017; S. Bankes *et al.*, 2013). To do so, exploratory modelling uses model-based scenario techniques, which explore large ensembles of plausible futures using sampling techniques (S. Bankes, 1993; S. Bankes *et al.*, 2013; S. C. Bankes, 2002; Van Asselt and Rotmans, 2002). There are generally two approaches used to explore an uncertainty space of a system; (1) open exploration and (2) directed search. The former uses systematic sampling, while the latter searches for scenarios in a directed manner using optimization algorithms (Kwakkel, 2017). In this research, both of these techniques will be used. With the former, insight will be gained into the behaviour of the model across the uncertainty space. With the latter, insights will be given in how directed search could be used to find desired scenarios. A further elaboration will be given in chapter 5.

As regards software packages, Netlogo will be used as software for developing the agent-based model, and the EMA workbench (Kwakkel, 2017) will be used for exploratory modelling. Netlogo was chosen because it is a simple environment in which complexity can be modelled easily, and allows for direct connection to the EMA workbench.

3.2. SETUP OF MODEL VERIFICATION

In terms of verifying the model, Ronchi *et al.* (2013) wrote a paper on how to validate and verify models in case of fires in buildings. Even though this paper focuses on fires inside buildings, I believe that some of these verification tests can be used to determine whether the implementation has been done correctly, since evacuation models overlap in core principles.

The tests in this paper distinguish five core components of evacuation models; 1) pre-evacuation time, 2) movement and navigation, 3) exit usage, 4) route availability , and 5) flow conditions/constraints. Table 3.1 shows the 5 core components and their respective tests which will be performed.

Table 3.1: Overview of verification which will be performed

Core component	Test
1	Pre-evacuation time distributions
2	-Group behaviours -Movement around corner
3	Exit route allocation
4	none
5	-Maximum flow rates -Congestion

3.3. SETUP OF MODEL VALIDATION

Validation is an important aspect of modelling. In general, validation is used to build confidence in the model with respect to its purpose (J. Sterman, 2002; Forrester and Senge, 1980). In this research, several tests were performed based on Forrester and Senge (1980); tests where the validity of the model was assessed without running the model (structure tests), and tests which involved running the model (behaviour tests).

As regards structure tests, the following tests were performed (1) Direct structure assessment test, and (2) Direct boundary adequacy test. The Direct structure assessment test is a test where the model's structure is assessed based on its concordance with the real system and laws of nature. The Direct boundary adequacy test tests whether the boundaries are adequate for the purpose of the model. That is to say, are the boundaries, for instance, large enough to capture key aspects. These structure tests were chosen because modelling social groups (while using agent-based modelling) is novel and has not been done before. The direct structure assessment test is done because literature has shown that modelling certain core elements can be done in different ways. The boundary adequacy test can give insight into whether the scope of this model is appropriate enough with respect to the purpose of the model.

As regards behaviour tests, the following tests were performed in order to determine the validity of the model: The (1) Extreme conditions behaviour test, (2) Visual observation of groups, and (3) Historical replicability. The Extreme conditions test is to test whether the model holds under extreme conditions, and to determine what those extreme conditions are if the model does not hold. The second test is the visual observation of groups test. This test originates from a paper written Köster *et al.* (2014). In this paper, there are a set of tests which can be formed in order to determine the validity of a model related to crowd dynamics which includes social groups. The visual observation tests sketches two situations: an open field, and a small corridor with an obstacle. In case of an open field, the test demands that groups walk abreast, stay together, and overtake slower groups. When in a small corridor with an obstacle, the test demands that groups circumvent the object as a whole or split up in front of it, and that the group reunites after passing the obstacle. The last test, historical replicability, is based on a guide by Nikolic *et al.* (2019) on good modelling practices. Based on this test, one can determine whether the model is good enough to be able to replicate historical data. These tests were chosen because modelling human behaviour during evacuations can be done in different ways, and this research is one of the first agent-based models which focuses on exploratory modelling of evacuations inside buildings.

Behaviour tests were performed because it's not only important to look at the model as something static, but also to look at it in a dynamic way. The extreme conditions test is a good way of testing the limits of a model and to see if it shows proper behaviour under basal circumstances. The visual observation group is an ideal test to determine whether groups show similar behaviour to previous findings. The historical replicability test is a suitable test for determining whether the model shows results in the same order of magnitude as the original experiment. It is important to keep in mind that with enough parameters, it is easy to replicate data. In science, this is also known as von Neumann's elephant (Dyson, 2004).

4

MODEL PRESENTATION, VERFICATION, AND VALIDATION

In this chapter, the model representation (section 4.1), and the verification and validation of the model will be discussed (section 4.2 and 4.3). In this research, the ODD protocol is used to present the model.

4.1. MODEL REPRESENTATION

Throughout the years, agent-based models have been criticized for being poorly documented and could, therefore, not be replicated accurately (Grimm, Berger, De Angelis, *et al.*, 2010; Lorek and Sonnenschein, 1999). This lack of replicability has been acknowledged by different disciplines, and different initiatives were proposed to solve this "replication crisis" (Fanelli, 2018; Monks *et al.*, 2019; Peng *et al.*, 2011; Wilkinson *et al.*, 2016). One of the proposed solutions for agent-based models is the 'ODD' (Overview, Design concepts, and Details) protocol created by Grimm, Berger, Bastiansen, *et al.* (2006).

4.1.1. PURPOSE OF THE MODEL

The purpose of this model is to understand how two of the decision-making schemes observed in social groups during evacuations influence the evacuation time in case of emergencies inside buildings. This is done by first exploring the behaviour of the model by sampling through the uncertainty space using Latin hyper cube sampling and the EMA Workbench. After sampling through the uncertainty space, the prim algorithm will be used to find the parameter ranges for a sketched example scenario. Subsequently, Netlogo's behaviour space will be used to specifically look at the effect of group decision-making schemes on the evacuation time. The map chosen to perform the experiments in is a self-made map. The map represents a room or area which contains multiple separate smaller areas. The main idea behind this map is that it can represent different general areas; a few examples of maps this could be a representation of is an office or a sub-section of a mall (see figure 4.1).

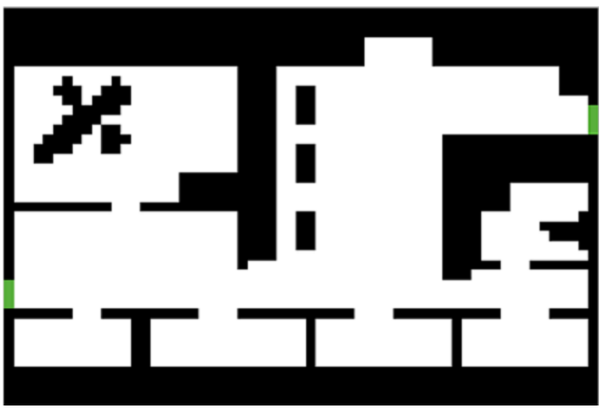


Figure 4.1: Representation of the map used in Netlogo

4.1.2. STATE VARIABLES AND SCALES

This subsection elaborates all the process that take place in the model. Each subsection will discuss a section of the model.

ENVIRONMENT

As regards the environment, only one process takes place, which is the initialization of the model. That is to say, patches are coloured and given variables such that agents can calculate their path towards the exit, know where they can walk, and walk towards their destination.

AGENTS

Each Individual, also known as 'person' in the model, is characterized by its own state variables such as 'leader?', 'defined-exit', 'agreed?', 'walking-speed', 'reaction-time', 'queue?', 'task?'. Each of these variables determine where they are going, where they are, or what role they assume in a group. On a group level, each group is characterized by its group number and type. Group number is just a number used to assign evacuees to a group. As regards group type, there are three types of groups which are determined by two variables; 'percentage-consensus', and 'percentage-leader-follower'. The percentage of the last group, the group of which members evacuate individually, is calculated by deducting the two aforementioned percentages from 1. Table 4.1 provides an overview of all important variables used in the model. That is to say, the variables that were used to, for instance, check if agents have spent their modelled time on a task. Standard variables such as 'patch-color' are not included.

Table 4.1: Overview of processes, parameters, and default values of parameters of model

Variable	Value	Description
Exit_patches		Set of patches which function as exit
Exit_queue		Variable which will contain a list of evacuees who are in a queue
Nr-of-people	120	Number of people in th emodel
Percentage-familiar	0.5	Percentage of people familiar with the building
Type-of-group	Consensus, leader follower, or evacuate individually	Describes what type of group the agent is in
Group-number	1	To indicate which group is which
Group-member	1	To indicate which agent is which group member
Percentage-consensus	0.33	Percentage of groups with the "consensus" type
Percentage-leader-follower	0.33	Percentage of groups with the "leader-follower" type
Walking speed	1	Walking speed of evacuees
Emergency?	False or True	Indicates whether there is an emergency going on
Task?	False or True	To determine whether an agent is performing a task
Agreed?	False or True	Determines whether a group member in a group with consensus agrees or not
Leader?	False or True	Is the member a leader or a follower?
Familiar?	False or True	Indicates whether a person is familiar with the building or not
Queue?	False or True	To determine whether an evacuee is currently queueing for an exit
Task-time	Random normal distribution (28, 22)	Time it takes to perform a task
Reaction-time	Random uniform distribution (1, 5)	Time to react before moving towards the set exit

This model proceeds in time steps of seconds. Within each second (which is equal to a 'tick' in this model), a few processes take place; figure 4.2 gives a general overview of the interactions between agents and the environment[1].

[1]A more detailed explanation of all the processes is given in section 4.1.3.

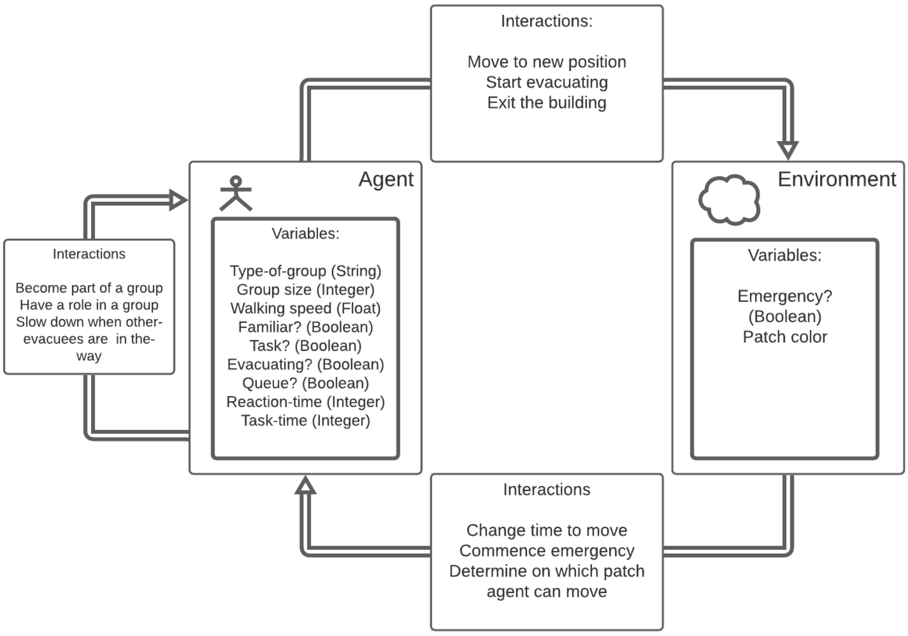


Figure 4.2: Overview of interactions between environment and agents, and their most important variables

In general, the environment in this model determines where evacuees are going, and where they are allowed to walk; the colour of the patch determines where they walk and where the exits are, and the 'Emergency?' variable determines whether agents are going to evacuate or not. Evacuees interact with themselves in the sense that they are part of a group and can be hindered by others while walking.Further more This model contains multiple maps used for different purposes. The map called 'cuesta' (figure 4.13) is used for validation purposes, the other map; 'office' (figure 4.1) is used for exploring purposes and for determining the effect of group decision-making schemes on the evacuation time. The dimensions of the rooms are as follows, the room used for validation purposes is 8 by 8 m. The room used for exploring purposes is 60 x 40 m. In all the maps, a patch is equal to $1m^2$. The total number of square metres which the agents can walk on is 1400.

4.1.3. PROCESS OVERVIEW AND SCHEDULING

This model proceeds in time steps of seconds. Within each second, a certain number of processes take place. In general, an agent can be in three states; normal, investigating, or evacuating (Reneke and Reneke, 2013). However, in this model, agents go straight from the normal state to the evacuating state (see figure 4.3); all agents believe that the alarm is a genuine alarm, and they should start to evacuate immediately. The reason behind this is that the purpose of the model focusses on the evacuation process, i.e. the evacuating state, and not the other states. Hence, agents move straight from the normal state to the evacuating state.

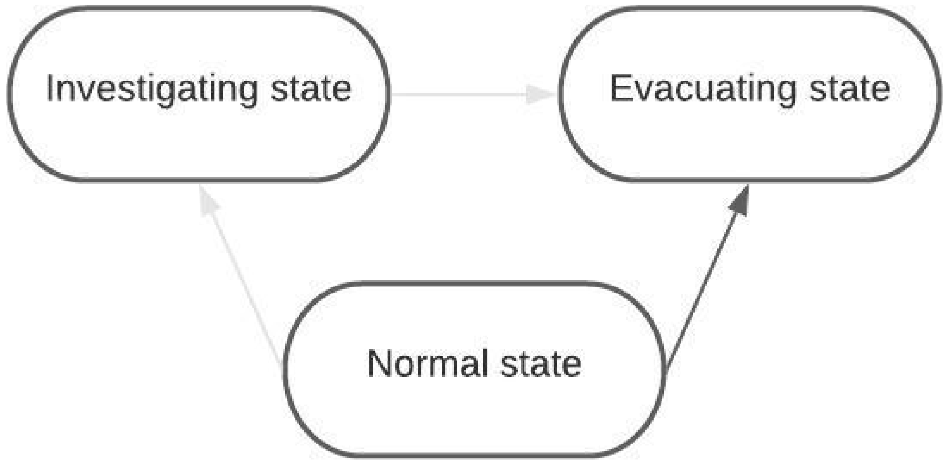


Figure 4.3: Overview of potential states

In the normal state, there are two possible actions; (1) walking around, or (2) doing a task. When walking around, an agent moves to a neighbouring patch every tick (read second). When doing a task, the agent does not move and spends a certain number of seconds in place. Furthermore, an agent always checks whether there is an emergency. If so, it transitions to the evacuating state. If not, it will continue doing its task, start a new task, or walk around. Figure 4.4 depicts a flow diagram of this state.

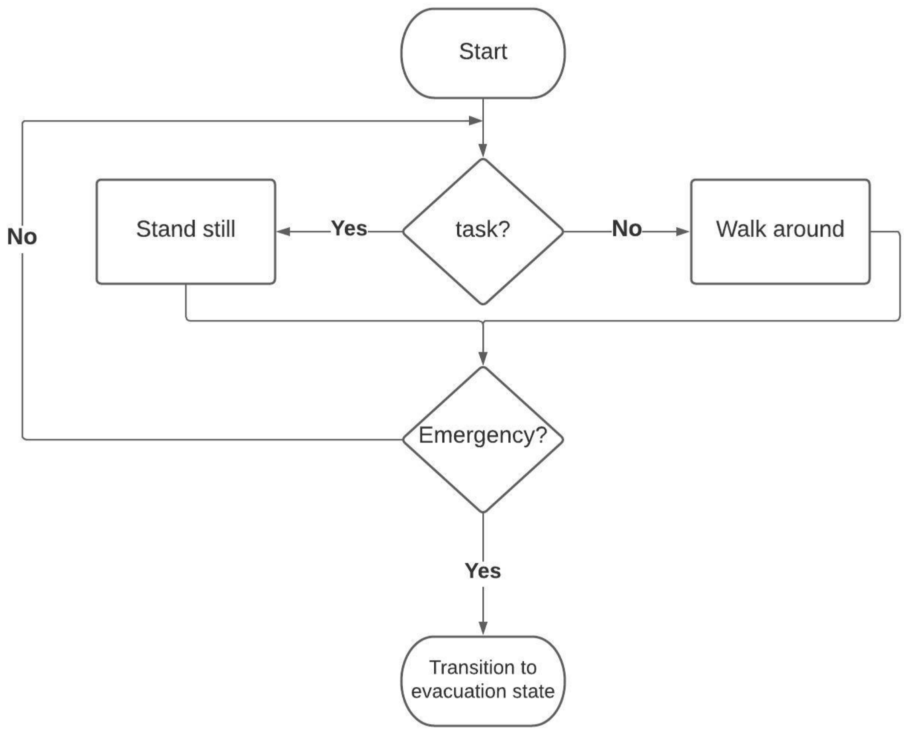


Figure 4.4: Flow diagram of normal state

In the evacuating state, three types of groups are modelled; (1) Leader-follower, (2) consensus, and (3) groups of which members evacuate individually. The first group type can be seen in figure 4.5. When an emergency happens, all the members of the group move towards the leader of the group (the leader of the group is the member with member ID equal to 1). Once they are near the leader, they are present. Once everybody is present, the leader determines where the group goes and everybody starts moving towards the exit. The destination of the leader depends on their familiarity. If they are not familiar with the building, they will move to the main exit. If they are, they will move to the closest exit.

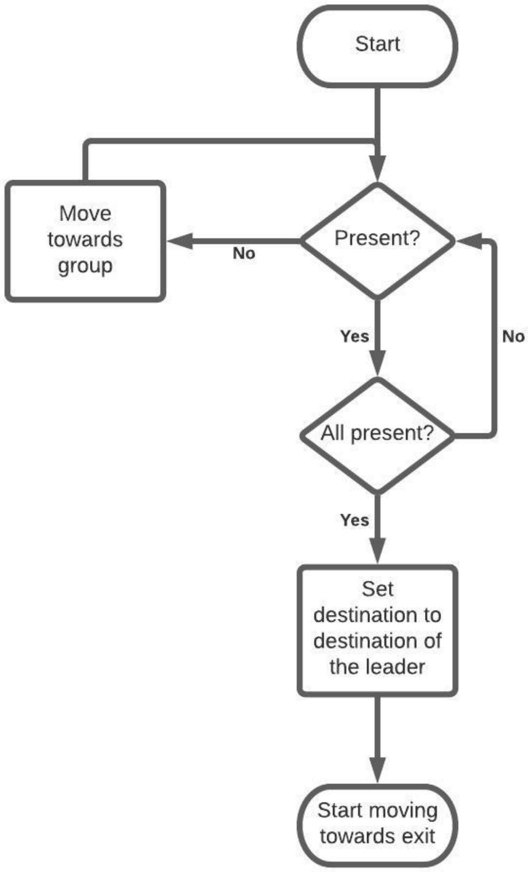


Figure 4.5: Flow diagram of leader-follower groups

Groups who are characterized by consensus have a somewhat similar process as groups with leader-follower (see figure 4.6. The main difference between these two groups is that consensus groups focus on distribution of information. Furthermore, as seen in the literature, people who are informed are able to convince others who are not informed and are able to guide them towards a certain direction. In this model, this is applied to groups with consensus. When the group uses consensus to decide where to go, they will always go to the closest exit if someone is familiar with the building. That is to say, about convincing others that group members who are familiar with know the best way out. This is modelled as follows; the chance of an agent agreeing increases with the number of agents in their group who are familiar with the building. Members of groups, of which the members evacuate individually, just evacuate by themselves; they each individually calculate their own path and evacuate. This type of group was implemented to be able to determine the effect between evacuating as groups and evacuating alone.

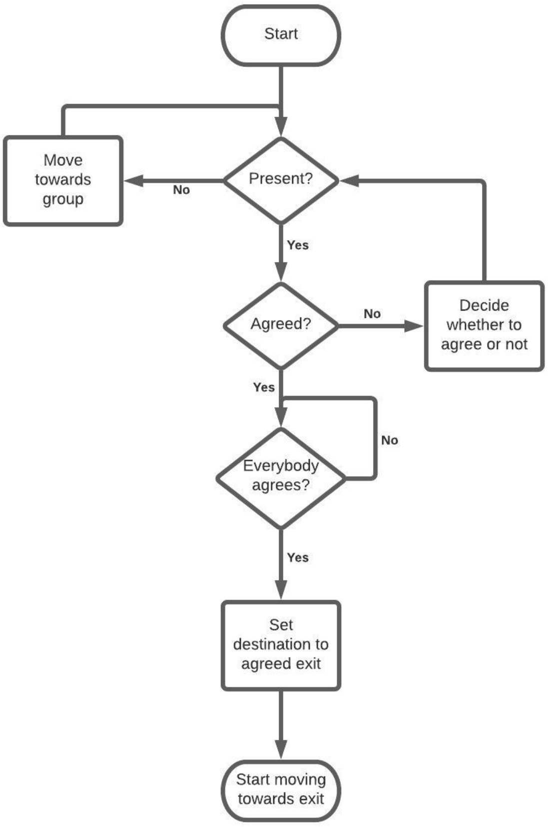


Figure 4.6: Flow diagram of consensus groups

Now, when all the group members know where they are supposed to go, they start to calculate their path and move towards their destination. Figure 4.7 provides an overview of the process of moving towards the exit.

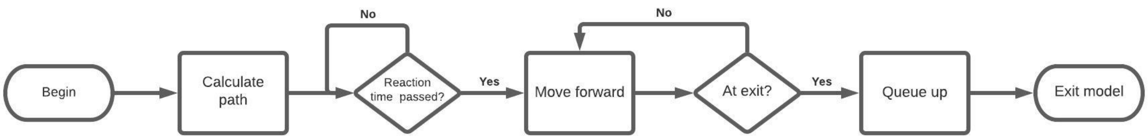


Figure 4.7: Flow diagram of the process of an agent after they have decided where to go

The first step towards walking towards an exit is calculating the path. The agents calculate their path by using the A* algorithm. This algorithm was introduced by Hart *et al.* (1968) and can be considered an extension of Dijkstra's algorithm.

After having determined their path, and before they actually start moving towards their destination, the agents first have a reaction time. The reaction time chosen for this model is based on research by Lovreglio, Kuligowski, *et al.* (2019). In this research, they reviewed over 103 evacuations and categorized them by mean evacuation time and categories. The mean and standard deviation of the pre-evacuating time was set to respectively 28 and 22 seconds. This was based on a rough estimation of the office section in this paper.

After they have passed their reaction time, the agents start moving towards their exit. As regards walking, walking speed, and interacting with other agents while walking; this model uses the social force model (Helbing and Molnar, 1995). The social model slows agents down when there are other agents in the same lane and in front of them because they are exerting force on one another. This 'congestion' factor is based on a paper by Ibrahim *et al.* (2016). In short, agents can walk at their desired speed when there is less than 1 person per m^2 and can hardly proceed any further when there is 8 people present per m^2 in front of them.

Table 4.2: Walking speed in the model based on density in front of agent

Density (Person/m^2)	Speed (m/s)
< 2	0.8
2	0.7
2 - 5	0.55
5 - 7	0.35
> 7	<0.1

Not everyone can leave the building at once. That is to say, agents have to queue up before they can leave the model. In this model, a maximum of 4 agents can leave the building per exit per second, which is based on Still (2014). In short, if there are more than 4 people in the queue, only 4 people leave the queue. If there are less than 4, all people in the queue leave the queue and, subsequently, the model (see figure 4.8).

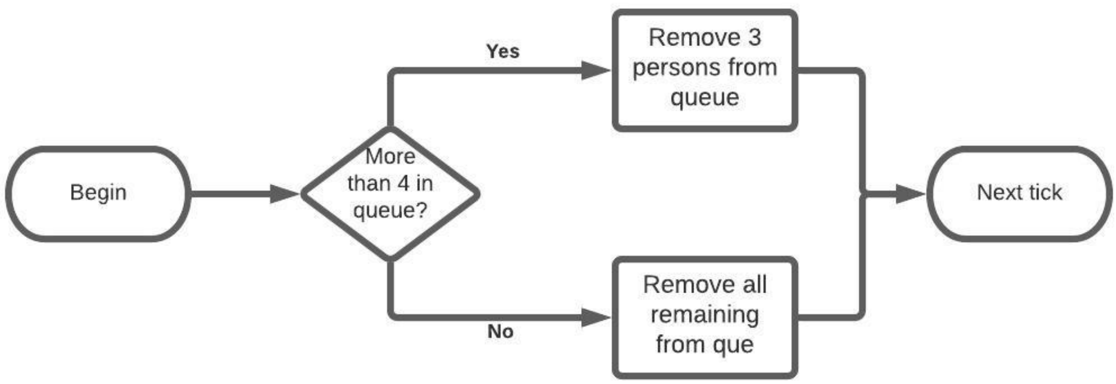


Figure 4.8: Flow diagram of the process in a queue

4.1.4. DESIGN CONCEPTS

Design concepts is a common framework used for communicating ABMs. It is a checklist where, if certain design concepts are present, they are discussed.

Emergence: evacuation dynamics emerge from behaviour on an individual level and from groups. Each group has its own type, and the interference of this type can lead to emergent behaviour. Furthermore, inside a group, emergent behaviour may occur as well as group members interact with each other.

Interaction: Interaction only takes place when groups characterized by consensus decision-making are exchanging information before evacuating, and when agents are walking. Agents influence each other when walking because they exert forces on each other.

Stochasticity: all parameters which are either regarded a chance or probability are drawn from a uniform distribution. An example of a parameter which uses a uniform distribution is 'task-time'; this parameter draws a value from a uniform distribution between 1 and 5 and determines how long an agent will take to perform a task. This was done as there was only empirical information on certain aspects, or no information at all. Modelling stochasticity in this model was done by comparing the probability of an input variable with a randomly generated number, which could have a value between 0-1. The distribution of group sizes is done using a uniform distribution. This may not be accurate because James (1953) showed that the distribution of group sizes is that of a negative binomial distribution. Unfortunately, this could not be implemented in the software package used (Netlogo).

Observation: for model testing and validation, the behaviour of both the individuals and groups was observed by looking at the display, analysing the code and flow diagrams, and comparing results of runs to existing studies. For model analysis, experiments were performed using the evacuation time as the main KPI.

Collectives: collectives in this model are represented as groups of people. They do not occur due to emerging phenomena; agents are part of a group when the model is initialized. The groups are separated through having different members, which cannot switch groups, a group ID, and a type of decision-making. Each type of decision-making has its own process (see 4.1.3).

4.1.5. INITIALIZATION

When initializing the model (see figure 4.9, a set of steps happen in a dedicated order. First, all the variables are reset. Secondly, the map is loaded, the colours of patches are corrected, and the agentsets and lists related to patches are initialized. Thirdly, the agents are created. When creating the agents, they are first distributed on the map location wise, after which they determine whether they are familiar with the building or not and set their known exit based on this familiarity. Fourthly, groups are configured and are then moved around the map. That is to say, once agents know what group they are part of, they will move to a close proximity of one another. Finally, the ticks are reset.

Figure 4.9: Flow diagram of the initialization of the model

4.1.6. SUBMODELS

This model did not contain any specific submodels, therefore this section can be disregarded.

4.2. MODEL VERIFICATION

Pre-evacuation time distributions

The pre-evacuation distributions test aims to test whether the pre-evacuation times are according to the desired distribution. This is tested by spawning 10 agents and checking their evacuation times. The expected result in this test is that agents should have a plausible evacuation time according to the used distribution. The result is that this model passed the test. After setting up the model 10 times, it can be concluded that agents show plausible evacuation times. No agent had a negative or extremely high evacuation time.

Group behaviours

This test was designed to perform a qualitative verification of the behaviour of groups. With this test, you identify whether sub-groups are available and if group behaviours can be reproduced. This test is performed by creating two groups where one is quicker than the other. The quicker group starts behind the slower group, and should overtake the group and end up together again. The expected result of the group behaviours test is that groups arrive at the same time, and the time of arrival between the first and last group member should not be more than 10 seconds apart[2]. This test was performed 10 times, and the result is that the model passed this test. The first group overtook the second group and arrived together at the other side with no more than 10 seconds between the first and the last person. The average time difference was around 5 seconds.

Movement around corners

The movement around corners test is to verify whether agents adhere to the boundaries of the model. In this test, twenty persons were spawned in a section of the model where they had to go around a corner. The expected result is that The result agents are able to navigate successfully around a corner. This test was done through physical observation, and it can be concluded that when agents are trying to navigate around a corner, they do not walk onto a black patch (these represent walls in the model). Therefore, this test has passed.

Exit route allocation

In this test, people are spawned in certain sections of the map and assigned a certain exit based on the shortest distance to those exits. The aim of this test is to determine whether agents move to appropriate exits. The result of this test was that a small section of the map (top left corner) chose the wrong exit. The agents calculate the distance to an exit as the crow flies. This resulted in some agents choosing the wrong exit as there was a big wall, and they had to walk around it. After fixing that part of the map, the model behaved accordingly.

[2]This number is arbitrary

Maximum flow rates

This test aims to verify whether agents leave at the programmed rate. This test was performed by assigning 100 agents the same exit and then tracking the queue size and number of agents in the model. After physically running the model 20 times and observing the queue, it was seen that the queue behaved accordingly. Therefore, it can be concluded that the model passed this test.

Congestion

In this test, agents have to walk through a smaller section and test whether they adjust their walking speed accordingly. After spawning a set of agents in a smaller section of the map and physically observing their behaviour, it was found that people hardly moved in bottlenecks, and were able to roam freely with their desired speed after the bottleneck. Therefore, this test was also passed.

4.3. MODEL VALIDATION

4.3.1. STRUCTURE TESTS

Direct structure assessment test

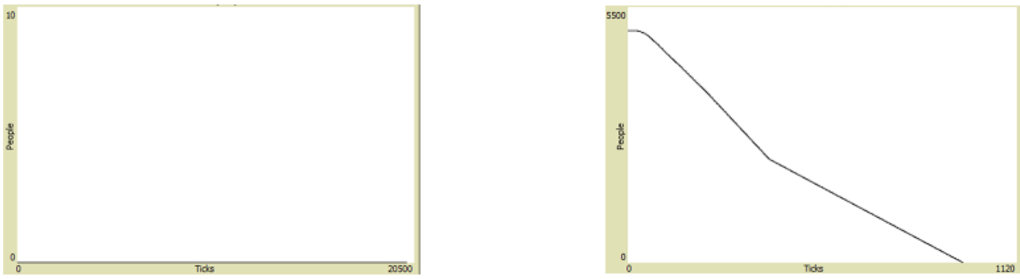
When looking at the structure of the model, it does show similarities to the real system. For instance, Groups stay together and follow one another; people evacuate when an emergency happens; people do not evacuate immediately, but have a reaction time; and only a certain number of people can leave the building per second. However, there are three aspects which may not exactly be according to the real system. First, locomotion models. In this model, the social force model is used as the locomotion model. In short, in models which use social force as their locomotion model, agents are either repelling or attracting other agents. If, for instance, a friend is in front of the agent he will be more inclined to move towards that agent while if there is a wall, the agent will be repelled. However, the social force model is not the only locomotion model available. In general, there are many types of locomotion models, ranging from force based models (e.g. the social force model) to heuristic based models (e.g. the behavioural heuristics model) (Helbing and Molnar, 1995; Seitz *et al.*, 2016). However, one is not necessarily better in every aspect (Kleinmeier *et al.*, 2019). Second, leader-follower behaviour and consensus decision-making. In this model, leader-follower behaviour is modelled in a general way. That is to say; the leader determines the path or exit and group members move towards the leader. However, there are still aspects of leader-follower behaviour which have yet to be incorporated. For instance, this model does not include backtracking (Y. Li *et al.*, 2021), or influence of other individuals on the leader (Mao, Fan, *et al.*, 2019; Mao, S. Yang, *et al.*, 2020). As regards modelling consensus decision-making, there are no agent-based models public which have incorporated consensus-decision making. Finally, the process of evacuating. In this model, once evacuees start moving towards their exit, they blindly walk towards that exit. This is not according to the real system. In the real system, evacuees may, amongst others, help each other (Drury *et al.*, 2009; Sivers, Templeton, Köster, *et al.*, 2014), change their exit choice mid-evacuation (Bode *et al.*, 2015), or trip while moving towards the exit (Santos and Aguirre, 2004).

Direct boundary adequacy test

The purpose of this model is to study the effect of groups on evacuation time. The main component in this model which answers that question is the presence of groups. Groups in this model are modelled in three ways; as a leader-follower group, a consensus decision-making group, or as groups with people who evacuate individually. One of the main assumptions in this model is that groups are fixed and members can, therefore, not change groups. this assumption limits the model in such a way that emergence may be suppressed because, in reality, members may become part of a different or bigger group (Lu *et al.*, 2017; Xiaoge *et al.*, 2014). Similarly, buildings often have multiple floors and research has shown that the presence of stairs influences evacuation dynamics (Huo *et al.*, 2016). Last but not least, this model does not contain a real emergency; it is only an alarm bell which sounds. In reality, the dynamics of an evacuation are different when different emergencies happen. Evacuees may react differently to, for instance, a shooter compared to a fire (Arteaga and Park, 2020; Kuligowski, 2013).
For the face validation, this model was presented to a number of experts in the field of evacuation studies. To be continued

4.3.2. BEHAVIOUR TESTS

Extreme behaviour test for the extreme behaviour test, two parameters were altered: Crowd size and reaction time. figure 4.10 and 4.14 show the results of this test. As can be seen, the model does not show peculiar results and holds under extreme conditions.



(a) Number of people left in the model against time with initially 0 people (b) Number of people left in the model against time with initially 5000 people

Figure 4.10: Extreme conditions test: Crowd size

Visual observation

Figure 4.11 shows a blank map where groups walk from one side to the other. As can be seen when walking across a field, groups stay together, walk more or less abreast, but do not overtake one another.

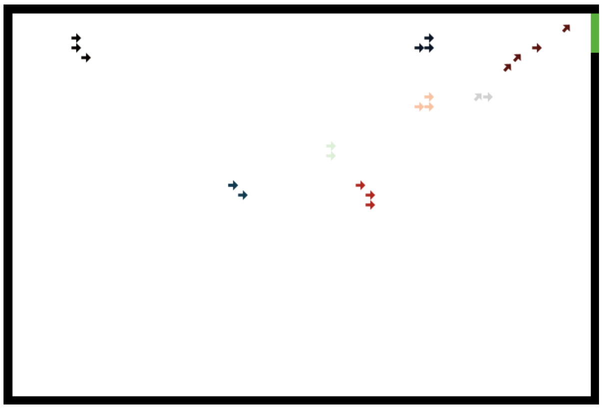
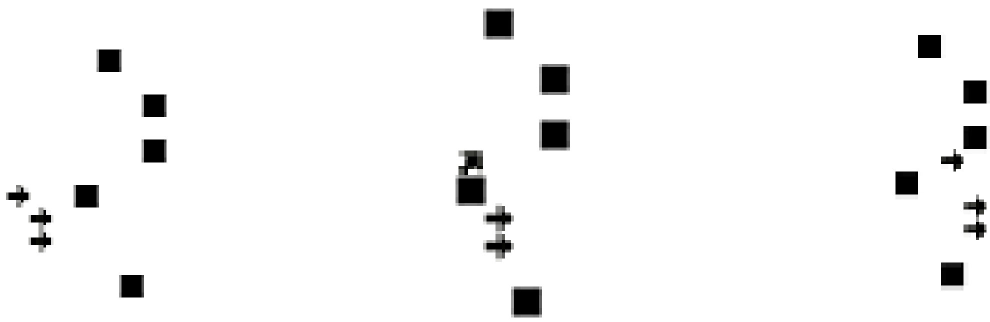


Figure 4.11: Groups walking across a field as a visual observation

In the corridor experiment (figure 4.12), it can be seen that both conditions are met. The group stay splits up and reunites after the obstacle.

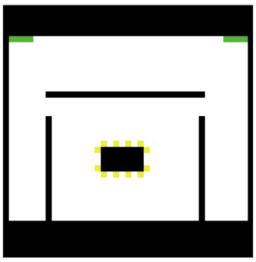


(a) Picture 1: before the obstacle (b) Midway the obstacle (c) After the obstacle

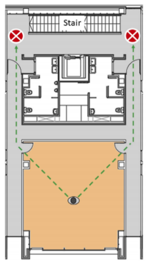
Figure 4.12: Group moving past an obstacle

Replicability test

For the replicability test, One studies was chosen as a benchmark. The first case study that will be used as part of the validation and calibration of the model is the research performed by Cuesta, Abreu, Balboa, *et al.* (2021). In this study they set up an experiment where they compared the evacuation decision-making between individuals and groups of varying size. The participants were placed in a room of 8.2 x 8.86 m (see figure 4.13) and had to evacuate when an alarm rang. They performed this experiment in three blocks: a block where each individual person was tested alone, one block in groups of 5, and one in groups of 12. After the experiment was done, they were asked to fill in a short questionnaire about the experiment. They found that larger groups are more efficient at evacuating than both individuals and smaller groups, groups had no preference with regard to exit choice, and that people who were trained tended to rise up and take up the role as a leader.



(a) Netlogo representation of the room



(b) Drawing of the room taken from Cuesta, Abreu, Balboa, *et al.* (2021)

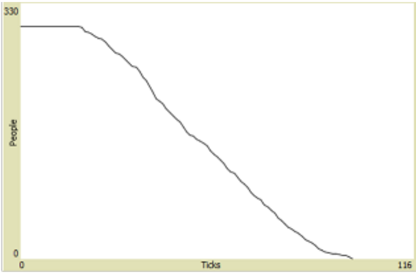
Figure 4.13: Drawings of the experimental setup

Table 4.3 shows the evacuation time of both the experiment of the case and the model. In the columns, you see the evacuation times of 24 experiments. Each number in the columns indicates the number of people in the room. The columns with 'model' in the header are the results of the same experiment, but then run through the model.

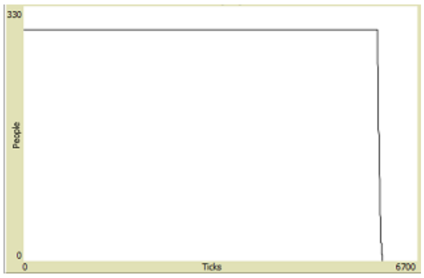
Table 4.3: Evacuation times in seconds of Cuesta's experiment versus evacuation times in ticks in the same setting, but then using the model

	Cuesta individual	Cuesta group of 5	Cuesta group of 12	Model individual	Model group of 5	Cuesta Group of 12
Run 0	17,02 (s)	20,72 (s)	18,78 (tick)	23 (tick)	43 (tick)	39 (tick)
Run 1	254,31 (s)	21,79 (s)	19,59 (s)	22 (tick)	34 (tick)	43 (tick)
Run 2	14,35 (s)	22,39 (s)	20,89 (s)	21 (tick)	33 (tick)	44 (tick)
Run 3	17,78 (s)	23,29 (s)	21,72 (s)	22 (tick)	36 (tick)	41 (tick)
Run 4	22,15 (s)	23,52 (s)	22,35 (s)	26 (tick)	31 (tick)	41 (tick)
Run 5	125,25 (s)	39,07 (s)	23,19 (s)	22 (tick)	30 (tick)	40 (tick)
Run 6	15,98 (s)	40,31 (s)	24,22 (s)	21 (tick)	34 (tick)	43 (tick)
Run 7	16,25 (s)	41,01 (s)	24,92 (s)	22 (tick)	32 (tick)	41 (tick)
Run 8	14,08 (s)	42,24 (s)	25,52 (s)	23 (tick)	30 (tick)	43 (tick)
Run 9	13,61 (s)	43,81 (s)	26,46 (s)	22 (tick)	33 (tick)	41 (tick)
Run 10	14,88 (s)	14,41 (s)	27,43 (s)	25 (tick)	34 (tick)	39 (tick)
Run 11	14,65 (s)	15,21 (s)	28,73 (s)	36 (tick)	36 (tick)	43 (tick)
Run 12	16,22 (s)	15,85 (s)	30 (s)	21 (tick)	37 (tick)	40 (tick)
Run 13	25,99 (s)	15,98 (s)	31,6 (s)	22 (tick)	36 (tick)	39 (tick)
Run 14	17,45 (s)	16,45 (s)	32,53 (s)	21 (tick)	36 (tick)	41 (tick)
Run 15	12,31 (s)	34,43 (s)	34,27 (s)	21 (tick)	31 (tick)	42 (tick)
Run 16	222,25 (s)	35,17 (s)	35,3 (s)	26 (tick)	36 (tick)	44 (tick)
Run 17	23,39 (s)	36 (s)	36,74 (s)	21 (tick)	39 (tick)	43 (tick)
Run 18	170,77 (s)	36,87 (s)	37,47 (s)	37 (tick)	34 (tick)	41 (tick)
Run 19	210,37 (s)	37,87 (s)	38,37 (s)	25 (tick)	32 (tick)	42 (tick)
Run 20	14,11 (s)	16,65 (s)	39 (s)	21 (tick)	35 (tick)	44 (tick)
Run 21	139,57 (s)	17,88 (s)	40,11 (s)	22 (tick)	32 (tick)	39 (tick)
Run 22	21,25 (s)	19,49 (s)	42,47 (s)	21 (tick)	34 (tick)	44 (tick)
Run 23		20,79 (s)	43,48 (s)	21 (tick)	38 (tick)	40 (tick)
Run 24		22,19 (s)	44,41 (s)	33 (tick)	33 (tick)	43 (tick)

The main difference between the results is that in the case study, a group of 12 is slower than a group of 5, while in the model, groups of 5 and 12 are about equally fast. Furthermore, through visual observation, it was observed that just like the case study, the evacuees did not show any preferences with respect to exit choice.



(a) Number of people left in the model against time with 0 reaction time



(b) Number of people left in the model against time with 6000 secs of reaction time

Figure 4.14: Extreme conditions test: reaction time

4

5

RESULTS

In this chapter, I will first discuss the experimental setup used for this research (section 5.1), after which I will show the results of the simulations (sections 5.2.1, 5.2.2, and 5.2.3).

5.1. EXPERIMENTAL SETUP

In this research, three sets of experiments were run to give an answer to the question of what the effect is of different group decision-making schemes on the evacuation time. Each experiment is run for a different purpose. The first experiment is meant to serve as an exploratory- and directed search experiment. This means that, a bigger sweep of parameters related to group characteristics will be done, but the size of the groups stays fixed. This experiment will be performed using the EMA Workbench (Kwakkel, 2017). With respect to the open exploration, 700 runs will be done, all of which will use Latin hypercube sampling to draw its values. Latin hypercube sampling is used because, compared to other sampling techniques, Latin hyper cube aims to distribute the sample points evenly across the given ranges. This even spread allows for a better overview of the potential behaviour of the model. Once the values are drawn, each run will be repeated of 150 times to cancel out randomness (see section 5.1.1). This means that 700 x 150 = 105000 runs will be performed in total. The length of each run is set to 800 ticks, since the workbench does not automatically go to the next run if there are no agents left in the model. This 800 tick limit does not influence the model and is only set for the purpose of the model moving on to the next run. With respect to directed search, this will be done based on a hypothetical scenario where it is considered unfeasible if there are still evacuees in the building after 8 minutes (approximately 500 seconds). The end result of this directed search is an overview of the parameter ranges, their precision, and their coverage. The algorithm used in this part of the experiment is the Patient Rule Induction Algorithm (PRIM). This algorithm was first introduced by Friedman and Fisher (1999), and uses subspace partitioning on the uncertainty space to find boxes which have the best trade-off between coverage (the fraction of the all outcomes which lay in the box) and density (fraction of outcomes which are of interest).

The second and third experiment were designed to give insight into the effect of different schemes on the evacuation time. This experiment was run using the behaviourspace tool supplied in Netlogo. Both of these experiments made use of a partial-factorial experiment and were also repeated 150 times (see section 5.1.1). A partial factorial was used, since a full factorial would require too much time given the timespan of this research. The difference between these two experiments is that in the second experiment, groups are set fixed to "Mix" while in the third experiment group sizes were altered (2,3,5). The respective runs are 5 x 5 x 5 x 11 x 150 = 206250 and 3 x 3 x 3 x 3 x 6 x 150 = 72900 runs.

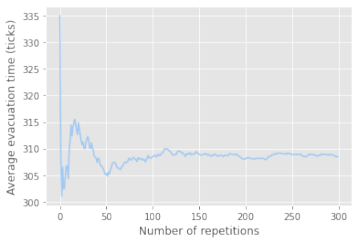
Table 5.1: Overview of the experiments, their variables, and their respective values

Experiment	Variable	Value	Type of experiment	Tool used
Model exploration and directed search (105000 runs)	Percentage-familiar Percentage-leader-follower Percentage-consensus Group-size Nr-of-people	(0,1) (0, 1) (0, 1) "Mix" (0, 500)	Latin hypercube sampling	EMA Workbench
Effect of different group types on evacuation time (206250 runs)	Percentage-familiar Percentage-leader-follower Percentage-consensus Group-size Nr-of-people	[0 0.25 1] [0 0.25 1] [0 0.25 1] "Mix" [100 50 500], (1000, 1500)	fractional factorial design	Behavior space
Effect of different group sizes on evacuation time (72900)	Percentage-familiar Percentage-leader-follower Percentage-consensus Group-size Nr-of-people	(0.33, 0.5, 0.66) (0.25, 0.5, 0.75) (0.25, 0.5, 0.75) (2, 3, 5) (150, 300, 450, 500, 1000, 1500)	fractional factorial design	Behavior space

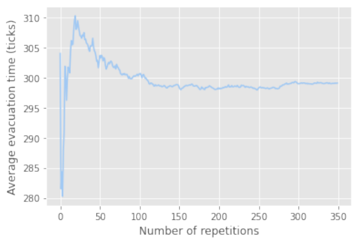
Table 5.1 provides an overview of the experiments, their respective parameter values, their type, and the tool used to run the experiment. In the value column, two different type of brackets are used. In the first experiment, the parentheses mean the ranges of the values of which will be sampled. In the second and third experiment, parentheses mean exact values used and brackets indicate begin value, increment, and end-value.

5.1.1. NUMBER OF REPETITIONS

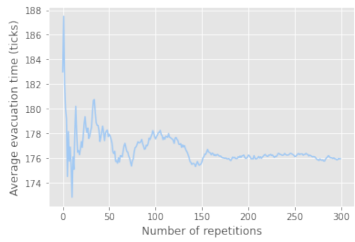
When exploring models, one must run the model more than one time. One must run a model multiple times as one must be sure that the results are a pattern, and not a one-time occurrence (Wilensky and Rand, 2015). Furthermore, when running agent-based models, one must be sure that a sufficient number of runs has been chosen. As can be seen in figure 5.1, after 150 repetitions, the average evacuation time stabilizes. Therefore, 150 repetitions was chosen as the threshold to run the experiments.



(a) Plot of a run with 300 repetitions and high density



(b) Plot of a run with 350 repetitions and high density



(c) Plot of a run with 200 repetitions and high density

Figure 5.1: Average evacuation time versus number of repetitions

5.2. RESULTS

5.2.1. SIMULATION RESULTS EXPERIMENT 1: OPEN EXPLORATION OF THE MODEL

The first experiment was performed to get a feeling of what potential behaviour the model can show and to illustrate the use of the EMA Workbench. Figure 5.2 shows a plot of the number of people left in the model plotted against the time in the model of all runs; each line represents a run. It can be deduced from this figure that this model shows both behavioural sensitivity and numerical sensitivity. The general trend is that the number of people in the model stays the same until about 40 ticks, after which in all runs the number of agents in the model starts decreasing. The decline in number of people left in the model differs. Some runs show a linear decrease, others show a step-wise decrease or a decrease in the efficiency of the evacuation. In general, the number of crowd size starts decreasing and at 800 ticks almost everyone has evacuated.

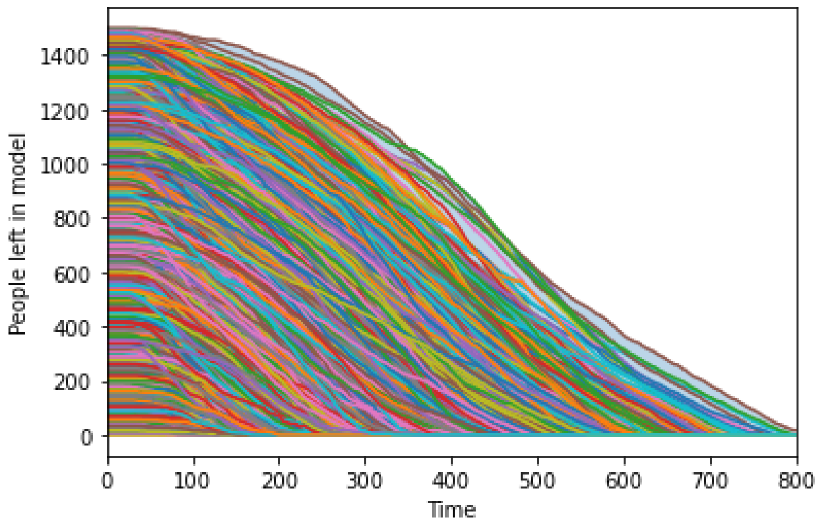


Figure 5.2: Number of people left in the model plotted against time under varying parameter settings using Latin hypercube sampling

Next to an open exploration, a directed search was performed as well to find the scenarios in which after about 8 minutes people were still left in the building. Figure 5.3 shows a summary of the results of the directed search using the PRIM algorithm. This figure has different pieces of information. On the left-hand side, the parameters, their p-values, and their respective value ranges are indicated. As regards p-values, these are respectively 0.13, 1.1e-79 and 0.12. With respect to the ranges, from this image, it can be deduced that the parameter ranges are respectively 0.1 to 1, 1.1e+03 to 1.5e+03, and 0 to 0.93. On the right-hand side, the density and coverage are shown. These two values indicate that with 67% of the experiments of interest can be described with 92% accuracy. In short, this image indicates that 67% of the experiments of interests can be described with 92% accuracy by imposing restrictions on 3 dimensions; having percentage of consensus groups between 10- and 100%, having the percentage of people who are familiar between 0- and 93%, and having the crowd size between 1100 and 1500. Furthermore, the range of crowd size is statistically significant as its p value is below 0.05.

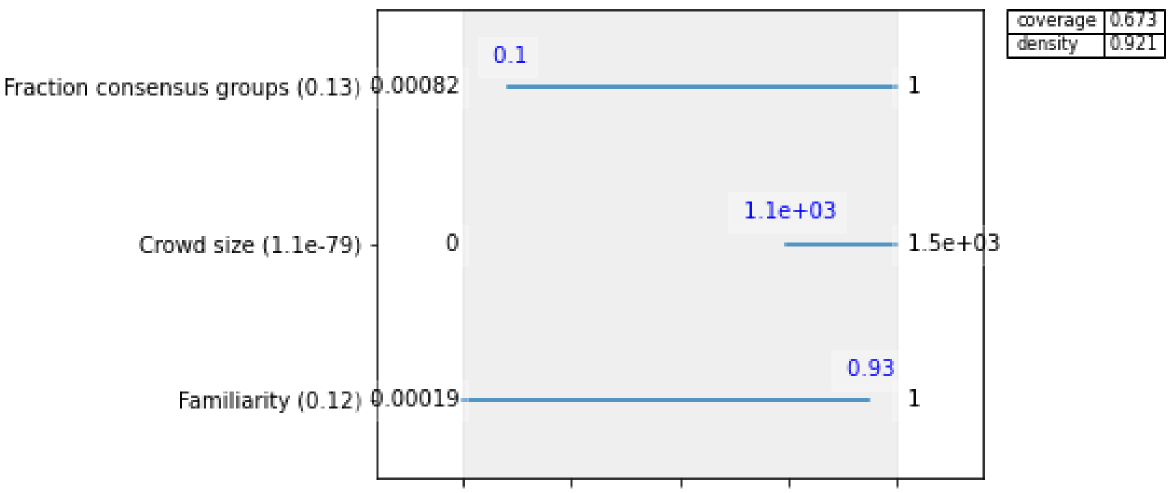


Figure 5.3: Overview of the respective parameters, values, and statistical significance of the parameters for the desired scenarios

Figure 5.4 shows the same result of the scenario discovery, but now in pair plots. In this plot, the orange dots indicate experiments which still have evacuees left in the model after 500 ticks and blue indicate experiments which have no evacuees left in the model after 500 ticks. From the two pair plots in the top right corner, it becomes clear that population does play a significant role in the evacuation times.

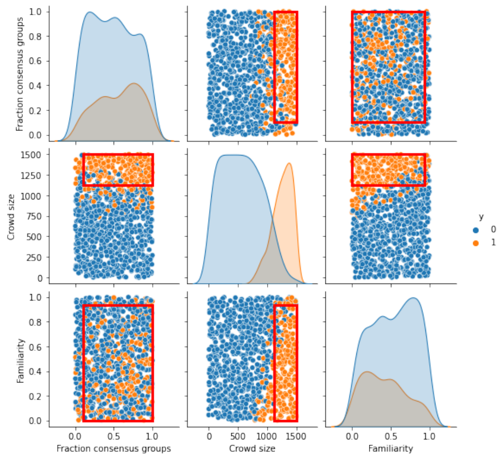


Figure 5.4: Pair plots of the result of directed search

5.2.2. SIMULATION RESULTS EXPERIMENT 2: THE EFFECT OF MIXED SCHEMES IN DIFFERENT CROWD DENSITIES

Figure 5.5 shows the result of the first experiment. As mentioned before, this experiment aims to give insight into the effect of different decision-making schemes on the evacuation time. In this figure, the mean evacuation time of different fractions of group decision-making schemes is plotted against crowd densities. This figure indicates that when groups are present in a building, the evacuation time becomes higher. That is to say, when a group is characterized by either leader-follower or consensus decision-making, they will take longer to evacuate than when they evacuate individually. This can be seen by looking at the third graph; when 100% of the crowd is evacuating individually (representing the scenario where there are no groups), the evacuation time is the lowest, no matter the density of the crowd. Another interesting observation in this case is that leader-follower and consensus decision-making show similar patterns and hardly differ from one another.

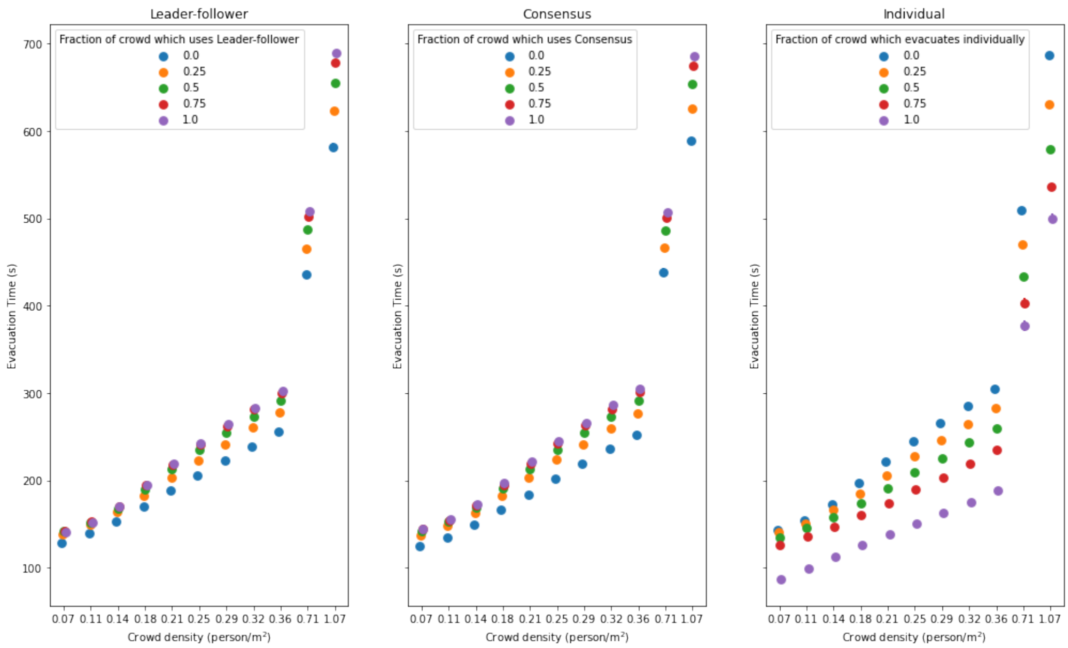


Figure 5.5: Plots of evacuation time under different percentages of groups under varying crowd sizes

Figure 5.6 shows the result of running different percentages of familiarity against different fractions of group decision-making schemes. These plots also show the average evacuation time of different percentages of group forms, but now using familiarity. In this case, the results show that when people evacuating together or individually, higher familiarity leads to lower evacuation times. At every crowd density used, 100% familiarity always leads to the lowest evacuation time, and 0% leads to the highest. Furthermore, when the fraction of the crowd which uses a certain decision-scheme exceeds 75%, and no one is familiar (0% familiarity), leader-follower is more efficient than consensus. Moreover, in case of people evacuating individually, 100% familiarity leads to the lowest evacuation time. Similarly, the higher the number of people who evacuate individually, the more significant the impact of 100% familiarity becomes. That is to say, at 25% of the crowd evacuating individually, the gap between 75% and 100% familiarity is smaller than the gap at 100% of the people evacuating individually.

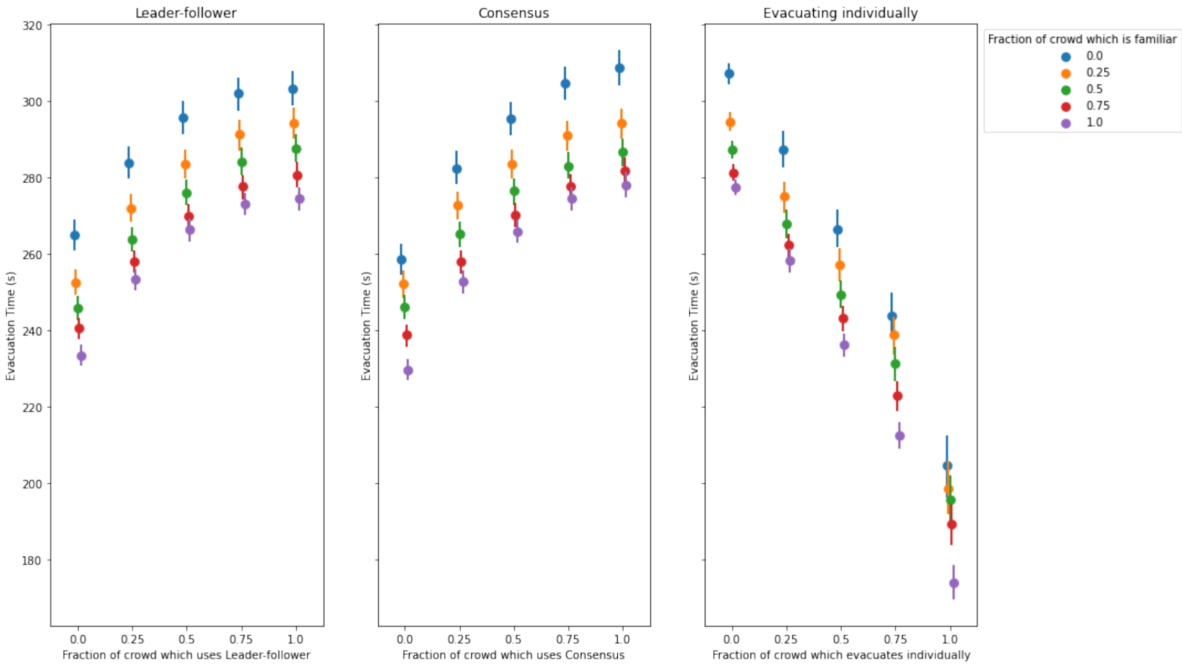


Figure 5.6: Plots of evacuation time under different fractions of group decision-schemes and different percentages of familiarity amongst the crowd

Interestingly, when having a closer look at lower densities (0.07 to 0.36), it actually can actually be observed that higher familiarity leads to higher evacuation times in case of a fraction number of groups (see figure 5.7). As the percentage of groups increases at lower densities, a higher familiarity will lead to a higher evacuation time. Another interesting observation is that when all the people are familiar with the building, different compositions of the crowd have different effects in lower densities. For instance, when 75% of the crowd is made up of people who evacuate individually, 100% familiarity leads to the lowest evacuation times. But, when 100% of the crowd is familiar and everybody evacuates alone (100% of the crowd evacuates individually), it will lead to the third-lowest average evacuation time.

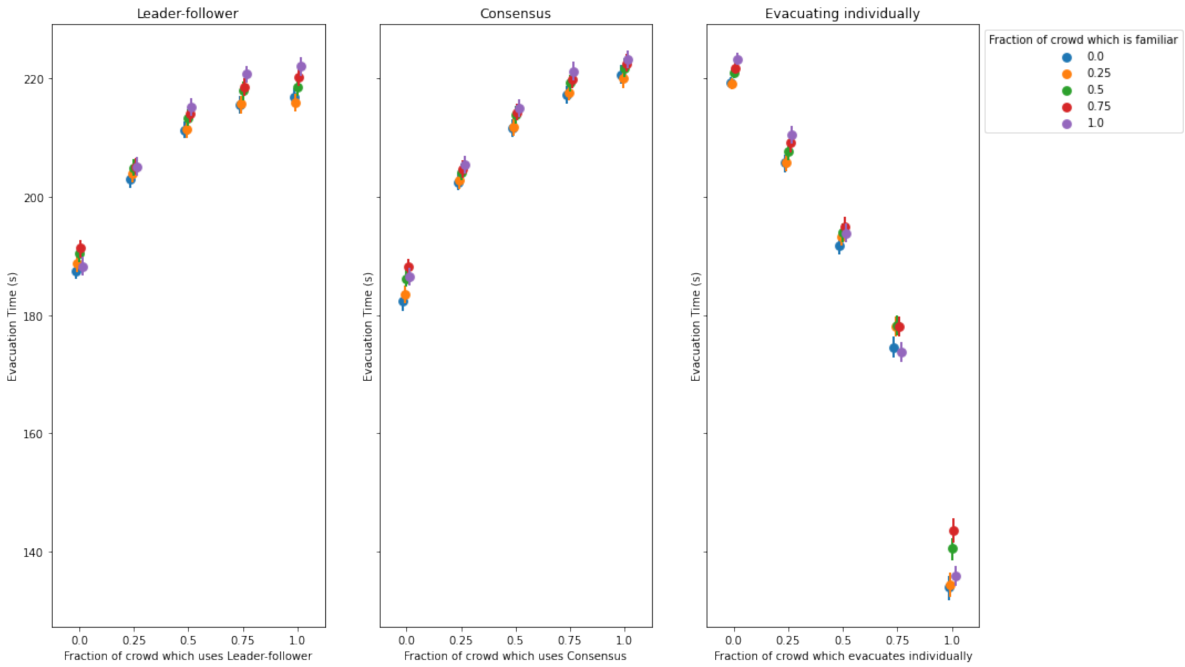


Figure 5.7: Plots of evacuation time under different fractions of group decision-schemes and different percentages of familiarity amongst lower crowd densities

5.2.3. SIMULATION RESULTS EXPERIMENT 3: THE EFFECT OF DIFFERENT GROUP SIZES AND CROWD COMPOSITIONS

In the third experiment, group sizes were altered to determine the effect of different group sizes in combination with different crowd compositions on the evacuation time. Figure 5.8 shows the effect of different group sizes in varying crowd densities. First, it can be observed that in all the crowd densities, bigger group sizes lead to higher evacuation times. Secondly, from this figure, it can be observed that as the crowd density increases, the gap between the smaller groups and bigger groups becomes more significant. For instance, in case of a crowd density of 0.36, the difference in average evacuation time is about 20 between group size 5 and 3, while in case of a crowd density of 0.71, this has increased to 50.

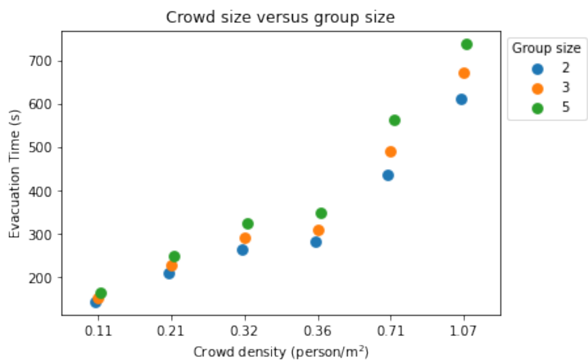


Figure 5.8: Plots of the effect of varying group sizes and crowd densities on the evacuation time

In figure 5.9, fractions of different groups is plotted against different group sizes. The small stripes above and below the dots are the 95% confidence intervals. From this figure, it can be deduced that as the group sizes increase, the evacuation time increases. Furthermore, when looking at the differences between consensus groups and leader-follower groups, it can be observed that they have similar evacuation times except for when the fraction of groups reaches 75%. If you compare the 0.75 percentage data, it shows that consensus groups are on average around 10 seconds faster.

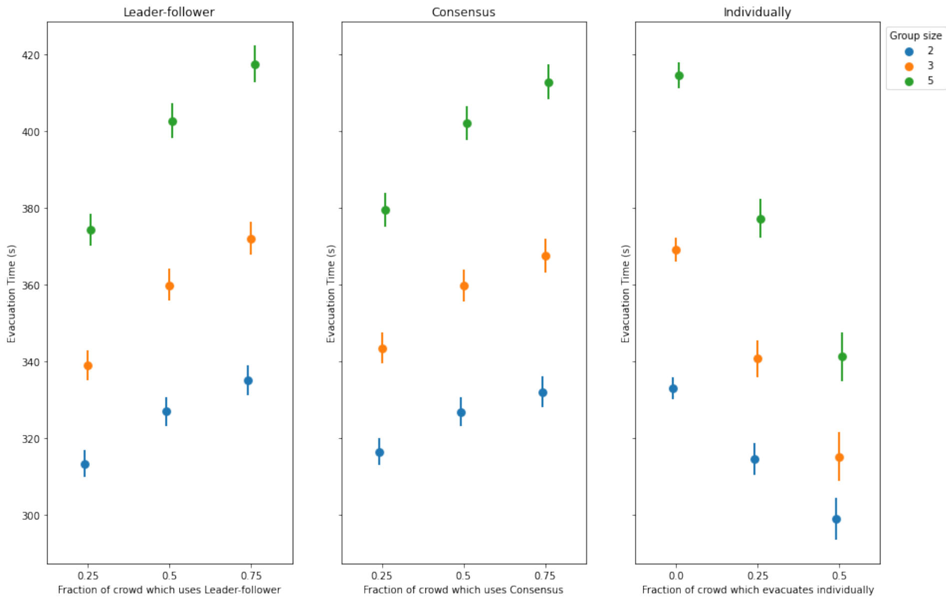


Figure 5.9: Plots of the effect of different compositions of groups on evacuation time

6

Conclusion and discussion

Studying the effect of groups is critical for preventing casualties during evacuations. Studying the effects of groups can be done by modelling. However, there are hardly any models present which include the notion of groups. This study aims to address this need by answering the following question: "*What is the effect of two different group decision-making schemes (consensus and leader-follower) on the evacuation time, compared to individual decision-making?*". In order to give an answer to this question, this study used an exploratory agent-based model built in Netlogo, and the EMA Workbench to explore the model. In the next section, The results of this research will be discussed. After having discussed the results, an elaboration will be given on the strengths, weaknesses, and implications of this research. Finally, conclusions will be drawn.

6.1. Discussion

First of all, it was found that the presence of groups significantly influences the evacuation time. Results suggest that the presence of groups increases the evacuation time significantly. This finding supports (Haghani, Sarvi, *et al.*, 2019; Bode *et al.*, 2015; Lu *et al.*, 2017), but also contradicts, previous findings(Van der Wal *et al.*, 2017; Cuesta, Abreu, Balboa, *et al.*, 2021). With respect to supporting previous findings, Bode *et al.* (2015) found that groups increase the total evacuation time because they take longer to initiate movement and take longer to move into the vicinity of the exits. As regards contradicting, other studies have concluded that groups are more efficient at evacuating (Van der Wal *et al.*, 2017; Cuesta, Abreu, Balboa, *et al.*, 2021). Cuesta, Abreu, Balboa, *et al.* (2021) suggest that bigger groups are more efficient at evacuating because of social structures and individuals of a group being less subjected to stress. Similarly, Van der Wal *et al.* (2017) argue that groups were more efficient at evacuating than individuals because of social contagion.

Secondly, digging one step deeper into the effect of groups, the size of the group has shown to be one of the biggest influences of groups on evacuation time. It was observed that the bigger the groups, the longer it will take to evacuate the whole building. This is in contradiction with previous findings (Bode *et al.*, 2015; Von Krüchten and Schadschneider, 2017; Haghani, Sarvi, *et al.*, 2019). They all argue that bigger groups are more efficient at evacuating. To the best of my knowledge, there are two possible explanations. First, a possible explanation for this result is that in this research, evacuees were modelled in such a way that they were not able to change their exit choice during the run. If an exit is chosen, they go to that exit, even if it is packed at that exit. In reality, if it is a very busy at a certain exit and evacuees are under stress, some groups may decide to change their exit decision and leave the building through at different exit (Sime, 1985). Especially if you combine that with the finding that under stressful conditions, groups are likely to switch their exit choice due to social influence (Haghani, Sarvi, *et al.*, 2019). That is to say, if a group decides to switch their exit choice, nearby groups may follow. Secondly, a possible explanation may be the fact that the exit dynamics may have not been modelled extensively enough. Empirical research has shown that at exits, groups focus on their own group and not on others (Von Krüchten and Schadschneider, 2017; Bode *et al.*, 2015). That is to say, when people are evacuating by themselves, they care about nothing else but themselves, which leads to potential conflicts in the queue. When groups are present, more order arises when queueing for an exit, decreasing the number of potential conflicts and speeding up the evacuation process. An interesting point to notice is that, contrary to empirical studies, some simulations models do show that the bigger the group-size, the higher the evacuation time (Lu *et al.*, 2017; You *et al.*, 2016). However, to my knowledge, these studies did not include an extensive queue process or social influence.

Thirdly, results show there is hardly any difference in average evacuation time between leader-follower and consensus given a mixture of familiarities. Thus far, there is no study present which has looked into modelling consensus decision-making, or the differences between consensus groups and leader-follower groups in case of evacuations. However, in this model, the process of a consensus group evacuating is in some way similar to that of a leader follower group; the groups first gather, and then evacuate together. The main difference between these two types of groups is that consensus groups first all have to agree before evacuating, while this is not the case with leader-follower groups. Furthermore, in case of consensus groups in this model, people who are familiar with the building are able to convince the others that they are right and know the closest exit. That is to say, in case someone in the group is familiar with the building, the group will always go to the closest exit. Similarly, the speed at which a group member agrees with the rest of the group is positively related to the number of people present who are familiar with the building. With this in mind, it may be that since consensus groups take longer to initiate movement towards an exit, but do go to the nearest exit more often, they may act like groups characterized by leader-follower where people who are familiar with the building act as leaders. In general, this may be a valid way to model consensus decision-making. Haghani, Sarvi, *et al.* (2019) have, for instance, concluded that in 50% of the cases in their experiment, people took the lead and claimed knowing the way. Similarly, Cuesta, Abreu, Balboa, *et al.* (2021) observed that within groups that used consensus with respect to evacuating, people often took the role of leader and initiated the evacuation process. Therefore, modelling a group with consensus decision-making as a leader-follower group with an additional information distribution process may well be a valid way.

6

Fourthly, three different findings were found with respect to familiarity, groups, and evacuation time. First, in higher crowd densities, higher familiarity leads to lower evacuation times in case of both groups and people who evacuate individually. This finding is supported by previous studies Horiuchi *et al.* (1986) and Richardson *et al.* (2019). Richardson *et al.* (2019) performed a study where they used an agent-based model to analyse the effect of familiarity amongst a crowd on the evacuation time. They found that the more people are familiar with the building, the lower the evacuation time will be. Secondly, In smaller crowd densities, it may have an adverse effect on the evacuation time. It was found that if a high percentage of the crowd is groups (75% or more), higher familiarity leads to higher evacuation times. A special case, however, is 100% familiarity. 100% familiarity gives different, and sometimes surprising, results under varying crowd compositions. For instance, if everyone is evacuating by themselves and 100% of the crowd is familiar with the building, evacuation times will not the lowest. However, if 25% of the crowd is now evacuating as a group, 100% familiarity does lead to the lowest evacuating times. Interestingly, 100% familiarity almost never leads to the quickest evacuation. Only in case of 75% of the people evacuating alone, is it the most beneficial. A possible explanation for this emergent behaviour could be that in this model, the capacity at exits was too little and agents do not change their decisions with respect to exit throughout the simulation. In other words, if everybody is familiar, they will all walk towards the same exit. If then the capacity of the exit is not great enough, a lot of congestion will emerge. If only half of the people were to be familiar with the building, people would spread more evenly. Similarly, not being able to switch decisions on exit choice may reinforce congestion at an exit. With regard to literature on capacity at exits, this is still understudied and may be based on assumptions which are not valid. Studies which look at exit capacity often assume that people have complete knowledge and know which exit is the least busy (e.g. Desmet and Gelenbe (2014), and Chen *et al.* (2015). This is not valid, as people may only know which exit is the least occupied through, for instance, smart systems (Nguyen *et al.*, 2019; Santana *et al.*, 2020). Thirdly, at 0% familiarity, and a high (over 75%) fraction of the crowd which uses a certain decision-making scheme, leader-follower is more efficient. This is plausible behaviour, since consensus decision-making has an additional distribution of information factor. Groups which use leader-follower evacuate immediately when the group has gathered, groups which use consensus first have to exchange information. At 0% familiarity, everyone in the building goes to the same exit. Extra time spending on discussing means longer evacuation times.

6.2. Strengths, limitations, and future research

To my knowledge, this study is one of the first to develop a model which includes the notion of group decision schemes during evacuations. Hardly any models, and in particular agent-based models, are made which focus on the notion of groups influencing evacuation behaviour. Similarly, this is one of the studies which uses an exploratory modelling approach to deal with uncertainty systematically. Modellers come across uncertainty throughout the whole process of developing a model (section 3.1), but modellers rarely deal with this systematically. Furthermore, the development of the model was based on insights gained from scientific literature and findings, and was validated extensively. The model was validated using multiple validation tests and by comparing the simulated data to that of an experiment (Cuesta, Abreu, Balboa, *et al.*, 2021; Forrester and Senge, 1980; Nikolic *et al.*, 2019). The model showed to be fit for the purpose of being a stepping stone towards modelling social groups in evacuations. However, this model does have its limitations.

One of the first limitations of this model is that there are different ways to model pedestrian movement. This model uses the social force model as its locomotion model, but different locomotion models, such as optimal steps (Sivers, Templeton, Künzner, *et al.*, 2016), should be used as well since different locomotion models could potentially lead to different results. Another limitation is that this study modelled leader-follower in a basic manner. In this model, when an emergency happens; all members gather, the one assigned as leader determines where the group goes, and the group just blindly follows the leader towards that exit without their decision-making being able to be influenced. However, research has shown that windows of opportunities do arise where evacuees can change their initial decisions during evacuations, and that implementing the possibility to change these decisions increases the accuracy of models (Haghani and Sarvi, 2019b). Furthermore, research has shown that groups can become part of bigger groups and individuals can become part of multiple groups or switch groups (Quarantelli, 1995). Similarly, leaders of a group may suddenly not be leaders any more (Mao, Fan, *et al.*, 2019), and non-group members may influence the group (Mao, S. Yang, *et al.*, 2020). As regards determining the leader, this model assigns the role of leader to the group member with the lowest "ID". This is one of the ways which is used to model the assignment of leaders. However, in practice there are other ways as well (e.g. the one closest to the exit (Qin *et al.*, 2018), or the one in the center (Zhang *et al.*, 2018)). One last important limitation is that modelling consensus decision-making is understudied. Since there is hardly any to no literature available on modelling consensus decision-making. This may have been done either too simplistically. Therefore, more research on consensus decision-making has to be done. One last limitation of the model is that it did not include social behaviour. As mentioned in the discussion section, social influence plays, amongst others, a role in exit choice. Therefore, implementing social influence is important. Considering the above-mentioned limitations, I will elaborate on several recommendations for future research in the next few paragraphs.

The first recommendation for future research is to expand the model by adding the following; the different ways in which leader-follower can be modelled, and factors which influence evacuations. With respect to the former, This model only included the basics of leader-follower behaviour, but the literature study has shown that there are different nuances to modelling leader-follower behaviour. For instance, some models included backtracking of the leader, while others allowed members to switch groups based on certain circumstances. These variations of modelling leader-follower behaviour could potentially have different effects on the evacuation time. Therefore, the different ways of modelling leader-follower behaviour should be added to this model. With respect to the latter, this study shows that groups have a significant impact on evacuation time. However, there are other factors which influence the dynamics of evacuations; factors such as social influence or emergent norms (see Aguirre, Wenger, *et al.* (1998)) are known to influence evacuation behaviour. Hence, models should be created where different factors are combined with social groups and are evaluated using exploratory modelling.

The second recommendation is that more research has to be done on consensus decision-making during evacuations, and more specifically modelling consensus decision-making. Literature has shown that consensus decision-making does occur, but there are hardly studies out there which discuss consensus decision-making during evacuations, let alone model consensus decision-making.

The last recommendation is that future research should also focus on the different phases of evacuation time. In this model, evacuation time is the time between the alarm going off and the person or group leaving the building. However, in this evacuation time different phases are identified. Proulx (2002) observed that the evacuation time is made up of; the reaction time, the decision time, and the actual period of moving. Analysing the effect of groups on different segments of the evacuation time could be beneficial for understanding the effect of groups on evacuations.

6.3. IMPLICATIONS

This research has both theoretical and practical implications. As regards theoretical implications, there are three implications. First of all, this research has shown that agent-based modelling is a suitable method for modelling group characteristics. In this research, the focal point was decision-making schemes. However, due to the diverse nature of agent-based modelling, other important factors, such as culture (Almejmaj and Meacham, 2014), may easily be modelled as well using agent-based modelling. Secondly, exit capacity should be taken into account when assessing evacuations. As familiarity increases, more people, and therefore groups, take the closest exit. If the capacity at that exit is too low, congestion will occur, eventually limiting the outflow. Similarly, studies which look at the capacity of exits assume evacuees know which exit is the least crowded; this is often not the case. Therefore, evaluating exit capacity, while keeping in mind that evacuees most of the time do not know the least crowded exit, could provide new insights into evacuation behaviour.

As regards practical implications, there are important implications for policymakers, but also emergency response officers. According to this study, groups increase the evacuation time, and different compositions of groups have different effects under different familiarities. This implies that when it comes to designing policies, policymakers have to take into account the context. For instance, at subway stations in a very busy city, different measures have to be taken compared to a really quiet station in the outskirts. In crowded dense cities, being familiar with a building always leads to lower evacuations times, while in places with lower crowd densities, familiarity may have an adverse effect. However, in general, all policies should take into account that evacuating individually is quicker than evacuating as a group. In case of evacuations, emergency response officers should tell all the evacuees to just leave the building and that they will warn their fellow group members (if they are present).

6.4. CONCLUSION

In sum, models on evacuations often lack the inclusion of psychological factors. One of these psychological factors which is known to influence evacuations is the presence of groups. However, the presence of group has yet to be modelled extensively, is the effect of groups. Therefore, this study aims to develop and validate an exploratory agent-based model on the effect of group decision-making schemes on the evacuation. To do so, this study tries to answer the following research question: *"What is the effect of two different group decision-making schemes (consensus and leader-follower) compared to individual decision-making on the evacuation time inside buildings?"*. Results suggest that evacuating in groups is slower than evacuating individually, bigger groups lead to higher evacuation times, and that familiarity has different effects in low and high crowd densities. An important new finding in this research is that when groups are present in low crowd densities, lower familiarity may actually lead to lower evacuation times. Similarly, leader-follower and consensus have the same effect on the evacuation time, except for when no one is familiar. In case of 0% familiarity, leader-follower leads to lower evacuation times. However, this study also has its limitations. For instance, one of the limitations of this study is that the two decision schemes may have not been modelled too extensively enough, that it made use of one locomotion model when there are multiple options available, or that it did not include social factors. In order to deal with these limitations, future research should focus on modelling different ways of modelling groups, on adding social factors, and on analysing the effect of groups on different segments of the evacuation time. Overall, this research provides a good stepping stone towards modelling groups using an exploratory agent-based modelling approach, and has important implications.

7

References

Aguirre, B. E., El-Tawil, S., Best, E., Gill, K. B., and Fedorov, V. (2015). "Contributions of social science to agent-based models of building evacuation". In: *Crowds in the 21st Century*. Routledge, pp. 163–180.

Aguirre, B. E., Wenger, D., and Vigo, G. (1998). "A test of the emergent norm theory of collective behavior". In: *Sociological Forum*. Vol. 13. 2. Springer, pp. 301–320.

Allport, F. H. (1924). "The group fallacy in relation to social science". In: *American Journal of Sociology* 29.6, pp. 688–706.

Almejmaj, M. and Meacham, B. (2014). "The Effects of Culture-Specific Walking Speed and Pre-Movement Data on Egress Modeling in Shopping Malls-A Comparative Analysis". In: *10th International Conference in Performance-Based Codes and Fire Safety Design Methods*.

Antonini, G., Bierlaire, M., and Weber, M. (2006). "Discrete choice models of pedestrian walking behavior". In: *Transportation Research Part B: Methodological* 40.8, pp. 667–687.

Antrop, M. (2004). "Landscape change and the urbanization process in Europe". In: *Landscape and urban planning* 67.1-4, pp. 9–26.

Arrow, K. J. (2012). *Social choice and individual values*. Yale university press.

Arteaga, C. and Park, J. (2020). "Building design and its effect on evacuation efficiency and casualty levels during an indoor active shooter incident". In: *Safety science* 127, p. 104692.

Asch, S. E. (1956). "Studies of independence and conformity: I. A minority of one against a unanimous majority." In: *Psychological monographs: General and applied* 70.9, p. 1.

Auping, W. (2018). "Modelling uncertainty: Developing and using simulation models for exploring the consequences of deep uncertainty in complex problems". PhD thesis. Delft University of Technology.

Aveni, A. F. (1977). "The not-so-lonely crowd: Friendship groups in collective behavior". In: *Sociometry*, pp. 96–99.

Axtell, R. (2000). "Why agents?: on the varied motivations for agent computing in the social sciences". In:

Bandini, S., Federici, M. L., Manzoni, S., and Vizzari, G. (2005). "Towards a methodology for situated cellular agent based crowd simulations". In: *International Workshop on Engineering Societies in the Agents World*. Springer, pp. 203–220.

Bankes, S., Walker, W. E., and Kwakkel, J. H. (2013). "Exploratory modeling and analysis". In: *Encyclopedia of operations research and management science*, pp. 532–537.

Bankes, S. (1993). "Exploratory modeling for policy analysis". In: *Operations research* 41.3, pp. 435–449.

Bankes, S. C. (2002). "Tools and techniques for developing policies for complex and uncertain systems". In: *Proceedings of the National Academy of Sciences* 99.suppl 3, pp. 7263–7266.

Bazghandi, A. (2012). "Techniques, advantages and problems of agent based modeling for traffic simulation". In: *International Journal of Computer Science Issues (IJCSI)* 9.1, p. 115.

Black, D. (1948). "On the rationale of group decision-making". In: *Journal of political economy* 56.1, pp. 23–34.

Black, D. *et al.* (1958). "The theory of committees and elections". In:

Bode, N. W., Holl, S., Mehner, W., and Seyfried, A. (2015). "Disentangling the impact of social groups on response times and movement dynamics in evacuations". In: *PloS one* 10.3, e0121227.

Bonabeau, E. (2002). "Agent-based modeling: Methods and techniques for simulating human systems". In: *Proceedings of the national academy of sciences* 99.suppl 3, pp. 7280–7287.

Bradley, G. (1993). “A proposed mathematical model for computer prediction of crowd movements and their associated risks”. In: *Proceedings of the International Conference on Engineering for Crowd Safety*, pp. 303–311.

Braun, A., Bodmann, B. E., and Musse, S. R. (2005). “Simulating virtual crowds in emergency situations”. In: *Proceedings of the ACM symposium on Virtual reality software and technology*, pp. 244–252.

Chen, L.-W., Cheng, J.-H., and Tseng, Y.-C. (2015). “Distributed emergency guiding with evacuation time optimization based on wireless sensor networks”. In: *IEEE Transactions on Parallel and Distributed Systems* 27.2, pp. 419–427.

Coleman, J. S. and James, J. (1961). “The equilibrium size distribution of freely-forming groups”. In: *Sociometry* 24.1, pp. 36–45.

Colombo, R. M. and Rosini, M. D. (2005). “Pedestrian flows and non-classical shocks”. In: *Mathematical methods in the applied sciences* 28.13, pp. 1553–1567.

Conradt, L. and List, C. (2009). “Group decisions in humans and animals: a survey”. In: *Philosophical transactions of The Royal Society B: biological sciences* 364.1518, pp. 719–742.

Conradt, L. and Roper, T. J. (2003). “Group decision-making in animals”. In: *Nature* 421.6919, pp. 155–158.

Couclelis, H. (2002). “Modeling frameworks, paradigms, and approaches”. In: *Geographic information systems and environmental modeling. Upper Saddle River, NJ: Prentice Hall*, pp. 36–50.

Couzin, I. D., Krause, J., Franks, N. R., and Levin, S. A. (2005). “Effective leadership and decision-making in animal groups on the move”. In: *Nature* 433.7025, pp. 513–516.

Crooks, A. T. and Heppenstall, A. J. (2012). “Introduction to agent-based modelling”. In: *Agent-based models of geographical systems*. Springer, pp. 85–105.

Cuesta, A., Abreu, O., and Alvear, D. (2015). *Evacuation modeling trends*. Springer.

Cuesta, A., Abreu, O., Balboa, A., and Alvear, D. (2021). “Alone or with others: Experiments on evacuation decision making”. In: *Fire Safety Journal* 120, p. 103018.

7

D’Orazio, M., Spalazzi, L., Quagliarini, E., and Bernardini, G. (2014). “Agent-based model for earthquake pedestrians’ evacuation in urban outdoor scenarios: Behavioural patterns definition and evacuation paths choice”. In: *Safety science* 62, pp. 450–465.

Daoliang, Z., Lizhong, Y., and Jian, L. (2006). “Exit dynamics of occupant evacuation in an emergency”. In: *Physica A: Statistical Mechanics and its Applications* 363.2, pp. 501–511.

Davis, J. H. (1973). “Group decision and social interaction: A theory of social decision schemes.” In:

Davis, J. (1969). “Group Performance Addison Wesley”. In: *Reading Mass*.

Desmet, A. and Gelenbe, E. (2014). “Capacity based evacuation with dynamic exit signs”. In: *2014 IEEE International Conference on Pervasive Computing and Communication Workshops (PERCOM WORKSHOPS)*. IEEE, pp. 332–337.

Drury, J. (2004). *No need to panic*.

Drury, J., Cocking, C., and Reicher, S. (2009). “Everyone for themselves? A comparative study of crowd solidarity among emergency survivors”. In: *British Journal of Social Psychology* 48.3, pp. 487–506.

Duives, D. C., Daamen, W., and Hoogendoorn, S. P. (2013). “State-of-the-art crowd motion simulation models”. In: *Transportation research part C: emerging technologies* 37, pp. 193–209.

Dyer, J. R., Ioannou, C. C., Morrell, L. J., Croft, D. P., Couzin, I. D., Waters, D. A., and Krause, J. (2008). “Consensus decision making in human crowds”. In: *Animal Behaviour* 75.2, pp. 461–470.

Dyson, F. (2004). “A meeting with Enrico Fermi”. In: *Nature* 427.6972, pp. 297–297.

Fanelli, D. (2018). “Opinion: Is science really facing a reproducibility crisis, and do we need it to?” In: *Proceedings of the National Academy of Sciences* 115.11, pp. 2628–2631.

Fogelson, R. M. (1971). *Violence as protest: A study of riots and ghettos*. Vol. 825. Doubleday.

Forrester, J. W. and Senge, P. M. (1980). “Tests for building confidence in system dynamics models”. In: *System dynamics, TIMS studies in management sciences* 14, pp. 209–228.

Fredkin, E. and Toffoli, T. (1982). “Conservative logic”. In: *International Journal of theoretical physics* 21.3, pp. 219–253.

Friedman, J. H. and Fisher, N. I. (1999). “Bump hunting in high-dimensional data”. In: *Statistics and Computing* 9.2, pp. 123–143.

Gallup, A. C., Hale, J. J., Sumpter, D. J., Garnier, S., Kacelnik, A., Krebs, J. R., and Couzin, I. D. (2012). “Visual attention and the acquisition of information in human crowds”. In: *Proceedings of the National Academy of Sciences* 109.19, pp. 7245–7250.

Goldstone, R. L. and Janssen, M. A. (2005). “Computational models of collective behavior”. In: *Trends in cognitive sciences* 9.9, pp. 424–430.

Grimm, V., Berger, U., Bastiansen, F., *et al.* (2006). “A standard protocol for describing individual-based and agent-based models”. In: *Ecological modelling* 198.1-2, pp. 115–126.

Grimm, V., Berger, U., De Angelis, D. L., Polhill, J. G., Giske, J., and Railsback, S. F. (2010). “The ODD protocol: a review and first update”. In: *Ecological modelling* 221.23, pp. 2760–2768.

Grosshandler, W. L., Bryner, N. P., Madrzykowski, D., and Kuntz, K. (2005). *Draft report of the technical investigation of The Station nightclub fire*. The Division.

Guo, R. and Huang, H.-J. (2008). “A mobile lattice gas model for simulating pedestrian evacuation”. In: *Physica A: Statistical Mechanics and its Applications* 387.2-3, pp. 580–586.

Haghani, M., Cristiani, E., Bode, N. W., Boltes, M., and Corbetta, A. (2019). “Panic, irrationality, and herding: three ambiguous terms in crowd dynamics research”. In: *Journal of advanced transportation* 2019.

Haghani, M. and Sarvi, M. (2016). “Pedestrian crowd tactical-level decision making during emergency evacuations”. In: *Journal of Advanced Transportation* 50.8, pp. 1870–1895.

— (2019a). “‘Herding’in direction choice-making during collective escape of crowds: How likely is it and what moderates it?” In: *Safety science* 115, pp. 362–375.

— (2019b). “Simulating dynamics of adaptive exit-choice changing in crowd evacuations: Model implementation and behavioural interpretations”. In: *Transportation research part C: emerging technologies* 103, pp. 56–82.

Haghani, M., Sarvi, M., Shahhoseini, Z., and Boltes, M. (2019). “Dynamics of social groups’ decision-making in evacuations”. In: *Transportation research part C: emerging technologies* 104, pp. 135–157.

Hart, P. E., Nilsson, N. J., and Raphael, B. (1968). “A formal basis for the heuristic determination of minimum cost paths”. In: *IEEE transactions on Systems Science and Cybernetics* 4.2, pp. 100–107.

Helbing, D., Farkas, I. J., Molnar, P., and Vicsek, T. (2002). “Simulation of pedestrian crowds in normal and evacuation situations”. In: *Pedestrian and evacuation dynamics* 21.2, pp. 21–58.

Helbing, D. and Molnar, P. (1995). “Social force model for pedestrian dynamics”. In: *Physical review E* 51.5, p. 4282.

Henderson, L. (1971). “The statistics of crowd fluids”. In: *nature* 229.5284, pp. 381–383.

Hollenbeck, J. R., Ilgen, D. R., Sego, D. J., Hedlund, J., Major, D. A., and Phillips, J. (1995). “Multilevel theory of team decision making: Decision performance in teams incorporating distributed expertise.” In: *Journal of applied psychology* 80.2, p. 292.

Horiuchi, S., Murozaki, Y., and Hukugo, A. (1986). “A case study of fire and evacuation in a multi-purpose office building, Osaka, Japan”. In: *Fire Safety Science* 1, pp. 523–532.

Hughes, R. L. (2002). “A continuum theory for the flow of pedestrians”. In: *Transportation Research Part B: Methodological* 36.6, pp. 507–535.

Huo, F., Song, W., Chen, L., Liu, C., and Liew, K. (2016). “Experimental study on characteristics of pedestrian evacuation on stairs in a high-rise building”. In: *Safety science* 86, pp. 165–173.

Ibrahim, A. M., Venkat, I., Subramanian, K., Khader, A. T., and Wilde, P. D. (2016). “Intelligent evacuation management systems: A review”. In: *ACM Transactions on Intelligent Systems and Technology (TIST)* 7.3, pp. 1–27.

James, J. (1953). “The distribution of free-forming small group size.” In: *American Sociological Review*.

Johansson, A., Helbing, D., and Shukla, P. K. (2007). “Specification of the social force pedestrian model by evolutionary adjustment to video tracking data”. In: *Advances in complex systems* 10.supp02, pp. 271–288.

Jones, B. and Hewitt, J. A. (1986). “Leadership and group formation in high-rise buidling evacuations”. In: *Fire Safety Science* 1, pp. 513–522.

Kasereka, S., Kasoro, N., Kyamakya, K., Goufo, E.-F. D., Chokki, A. P., and Yengo, M. V. (2018). “Agent-Based Modelling and Simulation for evacuation of people from a building in case of fire”. In: *Procedia Computer Science* 130, pp. 10–17.

Kerr, N. L. and Tindale, R. S. (2004). “Group performance and decision making”. In: *Annu. Rev. Psychol.* 55, pp. 623–655.

Kleinmeier, B., Zönnchen, B., Gödel, M., and Köster, G. (2019). “Vadere: an open-source simulation framework to promote interdisciplinary understanding”. In: *arXiv preprint arXiv:1907.09520*.

Kocher, M. G. and Sutter, M. (2005). “The decision maker matters: Individual versus group behaviour in experimental beauty-contest games”. In: *The Economic Journal* 115.500, pp. 200–223.

Köster, G., Treml, F., Seitz, M., and Klein, W. (2014). “Validation of crowd models including social groups”. In: *Pedestrian and Evacuation Dynamics 2012*. Springer, pp. 1051–1063.

Krause, J., Ruxton, G. D., and Krause, S. (2010). “Swarm intelligence in animals and humans”. In: *Trends in ecology & evolution* 25.1, pp. 28–34.

Krause, J., Ruxton, G. D., Ruxton, G., Ruxton, I. G., *et al.* (2002). *Living in groups*. Oxford University Press.

Kuligowski, E. (2013). "Predicting human behavior during fires". In: *Fire technology* 49.1, pp. 101–120.

Kwakkel, J. H. (2017). "The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making". In: *Environmental Modelling & Software* 96, pp. 239–250.

Laughlin, P. R. (2011). "Social choice theory, social decision scheme theory, and group decision-making". In: *Group Processes & Intergroup Relations* 14.1, pp. 63–79.

Le Bon, G. (1960). "The crowd: A study of the popular mind. 1895". In: *Reprint, New York: Viking*.

Li, K., Kang, Z., and Zhang, L. (2019). "Group structures facilitate emergency evacuation". In: *EPL (Europhysics Letters)* 124.6, p. 68002.

Li, Y., Lu, C., and Jin, J. (2021). "Simulation of a pediatric hospital in evacuation considering groups". In: *Simulation Modelling Practice and Theory* 107, p. 102150.

Lin, Q., Ji, Q., and Gong, S. (2006). "A crowd evacuation system in emergency situation based on dynamics model". In: *International Conference on Virtual Systems and Multimedia*. Springer, pp. 269–280.

Lo, S. M., Huang, H.-C., Wang, P., and Yuen, K. (2006). "A game theory based exit selection model for evacuation". In: *Fire Safety Journal* 41.5, pp. 364–369.

Lorek, H. and Sonnenschein, M. (1999). "Modelling and simulation software to support individual-based ecological modelling". In: *Ecological Modelling* 115.2-3, pp. 199–216.

Lovreglio, R., Fonzone, A., Dell'Olio, L., Borri, D., and Ibeas, A. (2014). "The role of herding behaviour in exit choice during evacuation". In: *Procedia-Social and Behavioral Sciences* 160, pp. 390–399.

Lovreglio, R., Kuligowski, E., Gwynne, S., and Boyce, K. (2019). "A pre-evacuation database for use in egress simulations". In: *Fire safety journal* 105, pp. 107–128.

Lovreglio, R., Ronchi, E., and Nilsson, D. (2015). "A model of the decision-making process during pre-evacuation". In: *Fire Safety Journal* 78, pp. 168–179.

7

Lu, L., Chan, C.-Y., Wang, J., and Wang, W. (2017). "A study of pedestrian group behaviors in crowd evacuation based on an extended floor field cellular automaton model". In: *Transportation research part C: emerging technologies* 81, pp. 317–329.

MacIver, R. M. (1952). *Society an introductory analysis*. The Macmillan comp.

Madireddy, M., Medeiros, D. J., and Kumara, S. (2011). "An agent based model for evacuation traffic management". In: *Proceedings of the 2011 Winter Simulation Conference (WSC)*. IEEE, pp. 222–233.

Mann, R. P., Faria, J., Sumpter, D. J., and Krause, J. (2013). "The dynamics of audience applause". In: *Journal of The Royal Society Interface* 10.85, p. 20130466.

Mao, Y., Fan, X., Fan, Z., and He, W. (2019). "Modeling group structures with emotion in crowd evacuation". In: *IEEE Access* 7, pp. 140010–140021.

Mao, Y., Yang, S., Li, Z., and Li, Y. (2020). "Personality trait and group emotion contagion based crowd simulation for emergency evacuation". In: *Multimedia Tools and Applications* 79.5, pp. 3077–3104.

Maria, A. (1997). "Introduction to modeling and simulation". In: *Proceedings of the 29th conference on Winter simulation*, pp. 7–13.

McConnell, N., Boyce, K., Shields, J., Galea, E., Day, R., and Hulse, L. (2010). "The UK 9/11 evacuation study: Analysis of survivors' recognition and response phase in WTC1". In: *Fire Safety Journal* 45.1, pp. 21–34.

Merton, R. K. (1968). *Social theory and social structure*. Simon and Schuster.

Milgram, S., Toch, H., and Drury, J. (1969). *Collective behavior: Crowds and social movements*.

Mir Mohammadi Kooshknow, S. A. R., Exter, R. den, and Ruzzenenti, F. (2020). "An Exploratory Agent-Based Modeling Analysis Approach to Test Business Models for Electricity Storage". In: *Energies* 13.7, p. 1617.

Monks, T., Currie, C. S., Onggo, B. S., Robinson, S., Kunc, M., and Taylor, S. J. (2019). "Strengthening the reporting of empirical simulation studies: Introducing the STRESS guidelines". In: *Journal of Simulation* 13.1, pp. 55–67.

Moussaïd, M., Helbing, D., Garnier, S., Johansson, A., Combe, M., and Theraulaz, G. (2009). "Experimental study of the behavioural mechanisms underlying self-organization in human crowds". In: *Proceedings of the Royal Society B: Biological Sciences* 276.1668, pp. 2755–2762.

Moussaïd, M., Perozo, N., Garnier, S., Helbing, D., and Theraulaz, G. (2010). "The walking behaviour of pedestrian social groups and its impact on crowd dynamics". In: *PloS one* 5.4, e10047.

Müller, F., Wohak, O., and Schadschneider, A. (2014). "Study of influence of groups on evacuation dynamics using a cellular automaton model". In: *Transportation Research Procedia* 2, pp. 168–176.

Nagai, R., Fukamachi, M., and Nagatani, T. (2005). "Experiment and simulation for counterflow of people going on all fours". In: *Physica A: Statistical Mechanics and its Applications* 358.2-4, pp. 516–528.

Neville, F. and Reicher, S. (2011). “The experience of collective participation: Shared identity, relatedness and emotionality”. In: *Contemporary social science* 6.3, pp. 377–396.

Nguyen, V.-Q., Nguyen, H.-D., Huynh, Q.-T., Venkatasubramanian, N., and Kim, K. (2019). “A scalable approach for dynamic evacuation routing in large smart buildings”. In: *2019 IEEE International Conference on Smart Computing (SMARTCOMP)*. IEEE, pp. 292–300.

Nikolic, I., Lukszo, Z., Chappin, E., Warnier, M., Kwakkel, J., Bots, P., and Brazier, F. (2019). “Guide for Good Modelling Practice in policy support”. In:

Oberhagemann, D., Könnecke, R., and Schneider, V. (2014). “Effect of social groups on crowd dynamics: empirical findings and numerical simulations”. In: *Pedestrian and Evacuation Dynamics 2012*. Springer, pp. 1251–1258.

Ogburn, W. F. and Nimkoff, M. F. (1947). “A handbook of sociology”. In: *Tijdschrift Voor Filosofie* 9.3.

Olabisi, L. S., Wang, R. Q., and Ligmann-Zielinska, A. (2015). “Why don’t more farmers go organic? Using a stakeholder-informed exploratory agent-based model to represent the dynamics of farming practices in the Philippines”. In: *Land* 4.4, pp. 979–1002.

Peng, C., Guiot, J., Wu, H., Jiang, H., and Luo, Y. (2011). “Integrating models with data in ecology and palaeoecology: advances towards a model–data fusion approach”. In: *Ecology Letters* 14.5, pp. 522–536.

Pires, T. T. (2005). “An approach for modeling human cognitive behavior in evacuation models”. In: *Fire safety journal* 40.2, pp. 177–189.

Proulx, G. (2002). “Movement of people: the evacuation timing”. In: *SFPE handbook of fire protection engineering*, pp. 342–366.

Qin, X., Liu, H., Zhang, H., and Liu, B. (2018). “A collective motion model based on two-layer relationship mechanism for bi-direction pedestrian flow simulation”. In: *Simulation Modelling Practice and Theory* 84, pp. 268–285.

Quarantelli, E. (1995). “Emergent behavior and groups in the crisis time of disasters”. In:

Reicher, S. and Drury, J. (2010). “Collective identity, political participation, and the making of the social self”. In: *Identity and participation in culturally diverse societies: A multidisciplinary perspective*, pp. 158–175.

Reicher, S. D. (1984). “The St. Pauls’ riot: An explanation of the limits of crowd action in terms of a social identity model”. In: *European journal of social psychology* 14.1, pp. 1–21.

— (1996). “‘The Battle of Westminster’: Developing the social identity model of crowd behaviour in order to explain the initiation and development of collective conflict”. In: *European journal of social psychology* 26.1, pp. 115–134.

Reneke, P. A. and Reneke, P. A. (2013). *Evacuation decision model*. US Department of Commerce, National Institute of Standards and Technology.

Richardson, O., Jalba, A., and Muntean, A. (2019). “Effects of environment knowledge in evacuation scenarios involving fire and smoke: a multiscale modelling and simulation approach”. In: *Fire technology* 55.2, pp. 415–436.

Ritchie, H. and Roser, M. (2018). “Urbanization”. In: *Our world in data*.

Ronchi, E., Kuligowski, E. D., Reneke, P. A., Peacock, R. D., and Nilsson, D. (2013). “The process of verification and validation of building fire evacuation models”. In:

Rubadiri, L., Ndumu, D. T., and Roberts, J. P. (1997). “Predicting the evacuation capability of mobility-impaired occupants”. In: *Fire Technology* 33.1, pp. 32–53.

Saloma, C., Perez, G. J., Tapang, G., Lim, M., and Palmes-Saloma, C. (2003). “Self-organized queuing and scale-free behavior in real escape panic”. In: *Proceedings of the National Academy of Sciences* 100.21, pp. 11947–11952.

Santana, J. R., Sánchez, L., Sotres, P., Lanza, J., Llorente, T., and Munoz, L. (2020). “A privacy-aware crowd management system for smart cities and smart buildings”. In: *IEEE Access* 8, pp. 135394–135405.

Santos, G. and Aguirre, B. E. (2004). “A critical review of emergency evacuation simulation models”. In:

Seitz, M. J., Bode, N. W., and Köster, G. (2016). “How cognitive heuristics can explain social interactions in spatial movement”. In: *Journal of the Royal Society Interface* 13.121, p. 20160439.

Sime, J. D. (1983). “Affiliative behaviour during escape to building exits”. In: *Journal of environmental psychology* 3.1, pp. 21–41.

— (1985). “Movement toward the familiar: Person and place affiliation in a fire entrapment setting”. In: *Environment and Behavior* 17.6, pp. 697–724.

Sivers, I. von, Templeton, A., Köster, G., Drury, J., and Philippides, A. (2014). “Humans do not always act selfishly: Social identity and helping in emergency evacuation simulation”. In: *Transportation Research Procedia* 2, pp. 585–593.

Sivers, I. von, Templeton, A., Künzner, F., Köster, G., Drury, J., Philippides, A., Neckel, T., and Bungartz, H.-J. (2016). "Modelling social identification and helping in evacuation simulation". In: *Safety science* 89, pp. 288–300.

Sterman, J. (2002). "System Dynamics: systems thinking and modeling for a complex world". In:

Sterman, J. D. (1994). "Learning in and about complex systems". In: *System dynamics review* 10.2-3, pp. 291–330.

Still, G. K. (2014). *Introduction to crowd science*. CRC Press.

Sumpter, D. J. and Pratt, S. C. (2009). "Quorum responses and consensus decision making". In: *Philosophical Transactions of the Royal Society B: Biological Sciences* 364.1518, pp. 743–753.

Tajfel, H. (2010). *Social identity and intergroup relations*. Vol. 7. Cambridge University Press.

Tajima, Y. and Nagatani, T. (2001). "Scaling behavior of crowd flow outside a hall". In: *Physica A: Statistical Mechanics and its Applications* 292.1-4, pp. 545–554.

Templeton, A., Drury, J., and Philippides, A. (2015). "From mindless masses to small groups: conceptualizing collective behavior in crowd modeling". In: *Review of General Psychology* 19.3, pp. 215–229.

Thompson, E. P. (1971). "The moral economy of the English crowd in the eighteenth century". In: *Past & present* 50, pp. 76–136.

Tindale, R. S., Smith, C. M., Dykema-Engblade, A., and Kluwe, K. (2012). "Good and bad group performance: Same process—different outcomes". In: *Group Processes & Intergroup Relations* 15.5, pp. 603–618.

Toyama, M. C., Bazzan, A. L., and Da Silva, R. (2006). "An agent-based simulation of pedestrian dynamics: from lane formation to auditorium evacuation". In: *Proceedings of the fifth international joint conference on Autonomous agents and multiagent systems*, pp. 108–110.

Turner, J. C. (2010). "Social categorization and the self-concept: A social cognitive theory of group behavior." In:

Turner, J. C., Hogg, M. A., Oakes, P. J., Reicher, S. D., and Wetherell, M. S. (1987). *Rediscovering the social group: A self-categorization theory*. Basil Blackwell.

Van Asselt, M. B. and Rotmans, J. (2002). "Uncertainty in integrated assessment modelling". In: *Climatic change* 54.1, pp. 75–105.

Van Der Schalk, J., Fischer, A., Doosje, B., Wigboldus, D., Hawk, S., Rotteveel, M., and Hess, U. (2011). "Convergent and divergent responses to emotional displays of ingroup and outgroup." In: *Emotion* 11.2, p. 286.

Van der Wal, C. N., Formolo, D., Robinson, M. A., Minkov, M., and Bosse, T. (2017). "Simulating crowd evacuation with socio-cultural, cognitive, and emotional elements". In: *Transactions on computational collective intelligence XXVII*. Springer, pp. 139–177.

Von Krüchten, C. and Schadschneider, A. (2017). "Empirical study on social groups in pedestrian evacuation dynamics". In: *Physica A: Statistical Mechanics and its Applications* 475, pp. 129–141.

Wang, H., Mostafizi, A., Cramer, L. A., Cox, D., and Park, H. (2016). "An agent-based model of a multimodal near-field tsunami evacuation: Decision-making and life safety". In: *Transportation Research Part C: Emerging Technologies* 64, pp. 86–100.

Wilensky, U. and Rand, W. (2015). *An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo*. Mit Press.

Wilkinson, M. D. *et al.* (2016). "The FAIR Guiding Principles for scientific data management and stewardship". In: *Scientific data* 3.1, pp. 1–9.

Wolfram, S. (1983). "Statistical mechanics of cellular automata". In: *Reviews of modern physics* 55.3, p. 601.

Wooldridge, M. and Jennings, N. R. (1995). "Intelligent agents: Theory and practice". In: *The knowledge engineering review* 10.2, pp. 115–152.

Xiaoge, W., Weiguo, S., Xuan, X., Zhiming, F., and Xiaolian, L. (2014). "Effect of group behavior on crowd dynamics". In: *International Conference on Cellular Automata*. Springer, pp. 453–461.

Xie, W., Lee, E. W. M., Li, T., Shi, M., Cao, R., and Zhang, Y. (2021). "A study of group effects in pedestrian crowd evacuation: Experiments, modelling and simulation". In: *Safety Science* 133, p. 105029.

Yang, L., Zhao, D., Li, J., and Fang, T. (2005). "Simulation of the kin behavior in building occupant evacuation based on cellular automaton". In: *Building and Environment* 40.3, pp. 411–415.

You, L., Hu, J., Gu, M., Fan, W., and Zhang, H. (2016). "The simulation and analysis of small group effect in crowd evacuation". In: *Physics Letters A* 380.41, pp. 3340–3348.

Zarboutis, N. and Marmaras, N. (2004). "Searching efficient plans for emergency rescue through simulation: the case of a metro fire". In: *Cognition, Technology & Work* 6.2, pp. 117–126.

Zhang, H., Liu, H., Qin, X., and Liu, B. (2018). "Modified two-layer social force model for emergency earthquake evacuation". In: *Physica A: Statistical Mechanics and its Applications* 492, pp. 1107–1119.

Zheng, X., Zhong, T., and Liu, M. (2009). "Modeling crowd evacuation of a building based on seven methodological approaches". In: *Building and Environment* 44.3, pp. 437–445.

Zhou, J., Guo, Y., Dong, S., Zhang, M., and Mao, T. (2019). "Simulation of pedestrian evacuation route choice using social force model in large-scale public space: Comparison of five evacuation strategies". In: *PLoS one* 14.9, e0221872.