QATAR UNIVERSITY

COLLEGE OF ENGINEERING

MODELING FAMILY BEHAVIORS IN CROWD SIMULATION

BY

LUBNA FAYEZ ELIYAN

A Thesis Submitted to the Faculty of
the College of Engineering
in Partial Fulfillment
of the Requirements
for the Degree of
Masters of Science in Computing

January 2017

COMMITTEE PAGE

The members of the Committee approve the Thesis of Lubna Fayez Eliyan defended on 26/12/2016.

Mohammad Saleh

Thesis/Dissertation Supervisor

Osama Halabi

Thesis/Dissertation Co-supervisor

Ryan Riley

Committee Member

Abdelaziz Bouras

Committee Member

Aiman Erbad

Committee Member

Approved:

Khalifa Al-Khalifa, Dean, College of Engineering

ABSTRACT

ELIYAN, LUBNA, FAYEZ, Masters: January: 2017, Masters of Science in Computing

Title: Modeling Family Behaviors in Crowd Simulation

Supervisor of Thesis: Mohammad, Saleh, Saleh.

Modeling human behavior for a general situation is difficult, if not impossible. Crowd simulation represents one of the approaches most commonly used to model such behavior. It is mainly concerned with modeling the different human structures incorporated in a crowd. These structures could comprise individuals, groups, friends, and families. Various instances of these structures and their corresponding behaviors are modeled to predict crowd responses under certain circumstances and to subsequently improve event management, facility and emergency planning.

Most currently existing modeled behaviors are concerned with depicting individuals as autonomous agents or groups of agents in certain environments. This research focuses on providing structural and state-based behavioral models for the concept of a family incorporated in the crowd. The structural model defines parents, teenagers, children, and elderly as members of the family. It also draws on the associated interrelationships and the rules that govern them. The behavioral model of the family encompasses a number of behavioral models associated with the triggering of certain well-known activities that correspond to the family's situation. For instance, in normal cases, a family member(s) may be hungry, bored, or tired, may need a restroom, etc. In an emergency case, a family may experience the loss of a family member(s), the need to assist in safe evacuation, etc. Activities that such cases trigger include splitting, joining, carrying children, looking for family member(s), or waiting for them. The proposed family model is implemented on top of the RVO2 library that is using agent-based approach in crowd simulation. Simulation case studies are developed to answer research questions related to various family evacuation approaches in emergency situations.

DEDICATION

To my parents:

Fayez Eliyan and Rima Asfour

To my brothers and sisters:

Faysal, Mohammed, Afnan, Areej and Edris,

To everyone who believed in me…

ACKNOWLEDGMENTS

Alhamdulillah, this is the first word I would like to say. I would like to thank Allah for blessing me over the course of my work and for giving me the strength and the ability to go on this journey.

To my supervisor, Dr. Mohammad Saleh: I would like to express my deepest gratitude for everything that you did for me on this journey. Thank you for your unconditional support, encouragement, patience, and understanding. Thank you for believing in me and my abilities, for trusting me, and for bringing the best out of me. You have been everything that a student could want in a supervisor.

To my co-supervisor, Dr. Osama Halabi: I would like to thank you for your guidance, great remarks, and care regarding the details in my work. You gave me excellent ideas to explore and always regarded my work in the best light.

To my parents, brothers and sisters: Thank you for standing by me during difficult times and for your support, patience, and encouragement. My parents, you were the first to tell me that a journey of a thousand miles begins with a single step. You were the first to put my steps on this journey, now this journey is over, please accompany me on my subsequent journeys. I will always need you by my side.

To my sister and soulmate, Afnan: Thank you for listening to me talk about my problems and daily interactions when you were tired and had many other things in your mind. You did it with lots of patience and understanding.

To my friends, Razan and Reem: Thank you for releasing my stress and for your continuous support and motivation. I am lucky to have such friends as you.

TABLE OF CONTENTS

LIST OF TABLES viii
LIST OF FIGURES ix
CHAPTER 1: INTRODUCTION 1
1.1. Motivation 1
1.2. Problem Statement 4
1.3. Research Objectives 5
1.4. Research Questions 6
1.5. Research Methodology 7
1.6. Thesis Outline 8
CHAPTER 2: BACKGROUND AND RELATED WORK 9
2.1. Crowd Simulation Approaches 9
  2.1.1. Cellular Automata Approach 10
  2.1.2. Social Force Model Approach 11
  2.1.3. Agent Based Approach 13
2.2. Human Decision Making 14
2.3. Modeling Behavior in Crowd Simulation 16
CHAPTER 3: SYSTEM MODEL 25
3.1. Model Overview 25
3.2. Family Modeling 27
  3.2.1. Family Model and Structure 27
  3.2.2. Decision Making and Family Behavioral Models 39
3.3. System Implementation 54
  3.3.1. High Level Architecture 54
  3.3.2. System Implementation and Verification 56
CHAPTER 4: CASE STUDIES 60
4.1. Event Settings 60
4.2. Simulated Case Studies 64
  4.2.1. Emergency Situation Case Studies 64
    4.2.1.1. Case Study One 65
    4.2.1.2. Case Study Two 82
  4.2.2. Normal Situation Case Study 87
CHAPTER 5: CONCLUSION AND FUTURE WORK 93

5.1. Conclusion 93
5.2. Future Work 95
REFERENCES 96
APPENDIX: SURVEY ABOUT FAMILY BEHAVIOR 108

LIST OF TABLES

Table 1: Males age-weight ranges 30
Table 2: Females age-weight ranges 30
Table 3: Males age-heart rate ranges 31
Table 4: Females age-heart rate ranges 31
Table 5: Join points based on states existence 47
Table 6: Percentage of evacuated family members in first 30 minutes 76
Table 7: Percentages of evacuated people within time under the two layout settings 86

LIST OF FIGURES

Figure 1: Arching phenomena 12
Figure 2: Extended BDI model 15
Figure 3: Overview model of the agent 29
Figure 4: Agent memory structure 32
Figure 5: Perceiving process overview 34
Figure 6: State generation process of agent 38
Figure 7: Decision making process 40
Figure 8: Decision making algorithm 41
Figure 9: Overview of split mechanism 46
Figure 10: Lost member behavioral model 48
Figure 11: Evacuation process 53
Figure 12: System high level architecture 54
Figure 13: Book fair event layout 61
Figure 14: People growth in the system 62
Figure 15: People distribution in the crowd 63
Figure 16: Evacuation process at different time stamps 68
Figure 17: Number of evacuated families per minute 70
Figure 18: Effect of the location on the evacuation time 71
Figure 19: Grids spanning over the hall area 72
Figure 20: Family state effect on the evacuation time 73
Figure 21: Number of evacuated individuals per minute 75
Figure 22: Number of evacuated family members per minute 75
Figure 23: Mean and standard deviations of evacuated family members 77
Figure 24: Number of evacuated leaders per minute 78
Figure 25: Number of evacuated children per minute 80
Figure 26: Number of evacuated elderlies per minute 80
Figure 27: Evacuated people rate 81
Figure 28: Evacuation process at different time stamps with four exits 84
Figure 29: People evacuation rates under the two layout settings 85
Figure 30: Mean and standard deviations of evacuated people in the two layout settings 87
Figure 31: Average satisfaction level of the family members 89

CHAPTER 1: INTRODUCTION

1.1. Motivation

Human behavior can be defined as the way an individual reacts toward other people, society, or objects. Such reaction could be considered normal or abnormal based on the norms of the society to which the individual belongs. Moreover, the reaction of individual results from the various factors that make individuals behave differently from one other. Some of these are individual distinctions, including physical, intellectual, personal, and emotional differences. However, these could also indicate environmental influences, such as differences in terms of the geographical factors that affect the way in which an individual talks and dresses, as well as differences in the social environment that surrounds the individual; psychological and physical disabilities; and finally, dissimilarities in family patterns, which could include the size and structure of the family as well as their economic and social stature. In addition to the differences in family patterns, the family itself plays an important role in shaping the individual's personality. Each family has its own unique "culture," by which the way a family member is thinking, feeling, judging, and acting is defined [1][2].

A better understanding of human behavior and the diverse factors that influence it helps in providing a model for it. Such model can be used in experimental scenarios to analyze the behavior of humans under certain circumstances. Then, based on the analyzed behavior, a prediction can be obtained about how humans would behave under similar scenarios if happen in real life. These scenarios could be relatively ordinary in nature, or emergency. Relatively ordinary scenarios could include public events, gatherings, festivals, concerts, or football matches that needs arrangements of layouts and items. On the other hand, emergency scenarios are related to the events that trigger an evacuation process of the area due to existence of danger stimuli as fire, bomb or natural disaster.

Modeling human behavior for a general situation is difficult, if not impossible [3]. Crowd simulation [4] represents one of the most commonly used approaches to simulate human behaviors. It has attracted a great deal of attention recently in normal and emergency contexts due to the increasing number of people [5]. In the context of simulating human behavior, crowd simulation is concerned with simulating the movement of a large mass of people gathered in certain social settings based on a model. Then, some solutions can be found to common problems related to people behavior, based on the simulated model. These solutions could subsequently improve facility and emergency planning, along with event management based on certain settings in different applications. These applications of crowd simulation can be seen in varied contexts. For example, in public event planning, there is a need to test the evacuation process of a large number of people with a minimum number of casualties within a fairly short period of time [6]. In comparison, with facility planning of buildings such as malls or airports, there is a need to test the evacuation capability and accordingly designate the number of exists and their locations, which may not only aid in emergency situations, but encourage a smooth and safe flow of movement in normal situations as well [7][8][9]. Other applications of the crowd simulation can be seen in designing aircrafts to have a safe disembarking process of passengers [10], infectious diseases spread [11], emergency evacuation due to a bomb explosion [12] or during concerts' venues [13], airports evacuation [14], and other different uses as confrontation operations [15].

Modeling human behavior in crowd simulation implies that some influences that affect the human behavior should be considered. These influences include physical, social and psychological factors. Physical factors mainly involve the movement of humans and the effects these may have on the crowd's overall progress. These physical factors include speed, position, and appearance of the human being simulated. Social factors on the other hand, include family relations, culture, and religion, which are usually based on social theories and observations in social studies research. Finally, psychological factors consist of the different emotions that represent the state of the human mind in certain situations [16].

In emergency situations, human behavior is affected by additional factors that may influence the decision-making process, some of which include experience, environment familiarity, and collision avoidance [16][17]. Moreover, in emergency situations, humans may lose their judgment ability due to the high influence of psychological factors such as fear and panic; therefore, they tend to follow the majority of the people, which results in forming herd behavior [18].

1.2. Problem Statement

The modeling of human behavior in crowd simulation should aim to be as realistic as possible. This is necessary for the better prediction of behavior if similar situations occurred in real events. Moreover, the modeling of human behavior should consider the different human structures that a crowd incorporates. These structures include individuals, groups, friends, and families. Most existing modeled behaviors are concerned with individuals as autonomous agents or groups of agents being simulated in a certain environment. Such modeling includes the decision-making, motion, and path-planning processes of these agents.

Nevertheless, there are few attempts to model family behavior by considering the family as a basic social unit that constitutes part of a crowd, hence; there is a need for further work in this area [1]. Considering families in this sense makes crowd simulation more realistic, hence, it would result in better predictions. Such a family model should consider specific behaviors and structures of the family that are modeled differently for primitive group or individual models. For instance, there exist strong relations between family members, causing decisions and behaviors to be biased towards maintaining family coherence and unity. This is not essentially the case in group modeling.

As for the structure of the family, there is always a need for a leader who holds certain special responsibilities. For example, ensuring family unity in the different situations that the family might be experiencing is one of these responsibilities. In such a structure, different types of family members, including children, the elderly, teens, leaders members, are closely associated. Some of these members need special treatment or attention from the family, which most likely affects the behavioral model of the family and, in some cases, its structure as well.

This research work proposes a model that describes family behavior and its associated activities in both normal and emergency situations. Such model considers some behavior-related activities of families in terms of splitting, joining, carrying children, and family members waiting or looking for each other. The behavioral model is based on a leader-follower approach [19]. In this approach, the leader of the family carries the responsibility of maintaining its unity as this is the main psychological constraint of this model. In emergency situations, other special concerns related to family aspects are considered. This includes cases where the family is having children along with the role of the parents in evacuating quickly. Furthermore, the model considers cases in which the family members have been split up prior to the emergency as well as the role of the leader in ensuring a safe evacuation while simultaneously maintaining the family's unity.

1.3. Research Objectives

The main objectives of the present research are

- To provide a model that describes family behavior at family-related events during normal and emergency situations;
- To provide an implementation of the model on the top of a crowd simulation library;
- To study family behavior in different contexts in order to predict its effects if similar situations occurred in real life;

- To contribute to the field of crowd simulation by providing a model for use in further investigations of family behavior in different contexts.

These objectives are achieved through the different stages of this research work as the subsequent chapters indicate.

1.4. Research Questions

The present research is sought to answer the following research questions:

RQ1: Does family behavior affect the crowd evacuation process in emergency situations?

- The aim is to investigate whether family-associated behaviors affect the overall crowd evacuation process.

RQ2: What is the effect of adopting common behavior by families on the evacuation process?

- The aim is to investigate the effect of commonly adopted behavior on the evacuation process. Such behavior is based on social and psychological theories.

RQ3: Does family disunity affect the family evacuation process in emergency situations?

- The aim is to investigate the effect of decisions made when family members are apart on the family evacuation process.

RQ4: Is it advisable for the family to split during an emergency situation?

- The aim is to investigate whether a family's splitting into groups of smaller sizes or individuals would affect the family evacuation process.

RQ5: How does increasing the number of exits within a certain layout affect the evacuation process?

- The aim is to study the effect of introducing additional exits to the layout of a certain event on the evacuation process.

RQ6: Does the family split affect its members' satisfaction level during a public event?

- The aim is to study the effect of splitting the family into smaller groups, with each one navigating independently during the event, on the members' satisfaction level.

1.5. Research Methodology

The different stages of the research were focused on determining the answers to the research questions. The first stage was a review of the literature, which addressed current work on modeling the behavior of agents and groups in crowd simulations. Next, was the design of a model that describes family behavior, taking into consideration some contributions from multidisciplinary research, and the conducting of surveys about adopted family behaviors in certain situations. The relevant research areas included the social sciences (to examine how groups of people act in relationships with each other), human psychology (which involved behavioral and mental processes such as reasoning, decision-making, and perception), and human physiology (to consider relevant physical and biochemical functions). On the other hand, the surveys conducted provided insights into some behaviors that families adopt in certain situations. At the fourth stage of the present research, the model was implemented on the top of a crowd simulation library, for which a simultaneous interaction is carried between the behavioral model and the crowd simulation library. Afterwards, the model was set to simulate a set of case studies under certain conditions. These case studies were intended to analyze how family behavior would affect different measured criteria, such as evacuation processes and family members’ levels of satisfaction, in order to answer the research questions.

1.6. Thesis Outline

The remainder of this thesis is organized as follows: Chapter 2 presents the background and literature review. These include a discussion of the different modeling approaches used in crowd simulation, the behaviors considered, and the decision-making processes. The proposed model to describe family behavior and the decision-making process are discussed in detail in chapter 3. The model was used to consider different case studies related to family behavior in normal and emergency scenarios. Chapter 4 discusses these experiments in detail. Finally, in chapter 5, the conclusion of the research, together with some insights regarding future research, are discussed.

CHAPTER 2: BACKGROUND AND RELATED WORK

This chapter discusses different aspects related to modeling in crowd simulation.

2.1. Crowd Simulation Approaches

Crowd simulation represents one of the most commonly used ways to model and simulate human behavior [4]. Approaches that have been proposed in crowd simulation can be categorized into two main groups: macroscopic- and microscopic-based approaches. Macroscopic-based approaches treat crowds as a whole without considering a single entity and its associated behavior under study. They consider crowds as a homogeneous collection of individuals in which their differences in physical abilities, movements, and actions are not considered, which lacks realism in some contexts [20]. This category includes the regression [21] and fluid-dynamic models [22]. The microscopic model, on the other hand, studies and treats crowd behavior as a result of a self-organization process [7]. Thus, each individual in the crowd is considered an autonomous agent that has associated decision-making processes, actions, behaviors, specific features, and interactions with other agents in the crowd. In microscopic-based approaches, the three main models are traditionally cellular automata (CA) [23], social force model (SFM) [24], and agent-based model [25]. CA approach models individuals' movement in discrete time and space being represented by cells that are continuously interacting. SFM, on the other hand, assumes individuals to be passive particles being governed by a collection of forces. Finally, the agent-based approach assumes each agent to be an individual entity that behaves autonomously.

The subsequent subsections discuss the different microscopic-based approaches of crowd simulation.

2.1.1. Cellular Automata Approach

Cellular automata models simulate crowd environments with a grid of different cells, where agents can move between the cells based on different cell states. The states of the cell are its occupancy conditions, being either free, occupied by an obstacle, or occupied by an individual. Based on these states, the agent can move from a current cell to a neighboring cell only if the neighboring cell is unoccupied. The states of the cells are updated simultaneously in discrete timeframes defined in the simulation parameters [1][20][26][27].

CA models are well suited to large-scale simulations. This is because they are based on a simple approach of movement [28] as well as having a low computational complexity [29]. Nevertheless, they lack realism [29][30], for a number of reasons. One of these is the fact they restrict the agent’s motion to grid-based movement [31], which negates the reality of dynamic crowd environments. Moreover, in such modeling approach, the effect of congestion and interaction between the agents can be underestimated [29] due to the restricted motion of the agent. This, in turn, creates difficulty in modeling the different velocities of moving agents and simulating heterogeneous crowd behavior [27][30]. And the third is the inability of the individuals within the crowd to make independent decisions about their movement. CA is the most frequently used model for crowd modeling in games [27].

2.1.2. Social Force Model Approach

The social force model (SFM), where crowds are modeled based on a particle system, was proposed in 1995 by Helbing [24]. In this model, different agents in the crowd behave as homogeneous and physically identical, passive particles. In 2000, Helbing extended his model [32] to model human behavior in panic scenarios. Here, the behavior of such particles is governed by a collection of socio-psychological and physical forces, in order to describe a collective panic behavior in a crowd. The socio-psychological forces govern the agent's movement such that it keeps a certain distance from other agents and obstacles within the area. The physical forces maintain the agent's movement toward a certain goal through the use of repulsive and attractive forces that adjust the agent's velocity within a certain time period.

Musse et al.[33] extend the Helbing model further, and introduces individual-level differences in the crowds, rather than just having homogeneous particles. This is the first work to aim at a generalization of the Helbing model. It is achieved through enabling agents to behave individually based on their own attributes, which are represented as different levels of altruism. Moreover, the work discussed in [33] is used to model groups in crowd simulation. In this research, the agents behave based on the group structure they belong to, while also considering their individual-level attributes.

SFM is generally used to describe the collective behavior of crowds in panic situations [32]. For example, it can be used to model arching or clogging around exits in emergency situations as shown in Figure 1.

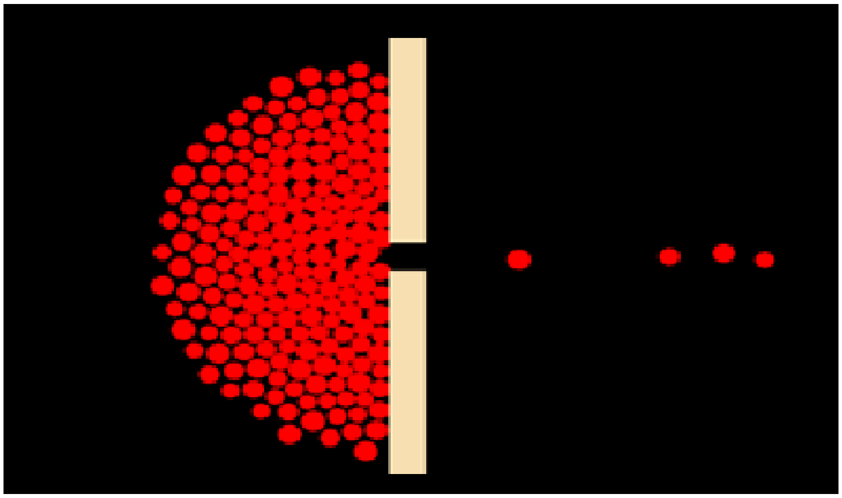


Figure 1: Arching phenomena

This is because the socio-psychological forces reflect the agent's intention to avoid colliding with other agents or obstacles, while physical forces reflect the movement of such crowds under certain circumstances. An example is a situation when crowd density becomes so high that individuals are forced to collide. Here the physical forces can reflect pushing or leaning behavior between agents, which affects the evacuation process [34][35]. Moreover, the simulation process of SFM is continuous; thus, individuals can move continuously in a two-dimensional environment. This enables modeling of realistic crowd phenomena during evacuation processes such as herding behavior and mass queuing to be reflected.

However, SFM does not consider decision-making, which is viewed as a limit of this modeling approach. Therefore some subtleties of individual behaviors, such as walking in pairs, stopping, and changing heading direction cannot be captured in this type of model [1][36].

2.1.3. Agent Based Approach

The third approach in the microscopic group is the agent-based one, where individuals are modeled as intelligent agents with perception and decision-making capabilities. This modeling approach was initiated first by Reynolds in [25], where the flocking behavior of birds and fish schools are modeled using individuals' local rules and perception skills. In the flocking behavioral model, the birds maintain a balance between two desires: to stay close to the flock and to avoid a collision with it. Later, in 1999, Reynolds extended his work in [37] to include steering behaviors at the individual level, to model more natural autonomous behavior.

Since Reynolds' original work, various researchers have aimed at extending his work in [37] to model more complex and realistic behaviors. The work discussed in [38] builds on the simulation of flocking behavior to model agents' speed adjustment, and introduces mechanisms that make the movement of a group's members more coherent.

In some crowd simulation applications, agent-based approaches are well suited for modeling heterogeneous crowds and complex human behaviors [39]. This is because of their flexibility and ability to model intelligent autonomous agents, where each agent can be assigned different attributes to reflect heterogeneous crowds. Moreover, these agents have the ability to perceive their surroundings, make decisions in response to the situation, and behave based on a set of defined internal rules [31][39][40]. However, despite the strengths of the multi-agent approach, it still lacks realism in modeling human behavior. This is due to a number of reasons, two of which are as follows. The first is that this approach is based on mathematical equations, though human behavior is a complex phenomenon that is difficult to capture in this way. Hence, some research provides models that are based on considerations of psychological and physiological theories. Nevertheless, these models do not consider all the underlying psychological and physiological elements behind human behavior, which means the behavior lacks realism [41]. The second reason is that there are difficulties in modeling certain aspects of human behavior, as it is challenging to model an agent intelligent enough to have human-like decision-making abilities [42].

2.2. Human Decision Making

An earlier well-known decision making model is Belief-Desire-Intention (BDI) [43]. Complex realistic reasoning are considered in this model that was best implemented by [44] according to [45]. Beliefs represent the information the agent has about the world, which may not be true and may change in the future, depending on the agent's perception. Desires are the states which the agent would like to bring about. Intentions represent desires which the agent is committed to fulfilling. In this model, the mental state of the agent before making a decision is governed by its beliefs, desires, and intentions.

Researchers have extended this model to suit modeling needs in specific contexts. For example, in [27] some additional attributes of the agents are considered, such as sensors, social forces, and the ability to interact with other agents Figure 2 shows the extended BDI model by [27]

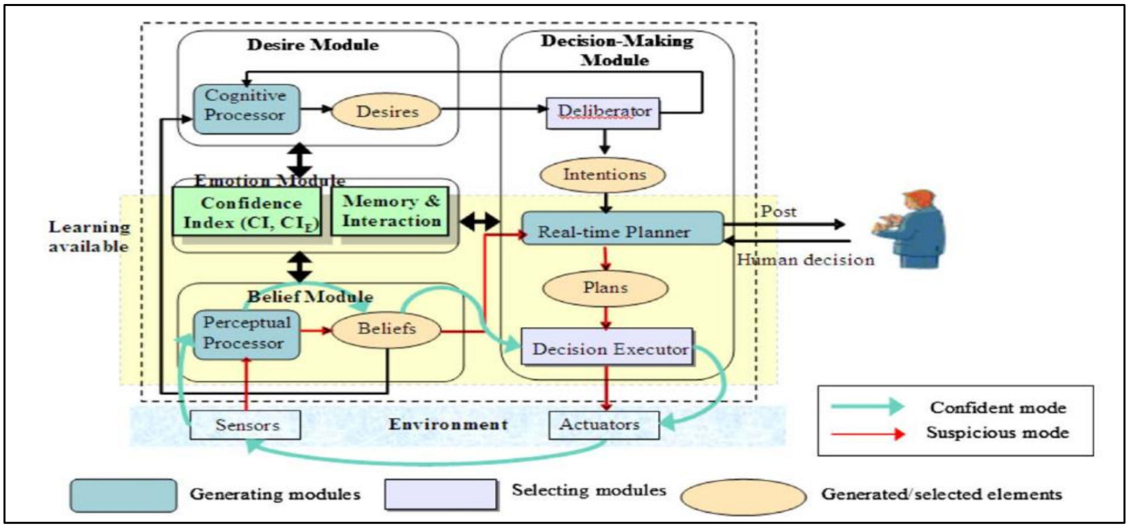


Figure 2: Extended BDI model

Then, the works in [3][12][46] use the extended version of the BDI framework proposed by [27] to model human behavior in response to an emergency event. An example is modeling human behavior in response to a terrorist bombing, as discussed in [12] and [46]. Zhao et al.[47] extended the BDI model by defining the confidence state that affects the agent's operation, such that its confidence reflects its optimism about achieving a certain intention. Being confident implies that it will continue to execute the current plan. Not being confident, on the other hand, implies that the agent will reevaluate its intentions.

Unlike using the BDI approach in modeling the role of reasoning and learning in human behavior, other works use the recognition-primed decision (RPD) model [48] to simulate the major cognitive and physical processes humans go through. The RPD model describes the high-level process of how humans make decisions based on recognition of the situation as well as past experiences. Once the recognition is formed, a matching of past experiences is made in order to decide on the action to be taken.

Some research models agents based on this RPD model. Luo et al.[16] models the decision process of agents based on RPD model [48] as well as appraisal theory [49]. The RPD model is used for the agents' decision-making processes while the appraisal theory is used for describing agents' emotional states. Since the RPD model describes the decision-making process of the agents at a high level, some additions to it are needed. The work in [8] considers a detailed representation of the experience-matching and the execution along with mechanisms for situation assessment.

For less complex reasoning regarding the behavior that agents should adopt, Sun et al.[50] model the decision-making of agents using the concept of a "smart environment". In such an environment, the agents are provided with the most appropriate behaviors to execute based on the consideration of certain attributes, which they have. These attributes include the agents' current locations, the level of urgency, the area affected by the emergency, and the agents' positions in the affected area. The agents then select behaviors to execute based on their physiological and psychological attributes through a rule-based system. Therefore, the agents do not need to perform any decision-making or complex reasoning about what behavior to adopt.

2.3. Modeling Behavior in Crowd Simulation

Hempe et al.[51] adopts the multi-agent approach proposed by Reynolds [37] to provide a real-time crowd simulation prototype. This prototype is intended to model agents' cognitive behavior. Such cognitive behavior includes an agent's ability to communicate with other agents, find and plan paths, and respond to its own desires, such as drinking, eating, etc.

Other approaches for modeling cognitive behavior have been developed by other researchers. The work in [20] models agents based on considerations of psychophysical and physiological studies. The psychophysical considerations include parameters as perception and velocity adjustment, while the physiological include achieving different goals. Psychophysical and psychological considerations have been considered by other researches as well. For example, Jun et al.[18] considers energy consumption, based on the level of physical activity along with an agent's psychological endurance capacity while avoiding jams in the crowd.

In emergency situations, researchers considered other behaviors related to the agents. For instance, Giitsidis et al.[10] models agent's ability to determine the closest exit in emergency evacuation in the form of the disembarking of an aircraft. Von Sivers et al.[52] model agents tendency to help each other or coordinate with each other during evacuation. They consider Self-Categorization Theory (SCT) [53] and Social Identity Theory (SIT) [54] in their work to model such social behaviors.

EvacSim [55] is another model that is concerned with modeling behaviors in emergency situation. Mainly, it models agent's responses to the different cues perceived from the physical environment and its interaction with other agents while considering the severity of the situation. Exodus [56] and SIMULEX [57][58] model multiple behaviors related to the emergency situation as queuing, congestion, and overtaking. In addition to that, these tools consider different abilities of the agent as evacuating from the nearest exits in buildings as well as agents' interactions with each other.

The effect of emotions and fear to model panic during emergency situations is studied by Jafer et al.[59] who modeled the panic of agents as adopting a random behavior during emergency situation. That behavior results in the agent moving in a random direction with double speed value compared to normal situation. The emotions effect during emergency situations is also considered by Bosse et al.[60]. In their work, emotions as fear affect beliefs and intentions of the agent and cause it to take protective actions such as covering ears, head and eyes or social actions like comforting other agents. On the other hand, Saunier et al.[61] investigated the effect of agent's beliefs together with other factors on its emotions. These factors are the agent's perception of the environment; event's effect on the agent's internal state; and the effect of the other agents' emotions on the agent. Based on the triggered emotion, the corresponding control action can be taken by the agent in response to the occurred event. Another research study [14] models how agents affect each other in terms of emotional and fear levels based on their interactions in emergencies. The study also considers panic as a random chance of forgetting the locations of exits during emergencies.

Besides modeling agents as individuals, modeling a group's behavior is considered an important step toward creating a more realistic crowd simulation. This is considered a challenging problem due to the heterogeneous nature of human behavior [33].

Studies show that the presence of social groups such as families or friend groups affects the collective behavior of a crowd [62][63][64]. For instance, family members who come to an event together tend to stay with each other and orient their actions and movements toward each other. These movements could be side by side, in a line-form that is perpendicular to the movement direction in case of low density crowds, or in V-shape in high density crowds [65]. In occasions, where family members get separated during the event, they tend to reunite before leaving [62]. Consensus decisions made by the family produces special actions that collectively affects the neighboring crowd and propagates to eventually reflect on the state of the whole event. [63].

Kamphuis et al.[66] uses SFM to model groups as a coherent unit in their movement, through the use of different forces. Such movement can be maintained by planning the path for a single agent, followed by constructing a virtual corridor around it that all the group's members need to stay inside. Similarly, the works discussed in [65] and [67] use the SFM to model coherent movement of group's members. That is achieved by exerting different repulsive and attractive forces by the group's members on each other.

The work presented in [68] adopts SFM together with leader-follower approaches to model the coherent movement of groups. It considers situations where the coherence is lost and how the group re-establishes it by waiting for the nonfollowing members. The same work is extended in [69] to include movement in sub-groups towards the leader. However, both studies did not consider behavioral related aspects of the group members or decision making processes.

The coherent movement of groups as a unit was modeled in [70] as well. It is done by reimagining the original flocking behavioral model proposed by Reynolds in [37] as a kind of constraint flocking behavior being a leader-follower model. In such model, the leader decides about the motion of the group's members while being followed by the rest of the members. The leader-follower group's modeling is also considered in [71], where sociological effects between groups and in individual relations are considered. They give group members the ability to switch their group based on certain sociological factors. Also, the researchers give every group member the ability to become a leader of a new group. However, their work does not consider situations such as panic cases and their corresponding groups' behavior. In addition, the model does not tackle situations where a group's plan can be changed in normal scenarios represented by a change of goals.

Other works considered different types of interactions between members of the same group as in [72]. In such work, different movement behaviors result from these interactions, including leader–follower, V-shaped, or line–abreast movements.

Ren et al.[73] introduce a generalized approach to simulate different types of group formations as leader-follower, crosswalks, or switching between groups. This is achieved through defining a relation matrix that sets the relation between an agent and its neighbors. Such relation defines the distance the agent needs to maintain in order to stay within a group as well as the number of following members of that agent. Based on these attributes a certain group formation is set. However, the work does not consider high level behaviors or activities for which the group members could have split, joined back, or performed other interactions.

To preserve group unity and the performance of different activities, Park et al.[74] consider the coordination between a groups' members in order to include the leader–follower, divide–proceed, and divide–wait activates. It is based on the common ground theory [75][76] where the different groups can coordinate between themselves to decide what actions to take. Later, the same work presented in [74] was extended in [77] to be based on multi-agent approach for coordination strategy. In this work, the agent considers different aspects related to its group members, such as spatial and temporal conditions, in order to select its own micro-coordination strategy and apply it. This is based also on the common ground theory. However, both works did not add an element of altruism related to modeling groups such as families, and also stochastically triggered some behavior, making it not very realistic. For example, an agent would suddenly go to a restroom or be drawn into a shop, causing it to add a new sub-goal.

Other considerations related to groups are considered by researchers. For example, Šochman et al.[78] models recognition between members of the same group. This is based on the concept of using different forces, that is, repulsive and attractive forces, to allow agents that know each other to find each other and then form a group. However, this works only for cases where agents do not move or are standing next to each other. Qiu et al.[79] considers other aspect of groups where it gives the agent the ability to leave its group and join others. It uses utility theory [80] and social comparison theory [81] in a multi-agent system, giving the agent the ability to behave adaptively in a changing environment. The agent selects one of the group's members to follow based on the matching characteristics between them.

The principle of coherence between family members appears in emergency situations as kin behavior, where family members tend to gather, backtrack, and wait for each other before evacuating in order to support and help each other. Not being able to be with family members during such emergency situations might lead to a particular type of panic that causes dysfunctional behavior. That panic stems from the threat of the loss of loved ones, not from the danger itself, and this, in turn, affects the evacuation process. In some cases, people who had been in a building with their relatives re-enter it after their first escape to look for missing family members [64][82][83][84]. Studies such as [65][85] claimed that the behaviors adopted by people who belong to families increase their evacuation time and therefore the probability to save their own lives is less. In their studies, they found that these behaviors affect the evacuation process of the other pedestrians that compose the crowd. This is due to the movement of family members as coherent units that could block movement of the other pedestrians, or in some cases due to their movement in an opposite direction to the flowing stream of pedestrians in order to gather or rescue the rest of the family members.

Several researchers applied social science finding in simulating crowed with groups in emergency situations and reported their findings. Pelechano et al.[86] modeled agents with the ability to explore and develop a cognitive map of an unknown building to find their way to exits during an evacuation. The work models knowledge-sharing between agents who belong to the same group, considered as inter-agent communication. While, Okaya et al.[87] considered social relationships between members of the same group using the BDI framework [43]. Based on the different beliefs, desires and intentions while considering relationship factor of an agent; different behaviors are adopted. These behaviors are restricted to evacuate immediately, look for a lost family member, or evacuate with the rest of the family. Ling et al.[88] defined the social relationships by a minimum group separation distance and a group-seeking attribute that determines the level of visibility of group members to each other. During emergency situations, members of the same group with close relationships approach each other causing delays in their evacuation time. A similar work in [89] models behaviors related to group members as approaching each other or looking for a lost member during emergency situations. The social relationships between members of the same group are also explored in [90] using virtual potential energies concept. The members of the same group need to stay within a conferral zone for which they are considered to be able to communicate and approach each to evacuate in emergencies. To keep group members coherent while performing other family related behaviors, Tsai et al.[14] modeled family members based on leader-follower approach. The work considers behaviors related to families as looking for a lost member or approaching each other during emergency situations. While, Kyžňanský et al.[91] considered other behaviors of families such as carrying children and maintaining family cohesion in emergency situations.

The present research is based on modeling the family as a special type of group in a crowd simulation. The family-type group model is comprehensive and considers multiple family behaviors at the same time. When modeling groups in crowd simulations, many researchers are concerned with producing coherent movement at the reactive motion planning level. However, it is necessary to consider different interactions between group members at the social, physiological, and psychological levels to produce more realistic behavior.

The present model includes these considerations regarding interactions between family members and reflects their movement. Moreover, it considers the physiological and psychological aspects at the member level to represent certain intentions that are not stochastically generated as was the case in some models. States that trigger a family member to take certain actions represent these intentions. Yet these states are not reveled immediately. This is because one’s membership in a family implies that other members’ states should also be considered to preserve the overall family behavior.

To reveal the family members’ states, this work structures the family based on a leader-follower approach that considers both movement and decision-making. The movement is applied through the dynamic reactive motion approach in an agent-based crowd simulation library, while the decision-making is applied through the concept of making consensus decisions at the family level. To make a decision in order to reveal different states by the family, each member shares his/her intentions about taking a certain action, while the family leader makes the final decision.

The model is goal-oriented: Family members have various goals to achieve during family gatherings. These are not static (unlike those which other models consider); rather, they can be alerted/cancelled or new goals could be inserted. Such dynamic updating of goals depends on the situation that the family member or family is experiencing and the states of the family members.

This model does not require complex reasoning and decision-making processes, yet it preserves the concept of the family in terms of structure and behavior. Moreover, the model is abstracted and independent of the reactive motion planning that simulation engines govern. Hence, it is a lightweight model. It models a family in a crowd and reflects its dynamic reaction to different situations. Moreover, since it is a state-driven model, different states can be added/removed as needed in a well-defined approach to be included in the model. These states can be verified and validated easily. The specifications and the detailed design of this model are discussed in chapter 3.

CHAPTER 3: SYSTEM MODEL

The present work is concerned with studying family behavior and its effects in different contexts in order to predict behavior in similar real-life situations. It is achieved by developing a model that considers the family concept in a crowd simulation environment under certain conditions.

In this chapter, the proposed model of the family concept is discussed in detail. Section 3.1 presents an overview of the system model, while section 3.2 discusses the model design in detail. That includes the family's representation, its structure and constraints. Moreover, the section discusses the decision making process at the family level, followed by the resultant behavioral models family adopts. Finally, the implementation and verification of the designed model is presented in section 3.3.

3.1. Model Overview

Modeling the concept of a family requires modeling family members as agents of different age categories being adults, teenagers, children, and elderlies of both genders and their corresponding roles. Each member of the family has the ability to select his or her own goals to reach during the event. These goals may be altered or increased based on situations the member encounters during the event, or new needs to be satisfied. These encountered situations may appear as emergency situations where the family needs to act in critical situations, such as evacuating an event due to the occurrence of fire, or having to look for lost family members. On the other hand, the needs that an individual member might experience include the need to go to a restroom, sit on a chair due for being tired, satisfy hunger, or alleviate boredom. Due to encounters with such situations and new needs, a family’s initial plan on arrival may be altered. The plan changes based on a decision making mechanism at the family level in order to satisfy the different members’ needs and act based on the current situation. New updates to the plan result in other behaviors the family takes, such as splitting into smaller sub-families, waiting at a certain spot, joining with other sub-families, evacuating the event, and looking for lost members, based on the situation the family is experiencing at that point of time.

The family concept is enriched by having a leader with certain responsibilities, and introducing the main constraint of the concept of family unity. According to [62] while in an event families and friends tend to stay together, such as arriving and leaving the event together. If they are separated, they are most likely to try to reunite. In this model, the unity concept implies that the family should be always kept as a unit; whenever there are nonfollowing/lost members or the family splits into smaller sub-families, the family should return and reunite. Family unity is maintained by the family leader, who is assigned several responsibilities. These responsibilities include checking continuously that all of the members are following or are in range of sight. Nonfollowing members would necessitate certain decisions by the leader, such as waiting in a visible location or looking for the nonfollowing member. Another responsibility of the leader is making considerations at the family level related to actions that follow the split behavior of the family into smaller sub-families. This means that when the family needs to split, the leader should plan the rejoining mechanism prior to the split in order to conform to the unity constraint. Finally, the family leader is responsible for making different decisions at the family level in order to satisfy members’ needs and act with respect to the current situation. Such decisions may include changing the initial plan the family set on the arrival to the event, changing the family structure through splitting the family for different purposes that include satisfying members' needs, or looking for nonfollowing family members.

In the case of an evacuation situation, special family concerns arise considering the family with children and elderlies and the role of parents. A fast evacuation process may require carrying the children and assigning other responsibilities to family members. Moreover, the role of the leader appears when considering a family that split prior to the evacuation; the leader has the additional role in communicating with the other sub-families in order to ensure that they evacuated safely in order to maintain the unity aspect of the family.

3.2. Family Modeling

This section discusses the family model along with its structure and associated decision making processes

3.2.1. Family Model and Structure

The family f_k is modeled based on a number of parameters set FP such that:

$$FP = \{A, FG, l, fs, ds\}, where:$$

A: is a set of the autonomous agents a_i that compose f_k which are the family members. FG: is a list of goals of all $a_i\ in\ A\ that \in\ f_k$, being ordered based on the shortest path algorithm having the entrance to the event as the initial point. l: is the leader of $f_k$that is an a_i being an adult or a teenager member. fs: is the current state of the family being split to sub-families or not. ds: is the dominate state of f_k that represents the state that most of the members have currently as tired, hungry, etc. The family structure has certain constraints that should be maintained in the family model that are; it should have a leader all the time, and should have two or more members in order to compose a family.

The behavioral model of the family is based on a leader follower approach where there is one leader assigned at a time, and the rest of the family members are followers who follow the leader in their movement.

A) Member structural model

As discussed earlier, family f_k is composed of a set of members A that are agents which compose the crowd. The crowd is also composed of individuals who don't belong to families. Each $a_i \in A$ has characteristics sets in order to mimic a human being. These characteristics sets are Physical Characteristics set PC_i, Individual Characteristics set IC_i, Event related Characteristics set EC_i, and Activities related Characteristics set AC_i. PC_i set describes the physical attributes of the agent, while IC_i describes individual differences between agents. For EC_i set it describes characteristics of the agent that are related to the event agent is attending whereas AC_i set represents the different activities the agent is doing. Each of these sets is discussed in details in the following subsections. Figure 3 shows the overview model of the agent.

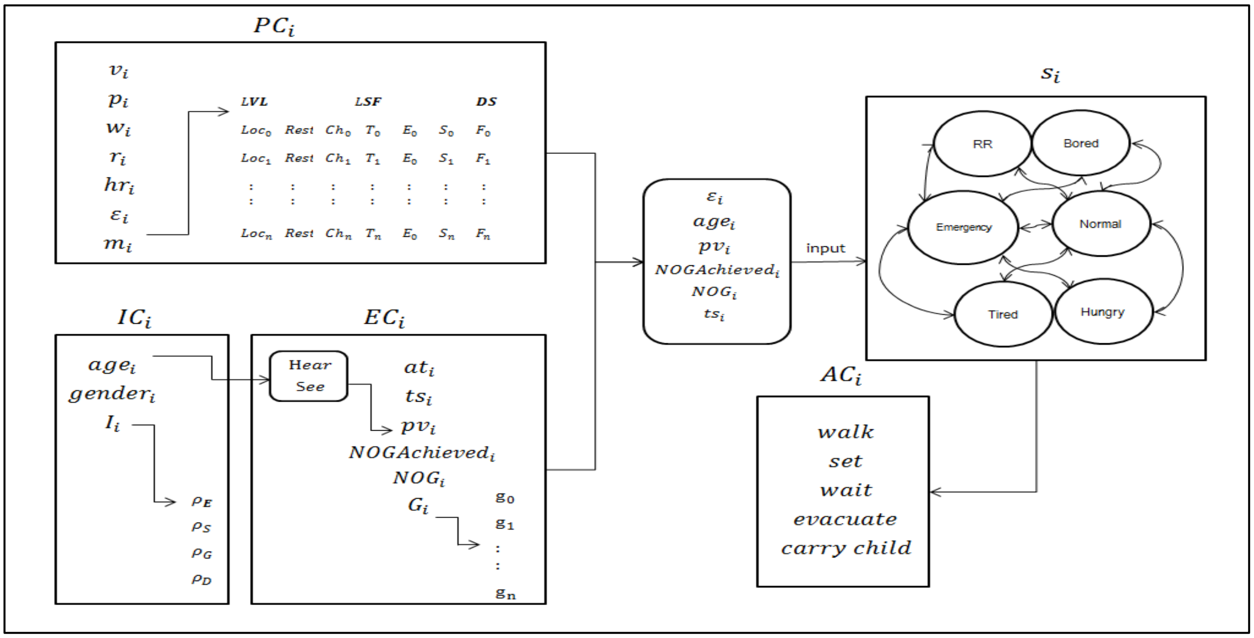


Figure 3: Overview model of the agent

A) PC_i set

PC_i set is composed of moving velocity v_i that includes speed and direction, current position p_i at a certain point of time, weight w_i in kilograms, size consumed in the space represented by a radius of a circle r_i, heart rate at certain point of time hr_i, energy level ε_i the agent has at a certain point of time and memory m_i that has the last seen facilities as well as the last visited locations by the agent and danger signs.

The maximum speeds for which an agent is moving at changes based on the activity being done by the agent, such that [92]:

$$Default\ moving\ speed = 1.8\ m/s$$

$$Evacuation\ speed = 2.5\ m/s$$

$$Setting\ waiting\ standing\ speed = 0.0\ m/s$$

These speed values might vary overtime due to crowd density, avoiding obstacles, and being closer to the goal to be reached. Additionally, the speed differs based on the agent's gender and age type being an adult, teenager, elderly or a child.

The position of the agent p_i describes its location in the 2D plan of the system such that:

$$p_i = (\mathrm{x}, \mathrm{y}), \mathrm{x}, \mathrm{y} \text{ are coordinates}$$

The weight of the agent w_i is considered based on its age and gender [93] as shown in Tables 1, 2 below, for males and females respectively.

Table 1: Males age-weight ranges

Males					
Age (years)	1-4	5-12	12 - 20	20 - 60	60 – 70
Age category	Child	Child	Teenager	Adult	Elderly
Weight (kilograms)	9-12	18-40	45-70	74-104	70-84

Table 2: Females age-weight ranges

Females					
Age (years)	1-4	5-12	12 - 20	20 - 60	60 – 70
Age category	Child	Child	Teenager	Adult	Elderly
Weight (kilograms)	9-15	18-41	46-58	58-82	60-70

For the heartrate value of the agent hr_i it's considered based on having an average fitness level [94][95]. Such values are estimated based on age and gender of the agent along with the activity being done as shown in Tables 3, 4 below for males and females respectively.

Table 3: Males age-heart rate ranges

Males									
Age (years)	1-2	3-11	12-17	18-25	26-35	36-45	46-55	56-65	65+
Hear rate(bpm)	98-120	80-120	60-100	70-73	71-74	72-76	71-76	72-75	70-73

Table 4: Females age-heart rate ranges

Females									
Age (years)	1-2	3-11	12-17	18-25	26-35	36-45	46-55	56-65	65+
Hear rate(bpm)	98-120	80-120	60-100	74-78	73-76	74-78	74-77	74-77	73-76

The energy level ε_i is consumed or replenished based on the different activities being performed by the agent. Such activities include its movement being navigation in the event or evacuating, resting on the chair or at restaurant, waiting for someone at certain spot or communicating. In order to calculate the energy consumption ratio, Energy expenditure (EE) equation is used that is obtained by [96] based on experimental studies in a sports science journal. The equation considers some of the agent's physical characteristics as hr_i, w_i and individual characteristics as age (age_i) and gender ($gender_i$) as shown below for the energy expenditure per minute in kilo calories (kCal) :

$$
\begin{aligned}
EE = gender_i * \ (-55.0969 \ + \ 0.6309 * \ hr_i \ \ + \ 0.1988 * \ w_i + \ 0.2017 * \ age_i) \\
+ \ (1 \ - \ gender_i) * \ (-20.4022 \ + \ 0.4472 \ * \ hr_i \ - \ 0.1263 \ * \ w_i \\
+ \ 0.074 \, x * \ age_i)
\end{aligned}
$$

The initial values of the energy level is set based on the amount of energy a human being needs to survive which are 3000 Kcal for males, and 2200 Kcal for males and females respectively [97].

Finally, the memory of the agent contains the Last Visited Locations (LVL) reached by the agent together with the different facilities it has seen. These seen facilities are updated dynamically to reflect the Last Seen Facilities (LSF) based on the time seen.

Additionally, the memory contains Danger Signs (DS) if seen by the agent as fire. Figure 4 shows the memory structure of the agent in this model.

LVL	LSF					DS
Loc_0	$Rest_0$	Ch_0	T_0	E_0	S_0	F_0
Loc_1	$Rest_1$	Ch_1	T_1	E_0	S_1	F_1
:	:	:	:	:	:	:
:	:	:	:	:	:	:
Loc_n	$Rest_n$	Ch_n	T_n	E_0	S_n	F_n

Figure 4: Agent memory structure

Where, each item in the memory is composed of a name of the facility and the location, for example:

$$Ch_i\ is\ a\ chair, located\ in\ (\mathrm{x}, \mathrm{y}), \text{coordinates}$$

B) IC_i set

The IC_i set on the other hand, includes characteristics that reflect individual differences between agents as age in years age_i, gender being male or female $gender_i$, and a set of interests that the agent has I_i. The interests set I_i is a four- dimensional vector, where each dimension represents a certain interest type of a_i at a certain context, such that:

$$I = \{\rho_E, \rho_S, \rho_G, \rho_D\}, where\ E, S, G, D\ are\ interests\ at\ certain\ locations\ at\ the\ event$$

C) EC_i set

The EC_i set contains some characteristics of the agent that are related to the event where the agent exits. These characteristics are the arrival time to the event at_i, time stayed so far at the event ts_i in minutes. Additionally, EC_i includes the agent's list of goals G_i for which it intends to reach during the event. Such G_i is a vector of goals that are initially set based on the agent's interests vector I_i, and updated throughout the navigation process of the agent as needed such that:

$$G_i = \{g: g\ is\ an\ (\mathrm{x}, \mathrm{y})\ \mathrm{coordinates}\}$$

Furthermore, $\mathrm{EC_i}$ set includes the number of goals achieved out of $\mathrm{G_i}$ list $\mathrm{NOGAchieved_i}$, along with the total number of goals $\mathrm{NOG_i}$ reached by the agent either being its own goals or the goals of other family members it have reached while navigating with its family. Finally, $\mathrm{EC_i}$ contains the perceived value by the agent $\mathrm{pv_i}$ that provides information about what it currently seen by the agent within in its range. Such $\mathrm{pv_i}$ of the agent, depends on its age as being an adult or teenager as well as on its type being a leader or a normal member. Adult and teenager agents are having a higher view range compared to a child or an elderly person as well as the leader agent who is having a higher attention compared to a normal member. Figure 5 shows an abstract overview of the perceiving process by the agent.

```
if fire || announcement exist then
    $pv_i$=fire
else if a $facilty_\omega$ exists then
    $pv_i$= $facilty_\omega$
        If $\exists facilty_\omega \in m_i$ then
            Move $facilty_\omega$ to top of $\omega$ $type$
        else
            Insert $facilty_\omega$ into $m_i$ $in$ $\omega$ $type$
        end if
else
$pv_i$=idle
end if
```

Figure 5: Perceiving process overview

The perceived value pv_i of the agent is updated based on its current location along with the different sings or facilities, or other agents it’s able to see or hear within its range. The seen items that include fire, exists, signs of exits, restaurants, restrooms, and chairs are inserted into the agent’s memory as may be used later. Perceived values that are based on the hearing process are represented by announcements within a certain area where the agent is located.

D) AC_i set

Finally, the $\mathrm{AC_i}$ set represents the different activities the agent is having as, walking, standing, waiting, setting or carrying a child.

B) Member behavioral model

The behavioral model of the agent is based on a goal oriented approach. This means the movement of the agent is adjusted in the speed and direction in order to reach the goal. Each agent needs to retrieve the next goal it needs to reach. Then, it needs to know its current position and velocity in order to adjust them towards the goal location while considering collision avoidance with the other agents and obstacles in the environment.

As the agent navigates into the environment in order to reach its goals; it obtains a certain state s_i that represents its current condition or a new need. Such state points toward the ideal action that the agent may take in order to satisfy its new need if exists. However, that need is not necessarily considered immediately, due to the family membership, as the rest of the members' needs should be considered as well to take a certain action.

The state of the agent is depends on partial attributes of its $\mathrm{PC_i}$, $\mathrm{IC_i}$ $\mathrm{EC_i}$ characteristics sets and hence, it is a function of these attributes:

$$s_i = f(\varepsilon_i, age_i,\ NOGAchieved_i, NOG_i, ts_i, pv_i)$$

Based on the different input attributes, one of several different possible states is dominated. These states are normal, emergency, bored, tired, hungry, and need to use restroom. The normal state of an agent reflects its normal condition where no emergency situation is occurring as fire existence in the area where the agent exits. Moreover, in this state, the agent is having an acceptable energy level, and it is not feeling bored, hungry, or in need of the restroom. Hence, the agent can pursue the current action being taken without the need to make changes, unless it is affected by another member's state, as will be discussed later. The emergency state appears when the agent encounters a critical situation like it sees a fire in the vicinity or hears an announcement that indicates a fire existence, which prompts the need to evacuate the location. The bored state on the other hand, is triggered in this model based on $\mathrm{ts_i}$ value of the agent together with $\mathrm{NOGAchieved_i}$ within that spent $\mathrm{ts_i}$. If the agent has stayed for some time without achieving enough number of its initial goals, the agent would have a bored state, such that:

$$NOGAchieved_i < 3\ goals\ \&\&\ ts_i > 20\ miuets$$

The ideal action for the bored condition in this model is to go achieve some of the previously determined goals.

The state of the agent becomes tired, when it has stayed for a long time in a certain location and visited a lot of locations where its energy level is decreased to low value. These factors are translated into the model, to trigger the tired state with low energy level value, high duration spent in the event such that:

$$ts_i > 30\ miuets\ \ \&\&\ \varepsilon_i < 1800\ KCal$$

The ideal action of this state is to sit on the nearest chair. However, if the agent is a child, his state would be that of being tired with the need to be carried. This child might be carried by one of the family members if possible, and if having his $\mathrm{age_i} < 5$ years.

Based on a conducted survey (refer to appendix), a human being usually feels hungry when he has stayed for a long time in a certain location or hunger might be directly triggered when he sees a nearby restaurant. In this model, these factors are reflected through the agent's attributes such that:

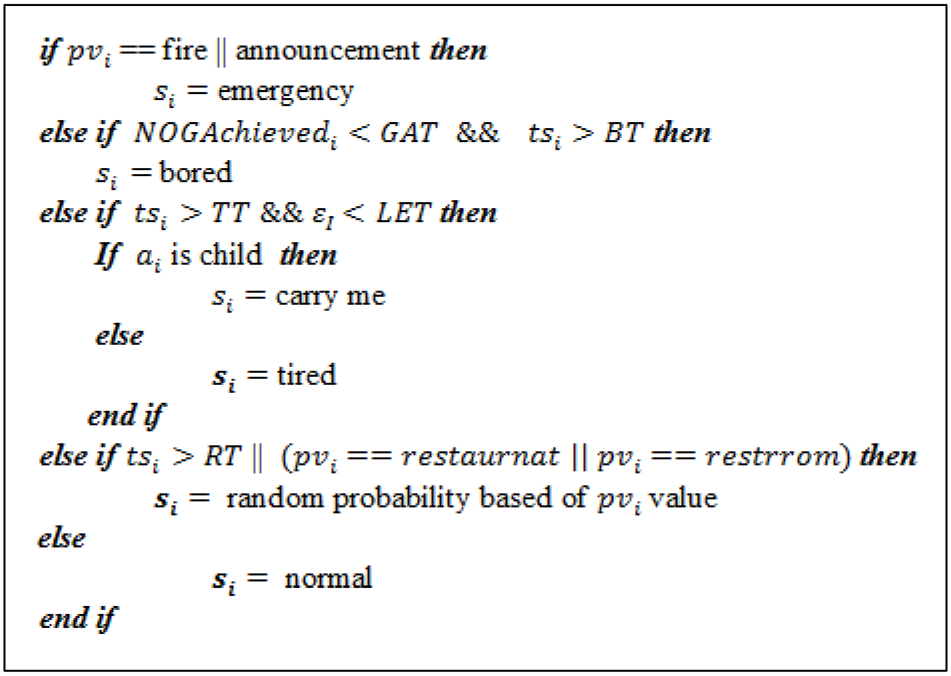
$$ts_i \ \in [40 - 90\,]\, miuets \,||\, pv_i = restaurant$$

The ideal action to be taken by the agent based on a hunger state is to go to the nearest restaurant, or the last seen restaurant at the area. However, as has been discussed earlier, other family's members' need should be considered before taking the ideal action as will be discussed later in the decision making process of the family section.

Similarly, based on the conducted survey (refer to appendix) , a human being uses the restroom if he has stayed in a location for quite long time or may visit the restroom if he has seen one. In this model, the agent might become in need of the restroom depending on the time the agent has stayed at the event and the perceived value of a nearby restroom. Such that:

$$ts_i \ \in [40 - 90\,]\, miuets \ \| \, pv_i = restroom$$

The overall all state generation process is shown in Figure 6



```
if $pv_i$ == fire || announcement then
        $s_i$ = emergency
else if $NOGAchieved_i < GAT$ && $ts_i > BT$ then
    $s_i$ = bored
else if $ts_i > TT$ && $\varepsilon_I < LET$ then
    If $a_i$ is child then
            $s_i$ = carry me
    else
            $s_i$ = tired
    end if
else if $ts_i > RT$ || ($pv_i == restaurnat$ || $pv_i == restrrom$) then
        $s_i$ = random probability based of $pv_i$ value
else
            $s_i$ = normal
end if
```

Figure 6: State generation process of agent

Where, GAT is the number of goals being achieved within time threshold BT for the bored state. While TT is the time threshold for an agent to be tired, while having energy less than Low Energy Threshold (LET). Finally, RT is the time threshold for which the agent would be hungry or in a need for the restroom.

Each of the states of the family members is input to the decision making process by the family to decide about the action to be taken at the family level.

Initially, once the family f_k arrives to the event, each member in the set A selects a number of goals G_i to be reached based on his/her interests vector I_i as was discussed earlier at the agent model section. Then, the family leader orders and checks the different desires of each member and tries to satisfy them, through visiting the different goals sequentially based on the shortest path order from the initial positon of the family which is event's entrance. Having the entrance as the initial point, the leader then selects the nearest goal from the family goals list FG. Then, after approaching that goal, if no updates occurred on the family's state or its members' conditions; then the family processed to the next nearest goal with respect to the current location that is the reached goal.

3.2.2. Decision Making and Family Behavioral Models

In this section, the decision making process at the family level along with the behavioral models taken by the family are discussed.

A) Decision making process

According to [62], families and friends tend to move with each other as a unit. The family needs to maintain unity constantly during its movement towards its different goals. This is achieved by each family member being a leader or a follower and through perceiving the environment. If the member is a leader, besides seeing the surrounding facilities in its current location, it needs also to ensure that all of its family members are following it. This is achieved through checking if all the followers are within a certain range around it. On the other hand, a follower needs to keep track of its leader's position, and tries to approach it as fast as possible. If one or more of the family members are not following the leader, the leader will have certain considerations that will affect the decision making process of the leader. This in turn, affects the whole family's actions and the initial plan it set on arrival to the event. Leader decision making is affected additionally by the different states of each family member that are considered when making a decision about the next action to be taken by the family, as discussed below.

Figure **7** shows the abstracted decision making process of the leader, along with the resultant behavioral models in the different stages.

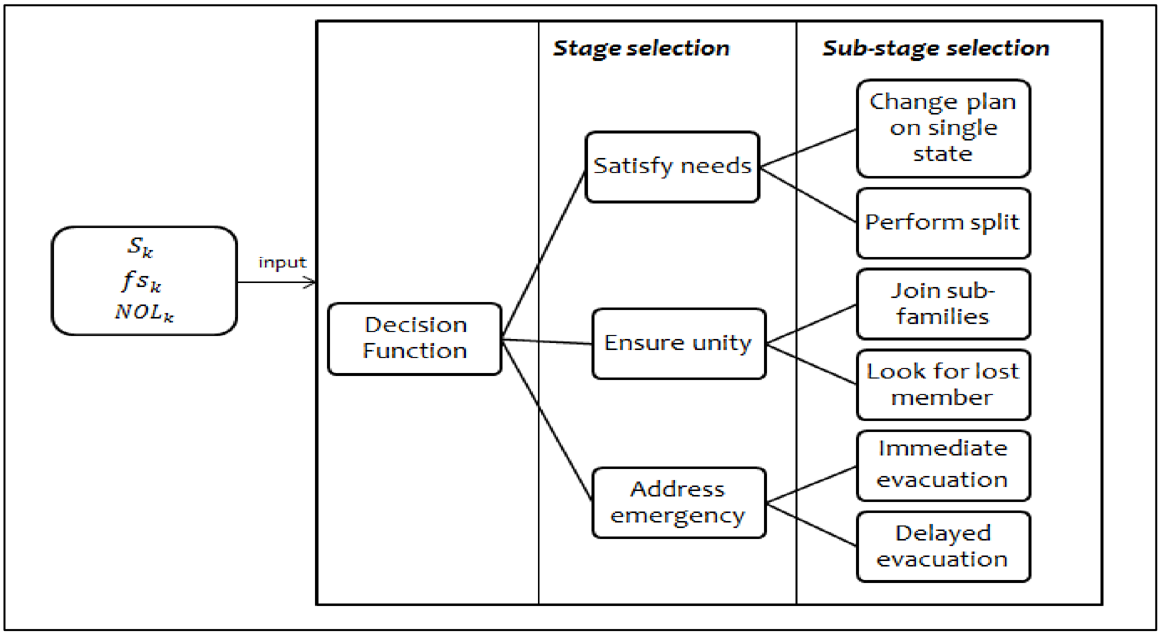
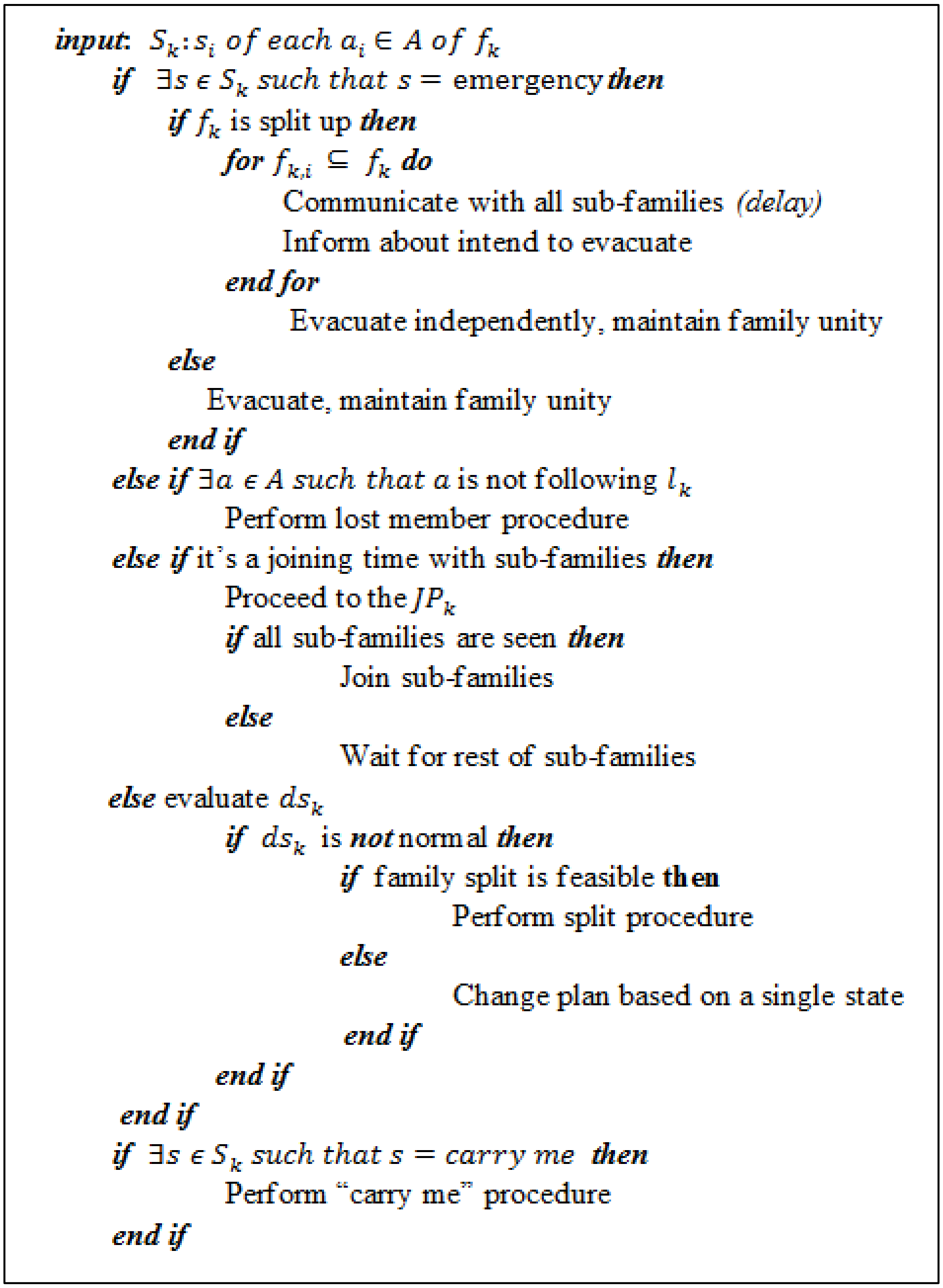


Figure 7: Decision making process

Such decision making process is centralized with family's leader, in order to allow the rest of the family members to make less effort compared to individuals not part of the group, as suggested by the Social Loafing Theory [98]. This implies that some group members make the decisions (leaders, in this model), while the rest of the members follow the leader. Some other aspects the leader considers in the decision making process include whether the family state was split into sub-families earlier or not and the number of possible leaders in the family. The possible leaders are other family members who are of the adult or teenage category who could become leaders of sub-families if needed.

The algorithm of the decision function is described in Figure 8.



```
input: $S_k : s_i$ $of\ each\ a_i \in A\ of\ f_k$
    if $\exists s \in S_k$ $such\ that\ s =$ emergency then
        if $f_k$ is split up then
            for $f_{k,i} \subseteq f_k$ do
                Communicate with all sub-families (delay)
                Inform about intend to evacuate
            end for
                Evacuate independently, maintain family unity
        else
            Evacuate, maintain family unity
        end if
    else if $\exists a \in A$ $such\ that\ a$ is not following $l_k$
            Perform lost member procedure
    else if it's a joining time with sub-families then
            Proceed to the $JP_k$
            if all sub-families are seen then
                Join sub-families
            else
                Wait for rest of sub-families
    else evaluate $ds_k$
            if $ds_k$ is not normal then
                if family split is feasible then
                    Perform split procedure
                else
                    Change plan based on a single state
                end if
            end if
    end if
    if $\exists s \in S_k$ $such\ that\ s = carry\ me$ then
            Perform "carry me" procedure
    end if
```

Figure 8: Decision making algorithm

Based on the considered aspects, various possible behavioral actions can be taken by the family. These behavioral actions are mainly categorized into three classes, from the simplest to the more complex: satisfying family needs, ensuring unity, and addressing emergency situations. Satisfying family needs basically means making changes to the current family plan in order to satisfy the members' needs based on their current states. Such changes might involve a family split into smaller sub-families depends on the situation. On the other hand, the family unity concept is about how the family behaves when it's the time to join with other sub-family(s) or when it has a nonfollowing member. In case of having a nonfollowing member, the family will first wait for it for some time, then if not found, the family will follow a look-up procedure based on the age category of the lost agent. Having the nonfollowing member a child or an elderly member, it will be considered more critically, and it might involve a family split or join. Finally, the emergency situation involves evacuation of the location, which might also involve possible splits and joins, communication between family members, and carrying children. Each of these behavioral models will be discussed in detail below in the next sections.

B) Change of plan behavioral model

A change of plan may result when the family needs to change what it is currently doing due to certain conditions or to satisfy the needs of its members. Two possible mechanisms that represent plan change decisions taken by the family leader; involving the whole family in a certain action or having the family members split into a number of smaller sub-families so that each sub-family can pursue a different action.

As an initial step in the decision making of the leader in the normal scenario where there is no emergency situation, the leader considers the state s_i of each family member. Then, the leader tries to find a dominant state,ds_k, where most of the members' needs may be met. Having more than one state existence makes the leader to try to satisfy as many members as possible. In this normal scenario, the treated states are hungry, tired, need to use restroom, bored, and the normal state. At the initial step of the decision-making process, as discussed earlier, the leader considers two more issues: whether the family was split earlier or not, and the number of the possible family leaders who could be leaders of sub-families in case the family leader decided to perform a split. If the family has only one leader, it can't do a split because it must maintain the family structure constraint that requires each family or sub-family should have a leader. Similarly, the family can't perform a split, in case it's already split into sub-family to have a second level split unless in some cases when encountering a lost member situation. Not being able to split in these normal situations, the leader changes the current action based on the highest priority state. The states are ordered from the highest to the lowest, as follows:

$$< hungry, tired, need\ to\ use\ restroom, bored >$$

Therefore, the decision about the action to be taken is based on the state that exists with the highest priority as a ds_k where most family members have. Each state should be resolved by a certain action, in order to satisfy the member with that state. In this model, having ds_k as a hunger state of the family implies that it needs to go the nearest restaurant. Once it approaches it, some time is spent inside and energy levels ε_i of the family members are recharged based on the time spent. The time spent in minutes by the family varies:

$$time\ to\ spend = rand(x), where\ x > 10, x < 45$$

Similarly, having ds_k as a tired state of the family implies that it approaches the nearest chair. After sitting for some time, members' energy levels ε_i are recharged based on the time in minutes they sits. The same concept applies to the restroom state. For the bored case, in a norm act, when someone is bored at a certain location, he might leave it or go to more attractive areas that match his interests within the location. In this model, the bored state in an agent implies that it goes to some of the initial goals it set at arrival at the event, based on its interests. Finally, having the normal state as the dominant state implies that the family need not change its plan and will continue with the current action being taken. It should be mentioned here that if the family can't do a split into smaller sub-families, then the whole family would be involved in performing a certain action even if some members don't have that state, so that the whole family would approach the nearest restaurant or chair. This is achieved except for the case when there are some children who are tired and need to be carried; these are carried based on a certain carrying mechanism.

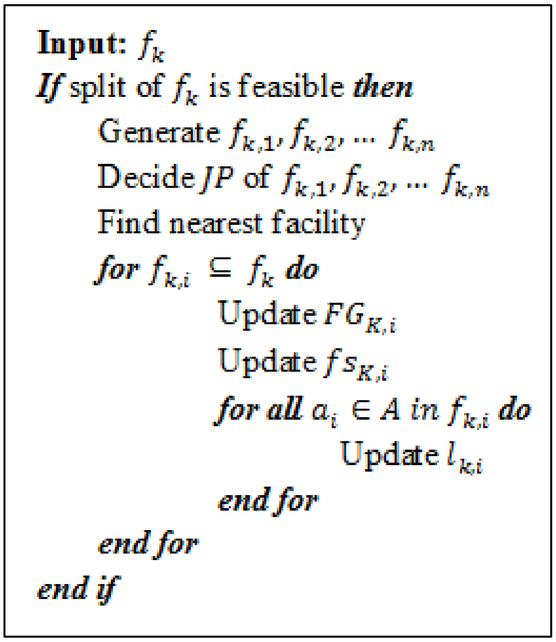
For a child to be carried, in this model, the child should be of age should be less than five years. The leader issues the order about who should carry the child; this should be an adult or a teen member who is not currently carrying a child—i.e. each member can carry only one child at a time. Initially, the leader looks for a member who has a normal state, since the carrying action would consume more energy than usual actions. If none of the members has the normal state, the leader assigns this task to another member that has any of these states, in sequence.

$$< bored, hungry, restroom, tired >$$

If none of the members exist with such criteria, then if the leader is not already carrying a child, he may carry the child; otherwise, the leader may consider approaching the nearest chair in order to have some rest. The child is carried for a length of time of around 10 minutes, based on a norm act, and then it resumes its movement. It should be mentioned here that if the family has approached a restaurant or a chair, then the carrying action stops. Additional effects that take place when an agent carries a child include more energy consumption due to heavier weight, a lower moving speed, and an increase in the size of the space occupied by the agent.

Having the family decide to approach a facility such as a restaurant, a restroom, or a chair, implies that it locates the nearest facility to its current location. This is achieved by having each family member share the information it has about the most recently seen facilities and their locations with the rest of the family members. Then the family leader determines the nearest facility among the shared locations through the use of the shortest path algorithm. After that, the family proceeds to the facility.

If the family has not split earlier and has more than one leader, there are more possible actions the family may take in order to satisfy more of the members' needs. This is achieved through the family split mechanism, which allows the family to be split into smaller sub-families, each with a leader. Then each sub-family, with its corresponding leader, proceeds to a certain location or facility in order to satisfy its members' needs. For example, one sub-family may approach to the nearest restaurant while the other sub-family approaches the nearest restroom. As shown in Figure 9 for the split mechanism.



```
Input: $f_k$
If split of $f_k$ is feasible then
    Generate $f_{k,1}, f_{k,2}, \dots f_{k,n}$
    Decide $JP$ of $f_{k,1}, f_{k,2}, \dots f_{k,n}$
    Find nearest facility
    for $f_{k,i} \subseteq f_k$ do
        Update $FG_{K,i}$
        Update $fs_{K,i}$
        for all $a_i \in A$ in $f_{k,i}$ do
            Update $l_{k,i}$
        end for
    end for
end if
```

Figure 9: Overview of split mechanism

For the case of having more than bored member or some members in the family who are having s_i is normal. If the family is able to split, then different sub-families are generated where each sub-family contains members who are having least conflict values between their members. For the leaders assigned for those generated sub-families, they are selected base on having the max conflict values between them.

It should be mentioned here that once the family decides to split, it should decide on a join point to return to after each split has satisfied its needs in order to conform to the unity constraint.

The join point is decided based on the actions following each split as shown in the Table 5 below.

Table 5: Join points based on states existence

Hungry state	Tired state	Restroom state	Bored state	Normal state	JP
1	X	X	X	X	**Restaurant**
0	X	X	X	1	**Goal of normal split**
0	1	X	1	0	**Goal of bored split**
0	1	1	0	0	**Chair**

Some special cases in situations where there are fewer leaders and more states are handled as well in this model. For example, having three states, such as hungry, tired, and bored, while having only two leaders. In such a case, members with tired states can be grouped with members with the hungry state if there is a restaurant that is closer than the chair. The second leader can then be assigned to the bored members. If the restaurant is too far, then the second leader can be assigned to the members who have a tired state, choosing not to take action for the members with a bored state, according to the priority in states.

C) Lost member behavioral model

Families tend to reunite when separated [62]. In this behavioral model, if one of the family members is not following the group, certain actions can be taken based on current family situation and structure. Figure 10, shows the procedure of the lost behavior

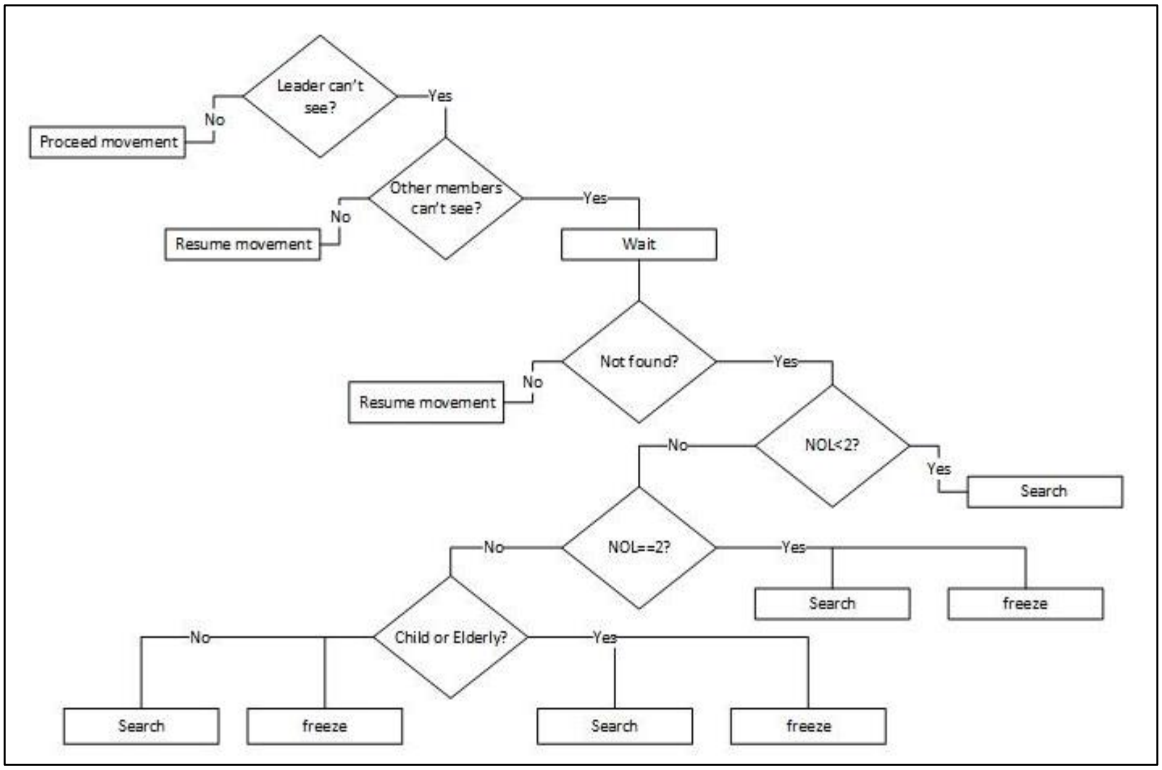


Figure 10: Lost member behavioral model

As mentioned earlier, the family's movement is based on a leader-follower movement approach, and the leader needs to ensure that all of the members are following it and in sight. If the family leader can't see one or more of the family members within its range, the rest of the following members check if they can see it, as they might be closer to the nonfollowing member. If none of the family members can see the nonfollowing member, the leader will decide to stop and wait for some time in one spot so that the nonfollowing member may approach the family. If the nonfollowing member approaches the family, the family resumes its movement; otherwise, the leader needs to make a decision in order to ensure family unity. The initial step the leader takes in making the decision in this situation is considering the number of possible leaders the family has to see what family splits are possible. If there is only one leader the family must go as a whole and look for the lost member, and cannot split. If there is more than one possible leader within the family, the leader has more options in regard to looking for the nonfollowing member. For example, if the family has exactly two leaders, then one of the family leaders waits with the rest of the family members in one place while the other leader goes to look for the lost member. Once the nonfollowing member is found, the searching leader joins up with the waiting split, and the family resumes its movement. This type of searching mechanism is called a search-freeze searching mechanism, as some of the family members wait while the other searches for the nonfollowing member.

The second type of searching mechanism that the leader might decide to take is search-search searching mechanism. This type of searching mechanism can be considered when the family has two or more possible leaders. This searching mechanism is triggered when the nonfollowing member is a child or is elderly. These nonfollowing members need to be found as fast as possible. In this type of searching mechanism, the family is split into two sub-families; one has a leader with one other adult or teen family member, and the other has the family leader with the rest of the family members. Then each of the formed sub-families moves and looks for the nonfollowing member. In case of having more than two nonfollowing members with this search mechanism, the two sub-families update each other through communication about the found nonfollowing member. Once all of the nonfollowing members are found, the leaders of the sub-families communicate with each other in order to acquire each other’s locations, then they join at a certain spot and the family resumes its movement together.

Finally, the third option the family leader could take if there are more than two possible leaders is to use a search-navigate searching mechanism, which is applied when the nonfollowing family member is an adult or a teen member and the situation is thus not very critical to the family. In this type of searching mechanism, the family also splits into two sub-families, but one sub-family searches for the nonfollowing member while the other sub-family containing the rest of the family members resumes their movements normally. Similar to the search-search split type, once the searching split finds the nonfollowing member, its leader communicates with the leader of the navigate-split to agree on a join point, and the family joins back up and resumes movement.

It should be mentioned that, the lost behavioral model is applied for situations that the family is joined, or split due to satisfying needs. However, in case of encountering a lost member in split of type search-search, search-freeze or search-navigate; no second level split, or search behavior is applied. In this case, the split just waits in place till the nonfollowing member approaches it.

Humans usually behave under the principle of least effort [99]. This principle states that, when there are a set of possible actions to take in a certain situation, humans typically choose the action that requires them to spend the least effort. In this model, the searching mechanism adopted by the agents in order to find the nonfollowing member is based on such principle. Accordingly, to look for a certain member, the searching members will go to recently visited locations instead of looking in random locations or traveling far from the current location. In order to have a more effective searching mechanism for the search-search type, one sub-family looks at the last visited locations based on timing, from the last visited to the first, while the second sub-family looks at the last visited locations but in the reversed order, so that more locations can be visited within a shorter time. If all locations have been visited and the nonfollowing member is still not found, then the family or the sub-family will look in random locations within the same area until the nonfollowing member is eventually found. Finally, in order to have the searching split move faster, they may set down any carried children and leave them with the other sub-split to allow the searching process to finish faster.

D) Emergency behavioral model

In this type of decision-making action, the emergency situation is identified through perception of the danger caused by a fire, or through an external stimulus, such as an announcement heard at the location or in a certain area. According to [1], families exhibit kin behavior, where the members tend to stay and wait for each other before evacuating. Moreover, humans in groups tend to delay their evacuation until all the members are able to evacuate [100]. In this model, such kin behavior is applied based on the current state of the family. The family leader considers certain issues before deciding on the evacuation mechanism. Such issues include whether or not the family has been split up earlier, along with the reason for the split and the number of leaders. Initially, regardless of whether or not the family has been split up or not, each child should be carried by an adult or teenager family member. Having the family split up earlier because of a member who does not follow implies that the searching sub-family split keeps looking for the non-following member and evacuates when he or she is found. Thus, the evacuation time of the family might be longer, which may threaten their ability to evacuate safely [101]. If the sub-family of type freezed or navigate sub-splits, the leaders of each split communicate with the other searching split and inform the members about their intent to evacuate the location. Then, after evacuating to a safe spot marked as an assembly point, the leaders communicate again in order to agree on a meeting place. Cases where the family is split earlier to satisfy a member's needs imply that each split's leader communicates with the others and then evacuates the location independently to reach the assembly point, communicating about the meeting place later. Finally, if the family wasn't split earlier, the family must evacuate the event immediately, while the leader ensures that all members are following him or her. Such evacuation processes increases the agent's heart rates and sets its speed to the maximum their which, in turn, consumes more energy than normal actions.

In emergency situations, humans tend to choose routes that are familiar with [1], [102]. In this model once the family decides to evacuate, it chooses the known exits to it, or signs of the exits. These exits or signs have been seen prior to the emergency situation by the family members. Each member shares its information, and the leader determines the nearest one. The overall process is described in Figure 11.

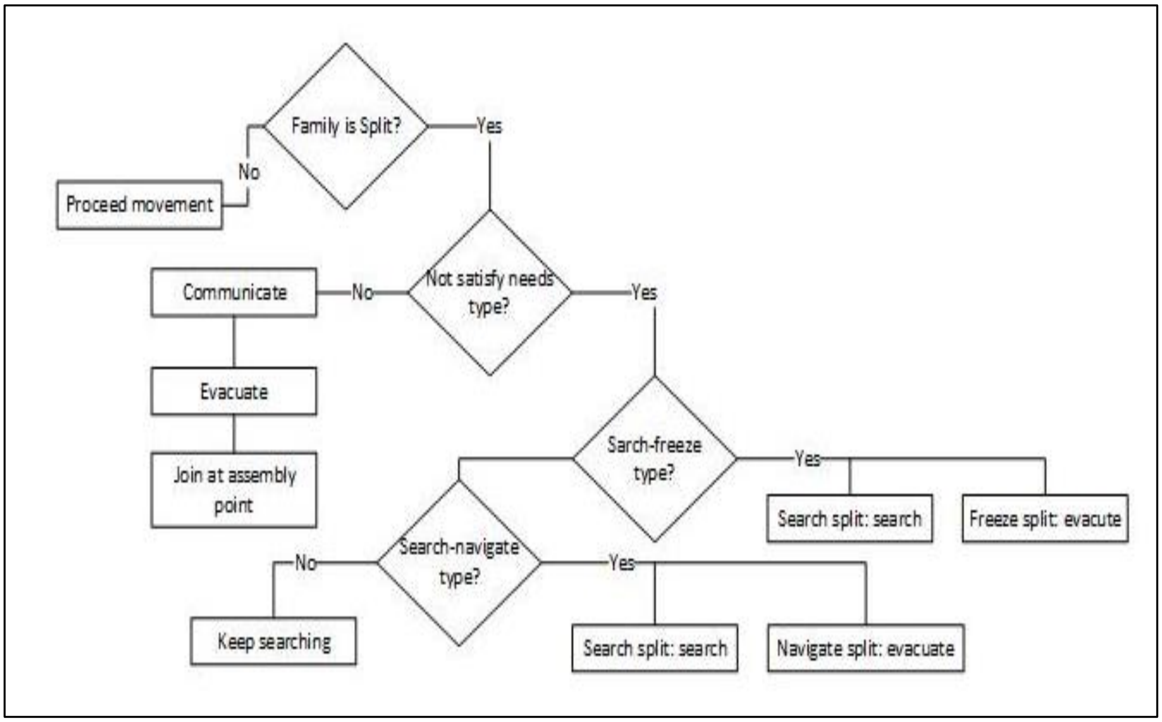


Figure 11: Evacuation process

As can be seen, there are cases where the family evacuates immediately, for example when being joined, or experiences some delays before evacuation due to being split up prior to the emergency occurrence, or having a lost member situation.

3.3. System Implementation

This subsection discusses the high level architecture of the system as well as its implementation and verification.

3.3.1. High Level Architecture

The high-level architecture of the system is shown in Figure 12.

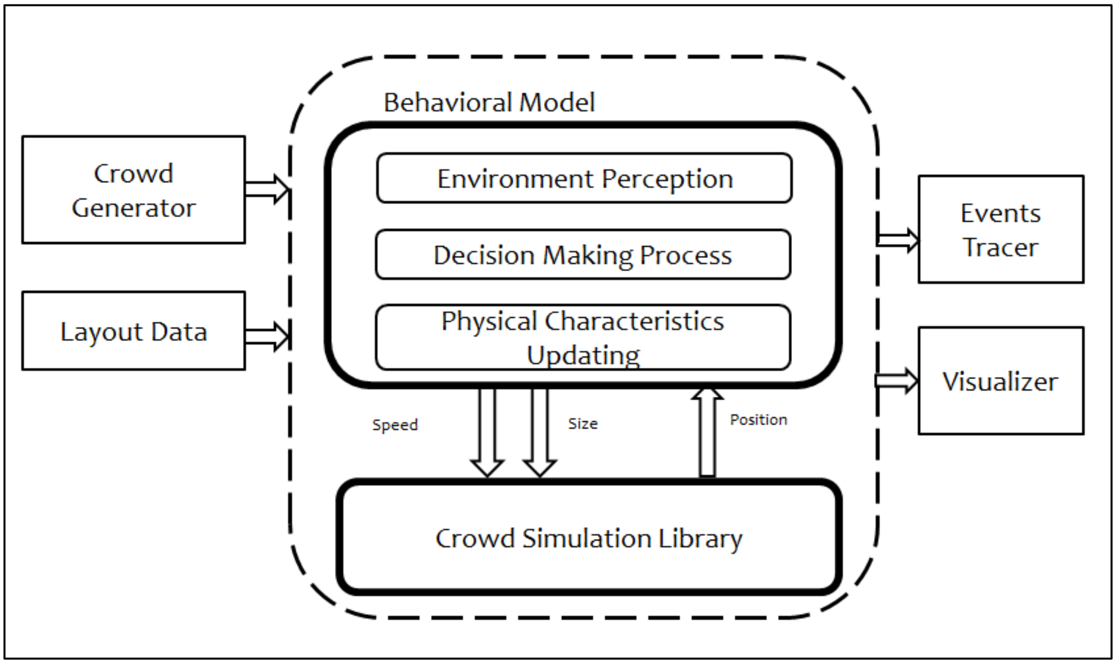


Figure 12: System high level architecture

Initially, the crowd generator module generates the agents based on an input arrival pattern. Then, these agents act in the environment autonomously based on simultaneous interaction between the behavioral model and crowd simulation library. The behavior of the agent is affected by some factors, including its sensation of the environment, current needs, and family membership considerations. Then, based on the decision about the behavior to adopt, the agent decides which goal to reach. The movement of the agent towards that goal is achieved through the use of the crowd simulation library. The library employed is the Reciprocal Collision Avoidance for Real-Time Multi-Agent Simulation (RVO2) [103]. It is an open-source implementation of a multi-agent based approach in which each agent's movement is handled independently. The movement of the agent is based on computing a collision-free path by formulating the optimal reciprocal collision avoidance (ORCA) [104].

The system provides the library with the layout of the environment, together with the partial characteristics of the agents. The layout data of the environment include the different obstacles and their locations, which are provided before the simulation start. On the other hand, the partial characteristics of the agents are presented as constituting two types: those that are updated throughout the simulation run time and those that are static.

The updating type points to the library's need to simultaneously obtain the updated values of the agents' characteristics from the behavioral model. The set of characteristics includes the preferred velocities, maximum speeds, positions, and sizes of the agents, which are derived from and updated in the behavioral model. The static set of characteristics, which are not updated in the behavioral model, include the maximum number of neighbor agents and their maximum distances an agent needs to consider while computing its free-collision motion. Other necessary characteristics re related to the agent's response time in the presence of other agents or obstacles.

Finally, during the run time of the simulation, the agents' data, which the behavioral model is set to update, are sent to the library to reflect their motion. Moreover, during the run time, the agents' movement is visualized, and some data related to measurements are traced.

3.3.2. System Implementation and Verification

The model is coded using the parallel vector concept: Four main vectors in the system are shared between all system modules. One out of these vectors is used to handle data related to families, while the other three vectors are used to handle data related to agents. The family vector contains elements of type family that contains family structure as modeled in the behavioral model.

The first vector of the agents' data is located in the behavioral model layer. It includes elements of type agent, where each agent element contains an agent's data as modeled in the behavioral model layer. The second vector is located in the underlying layer of the system, which is the RVO2 library. Similarly, it contains agents' data but as represented in the underlying crowd simulation library. The third vector contains elements of type vector, where each vector element contains the goals of a certain agent.

Initially, when an agent is created, it is inserted into the vectors that handle agents' data in both layers of the system. His goals are inserted into the vector of goals. As discussed earlier, an agent acts in the environment based on the different simultaneous interactions between the behavioral model and the crowd simulation library. This is reflected through the different modules' simultaneous updates of the data contained in the vectors. Based on the behavioral model, an agent intends to approach a certain goal. Such a goal is obtained from the vector of the goals associated with that agent. In order to achieve that goal, two levels of navigation processes are applied namely, local and global path planning. The local path planning is achieved through the underlying layer, which is the crowd simulation library. Such a library is responsible for the collision-free motion of the agent while adjusting its speed. A collision-free motion ensures agent's movement without colliding with other agents or with the existing static obstacles within the environment. However, other aspects of path planning in which the agent should move in order to achieve the specified goal are not considered. Therefore, there is a need to provide the agents with some routing hints regarding the goal to be approached, that is global path planning. According to Gärling et al. [105], people tend to adopt subsequent movements toward their final destination. This is achieved by introducing a virtual routing mechanism in the system. Based on the goal location defined in the environment, the agent approaches virtual routing points. The agent follows the virtual routing points thus, approaches gradually to arrive at the intended goal.

The system is validated through the different stages of its development. Unit testing is applied such that individual system modules are verified in terms of functionalities to produce predicted outputs. Then several related system modules are integrated and tested in the component-testing stage. That includes verifying the interfacing between the different modules as well as the parameters passing. Finally, full system testing is applied, where all components of the system are integrated and tested as a whole and their interactions are verified.

In this chapter, the model design is discussed followed by its implementation. This model is comprehensive and considers multiple family behaviors at the same time. Such a model is constrained by the set of social and psychological theories considered. For example, the family should have a leader at all times, elderly people or children should not be left alone under any circumstances, and the family members should stay together while attending a family gathering. These constraints do not necessarily appear in a primitive group's modeling.

Family unity is the main constraint considered in the family behavior. That applies in the three situation types under consideration: normal situations, situations with non-following members, and emergency situations. In a normal situation, once the family decides to split up, it must agree on a gathering point at which to reunite. In a situation with a non-following member, the family can adopt three possible behaviors to find the non-following member. The behavior adopted depends on the characteristics of the non-following member (that is, whether the family member in question is an adult, teenager, elderly person, or child) as well as the family structure and state of being split up or joined. Finally, in an emergency situation, the unity of the family is maintained by ensuring the safe evacuation of the family members and waiting for and helping each other before evacuation.

Physiological considerations are addressed at the member level to generate a state that represents a certain intention. However, such an intention cannot be revealed immediately as other members' intentions should also be considered. In primitive groups, such considerations do not necessarily apply. For the family decision-making process, the family leader considers the family structure and each member's characteristics and intentions (represented by states) such that the decision is made at the family level. The effect of the family structure on the decision being made is that, based on the number of leaders in the family, the family state involves being split up or joined. The leader is assigned the responsibility of making the final decision as he/she it has been modeled to have more knowledge than the others regarding the constraints within the family that must be met. Moreover, the model adopts the dynamic change in goals based on the different needs of the family members. It addresses specific behaviors regarding children, for instance, carrying them when they are tired or during emergency situations. Chapter 4 discusses case studies to analyze the effect of the family behavior in certain contexts. Moreover, other behaviors of the family in emergency situations are modeled and analyzed.

CHAPTER 4: CASE STUDIES

The system model is used to study family behaviors in normal situations as well as emergencies. A set of case studies are simulated for a book fair event held at the Doha Exhibition Center in Qatar in 2014. The intention of these case studies is to analyze how family behavior affects different measured criteria, such as evacuation processes and the family members' level of satisfaction.

Section 4.1 presents the event settings considered for the case studies that includes event layout and people arrival pattern to the event. The case studies of emergency and normal situations are discussed in section 4.2.

4.1. Event Settings

The book fair event of 2014 was held at Doha Exhibition Center in Qatar. A number of booths were set up for this purpose in the hall of the exhibition center. The hall area has a few restaurants and other facilities such as restrooms and seating areas, and has two main entrances that were also used as exits. The layout of the event is depicted in Figure 13. There are 108 booths geared toward different interests, along with two restaurants and three restrooms.

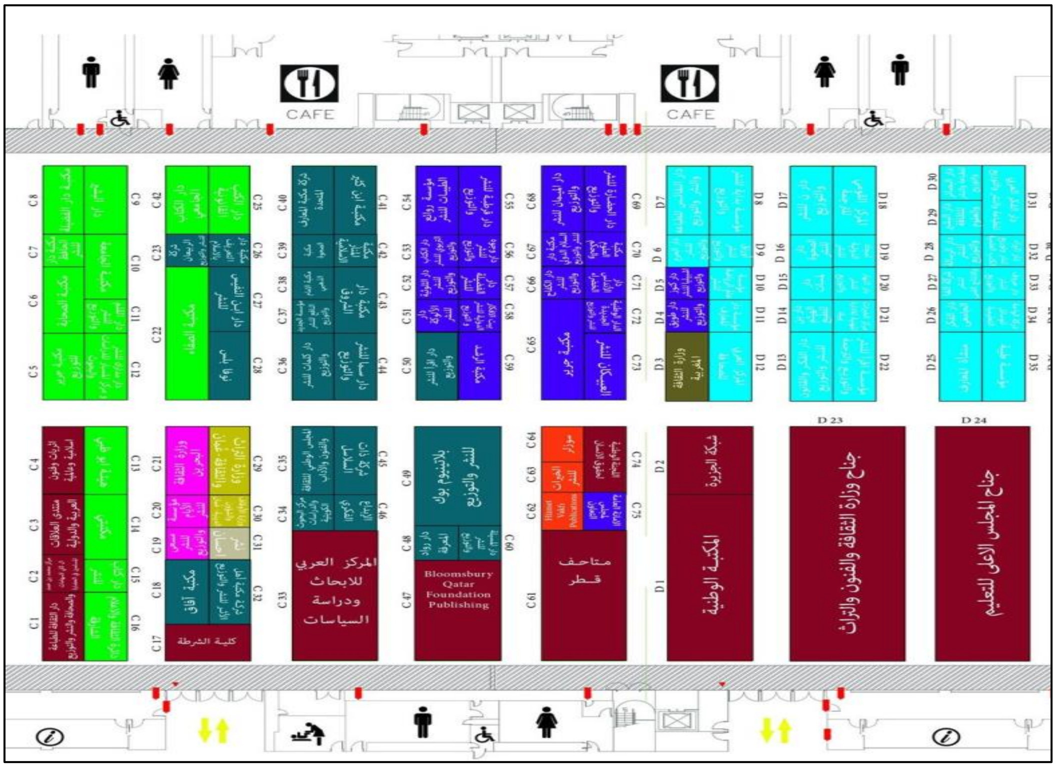


Figure 13: Book fair event layout

The source [106] provides the layout for this event only with Arabic labeling for the booths.

Under the assumption that people at the event behave in a normal way, each individual or family reads a brochure about the event and the different booths upon arrival. Hence, they can know the way to a booth when needed. Each individual or family member selects a set of booths to visit based on their own interests. Some of the booths included in the event revolve around science, education and technology, and there are also booths for children. The family or individual will determine the best way to visit the booths of interest to them, mostly by identifying the shortest path between them. Visitors usually spend some time inside each booth, exploring the different items there. This time might vary based on the interest of visitors and what is available at the booth as well as how crowded is the booth. Because of members of a family might have different interests within that booth t, the family might split forming what is referred to as sub-families. In this case, each sub-family explores the booth independently, and join back at the when exiting that booth which might involve waiting for each other.

Event Arrival Pattern

The event runs for a full day, with some breaks in between. To be more specific, it runs from 9:00 a.m. to 1:00 p.m. and continues from 4:00 p.m. to 10:00 p.m. The event is simulated for the first two hours of its start-up time to limit the simulation time. The people growth in the system for the first two hours is shown in Figure **14**.

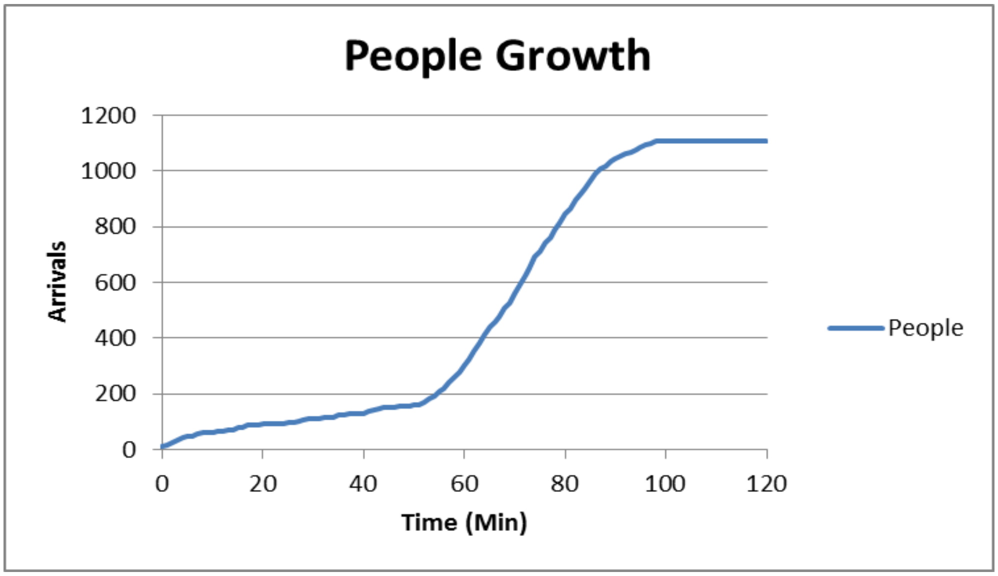


Figure 14: People growth in the system

At the first quarter of the event start time, the event expects low arrival bulks. These bulks gradually increase as the event is ongoing. Furthermore people who leave within the first two hours of the event time are less expected.

During this period of time, the system simulates 120 families with an average family size of seven members. These families compose 77% of the people, while the other 23% are individuals who don't belong to families. These people belong to different age categories, being adults, teenagers, elderlies, or children. The distribution of people who attend the event is shown in Figure 15.

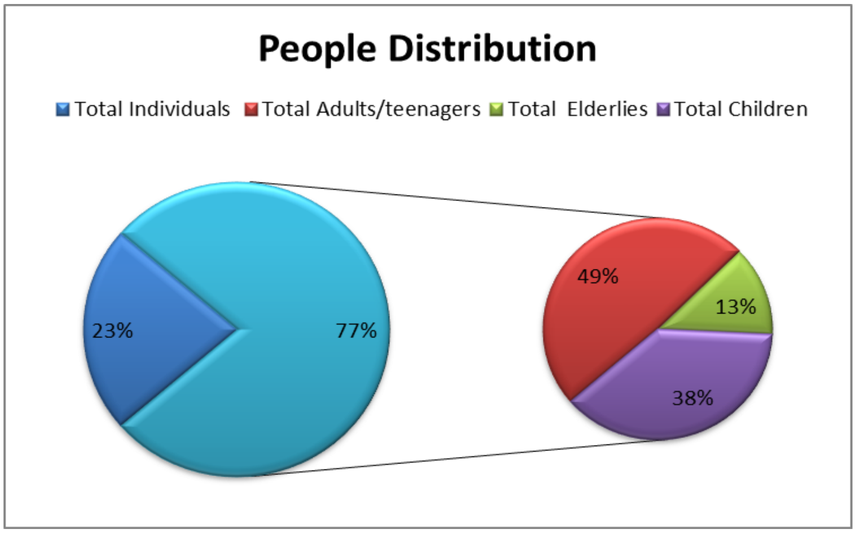


Figure 15: People distribution in the crowd

Based on a conducted survey of the family structure (refer to Appendix A), around 40% of the family members are adults or teenagers, while 29% are children and the rest are elderlies.

4.2. Simulated Case Studies

This section presents the different family behavior cases of studies used to study in emergency and normal situations.

4.2.1. Emergency Situation Case Studies

The developed model is used to conduct a set of experiments under emergency conditions and is simulated in a crowd simulation environment under two case studies. The first is related to the effect of family behavior on the evacuation process, while the second studies the effect of the event layout on the evacuation process. Each of these case studies is based on a hypothesis, which is to be proven or disproven, and accompanied by a set of research questions. For each case study, the simulation is set to run ten times.

In the different case studies considered, a set of assumptions are set:

- Once a fire exists in a certain area, it's assumed that all people located in that area are made aware of the existence of the fire via the fire alarm, which is heard by everyone attending the event.
- All the hall exits are opened and cleared so that none of them are blocked in an emergency situation and all exits are reachable by the agents.
- The view of the area is clear during the evacuation; i.e., there is no smoke blocking the agents' view. The concern here is more about the effect of behavior being adopted during the evacuation process than the effect of the emergency situation and its related parameters, such as the presence of smoke or path blockages.
- Once an agent reaches an exit, is considered successfully evacuated.

4.2.1.1. Case Study One

This subsection discusses the first case study, including an overview of the hypothesis, research questions, and simulations setup, followed by a description of the results.

Case Study Description

Hypothesis

Based on people's perceptions, families' splitting up in evacuation situations during public events leads to high causality percentages per family.

Research Questions

RQ1. Does family disunity affect the evacuation process?

RQ2. What action should the family take in evacuation situations that leads to best evacuation rates?

RQ3. Can the evacuation process of the families be improved, based on common behavior being taken by the families under study?

RQ4. How would the evacuation rate be if a set of families exhibited different behaviors based on a sample set of families conducted by a survey?

Situation under Study

During the family navigation of the event, a fire alarm is on, indicating a need to evacuate the area as fast as possible. A survey is conducted on 100 families (refer to appendix), who question their behavior in case of an emergency situation at a family-related event, and the results show that families usually adopt a set of different behaviors. In order to study the effect of these adopted behaviors on the evacuation process, each of them is studied independently, such that all families are considered adopting the same behavior. Then, the evacuation process is studied based on the composition of the families that adopt behaviors based on the conducted survey results.

The following set of simulation sets is conducted in order to study the effect of each behavior on the evacuation process.

a) Having the family split up prior to the occurrence of the emergency situation requires that all the family's subgroups reunite, then evacuate as a unit. On the other hand, the family evacuates immediately as a unit in case it is joined. In this study, this behavior is referred to as waitEva, which stands for wait for each other, join back, then evacuate if the family is split.

b) Having the family split up prior to the occurrence of the emergency situation implies that each family subgroup evacuates independently. This behavior is referred to as indepEva, which stands for independently evacuate as a subgroup. Similar to waitEva, the family evacuates immediately as a unit if it's already joined.

c) Regardless of the family state prior to the emergency situation, the family splits completely into its possible leaders. Each leader then evacuates independently of the family's or subgroup's movement, carrying a child, if possible. This behavior is referred to as splitEva, which stands for split up and then evacuate.

d) The combination of these behaviors (a, b, and c) is based on the percentage values obtained from the survey.

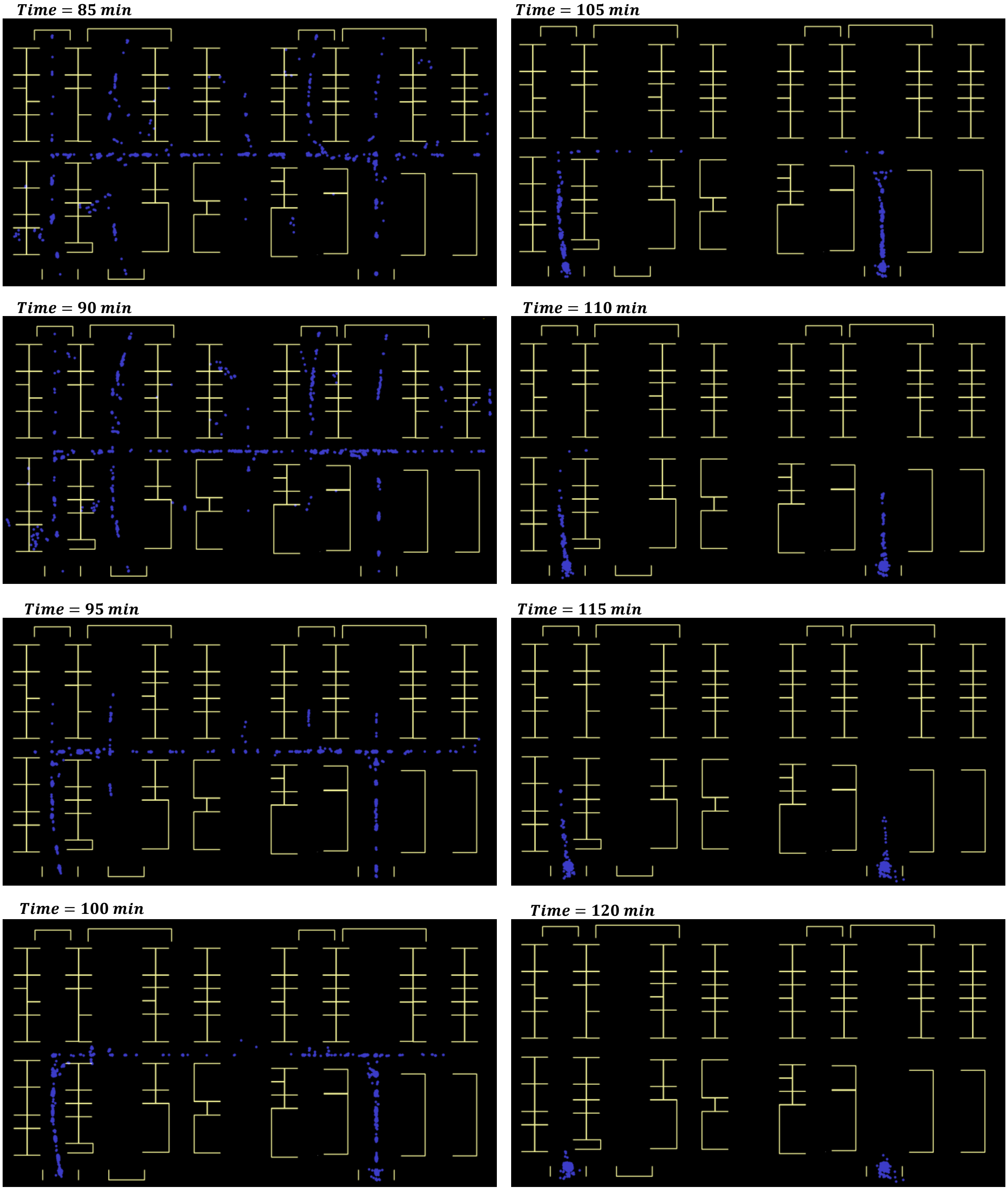
Simulations Setup:

- Fire that triggers the evacuation process exists at minute 90—i.e., an hour and a half after the start of the event. So, it's guaranteed that there exists a sufficient number of people based on the considered arrival pattern.
- As a time-controlled simulation, there is a determined time window for people to evacuate.
- Each simulation run has a fixed number of families, with the same structure.

Case Study Results

This section discusses the results based on the conducted simulation sets presented in the previous section. This is divided into three subsections. The first discusses the effect of the behavior adopted by the families during the evacuation process, while the second discusses the effect of the adopted behaviors of the people that compose the crowd: family members and individuals who don't belong to families. Finally, the third subsection discusses the effect of families' adopting behaviors with percentages based on the conducted survey of the evacuation process.

A key limitation of this study is the lack of real data to verify the simulation results for the book fair event, such as surveillance videos showing the people's behavior. Figure 16 shows a snapshot of the evacuation process in this case study.


$Time = 85\ min$ $Time = 105\ min$

$Time = 90\ min$ $Time = 110\ min$

$Time = 95\ min$ $Time = 115\ min$

$Time = 100\ min$ $Time = 120\ min$

Figure 16: Evacuation process at different time stamps

Prior to the emergency situation at time equals to 85 minutes, people were distributed in the hall exploring the booths or at the different facilities. As the fire alarm started at time equals to 90 minutes, the people need to evacuate the location. They got out of the booths and facilities and moved towards the corridors as can be seen at time equals to 95 minutes and time equals to 100 minutes. Finally, they approach the exits located at one side of the hall.

A) Evacuation process of families

Figure 17 shows the cumulative number of the evacuated families during the first thirty minutes of the evacuation process, the start time for the three adopted behaviors. As can be noticed, the simulated model predicts higher evacuation rates of families that adopt the splitEva behavior compared to the indepEva or waitEva behaviors.

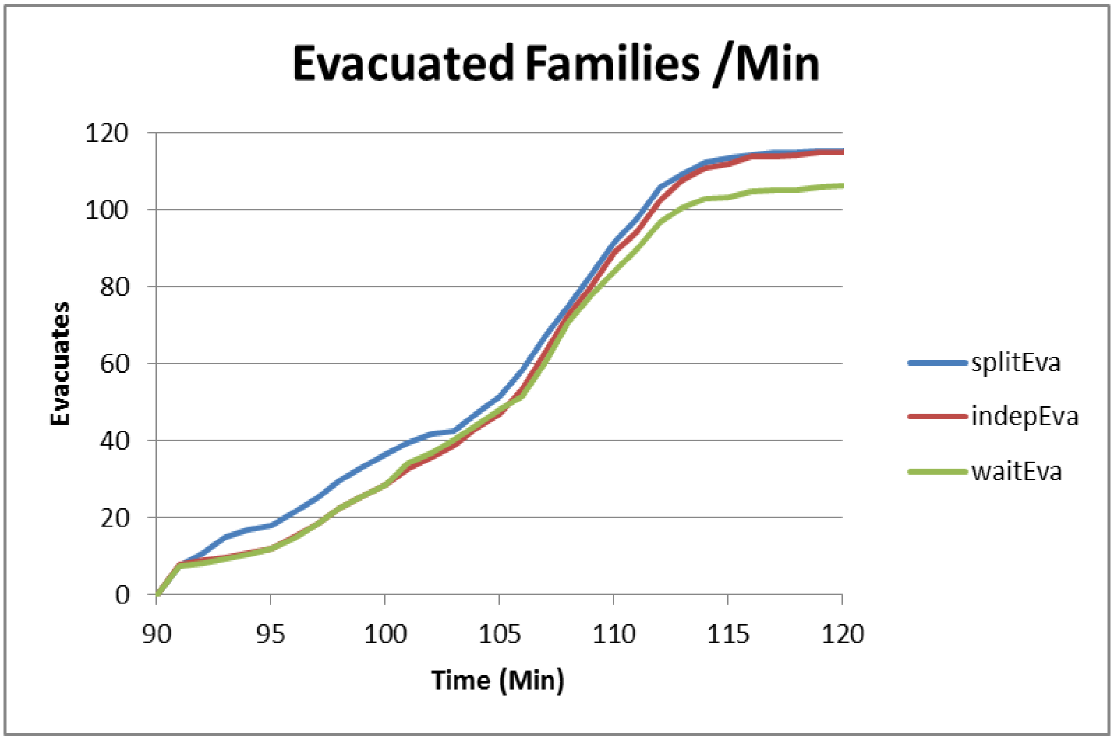


Figure 17: Number of evacuated families per minute

Initially, during the first three minutes of the evacuation process, the difference between the splitEva behavior and the other two behaviors is very small. This is because, during this period, high percentages of families that adopt the indepEva or waitEva behaviors were located within areas close to the exit gates. This is shown in Figure 18 comparing the percentages of families that evacuated during a certain period of time against their location at the time of the emergency situation for the three types of adopted behaviors.

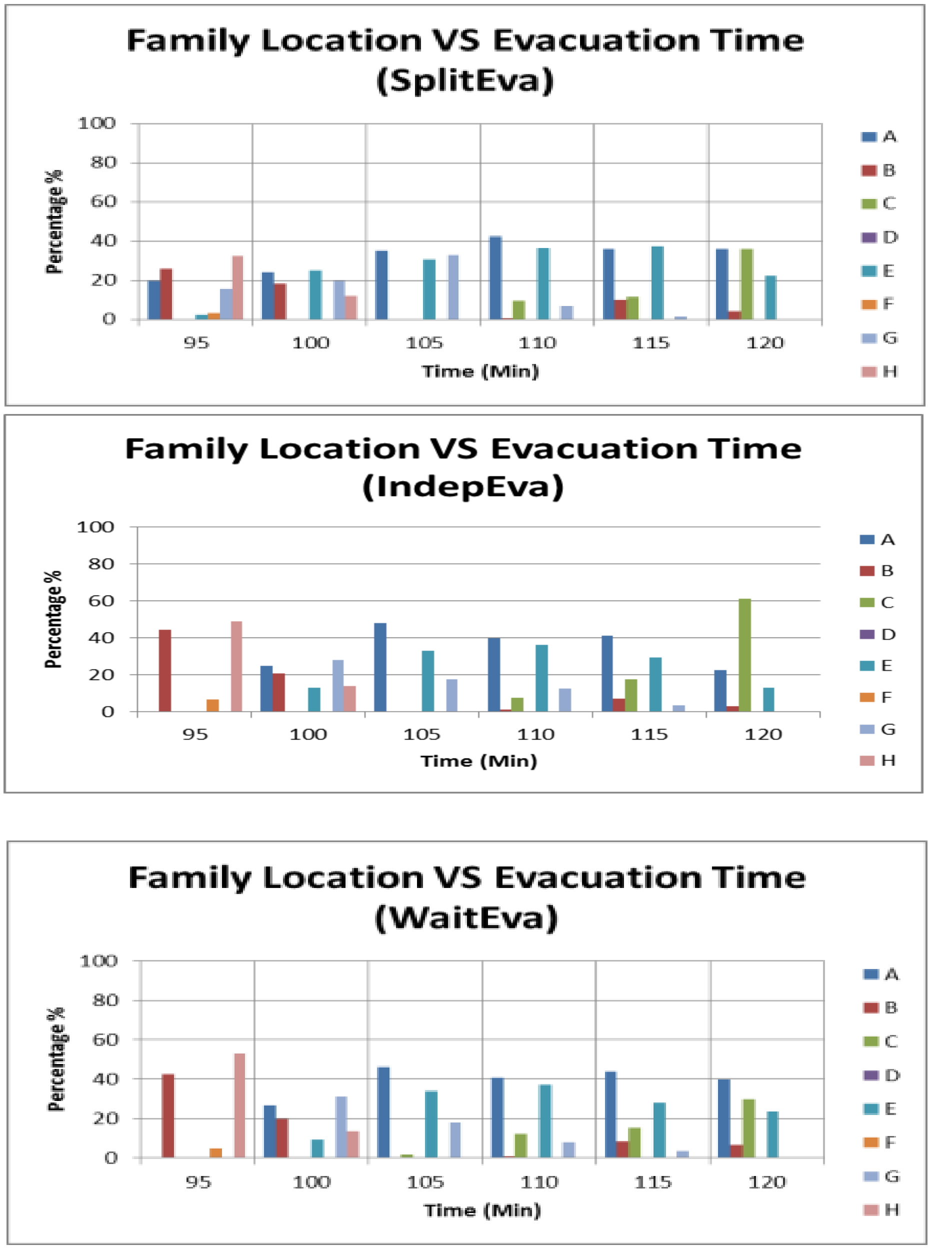


Figure 18: Effect of the location on the evacuation time

The letters A, B, etc. indicate areas in the layout referred to as grids as shown in Figure 19.

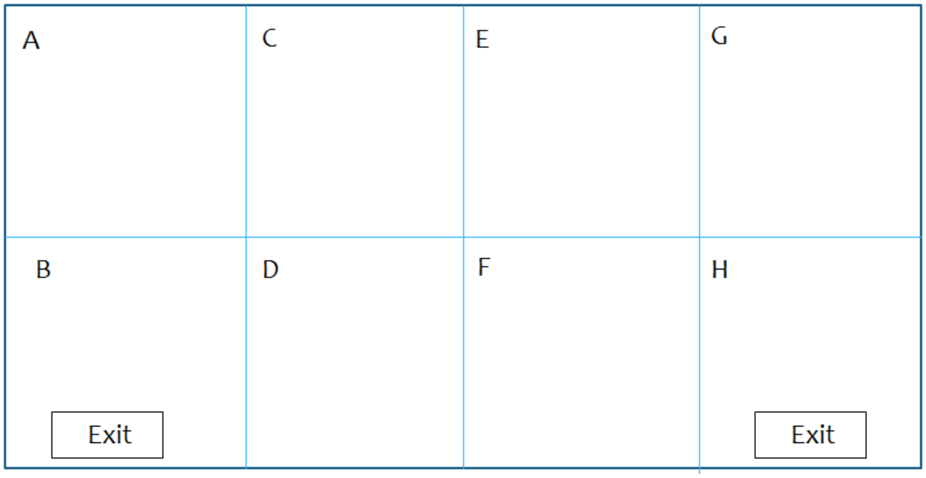


Figure 19: Grids spanning over the hall area

As can be seen in Figure 18, high percentages of the evacuated families during the first period of the evacuation process were located in grids B and H. These two grids include the exit gates of the hall. It should be mentioned that families located in the first half of grids, A and G, are able to evacuate faster than other families located in the second half or in other grids located at the middle of the layout, such as C and E. This is because the exit is closer with respect to their location. Then, as the time elapses, the different families that were located at farther areas in terms of grids approach the exit points, as the families exist at grids C, E, or in the second halves of grids A and G. Hence, the different adopted behaviors become closer to each other, while splitEva scores the highest.

The family state prior to the emergency situation is an important factor that affects the decision process of the family. Such a state determines whether the family evacuates immediately as a unit, splits into its possible leaders, or approaches other subfamilies to reunite. The effect of such a state is shown in Figure 20. The figure shows the relation between percentages of the evacuated families based on the states being split or joined for each behavior and the time when these families evacuated.

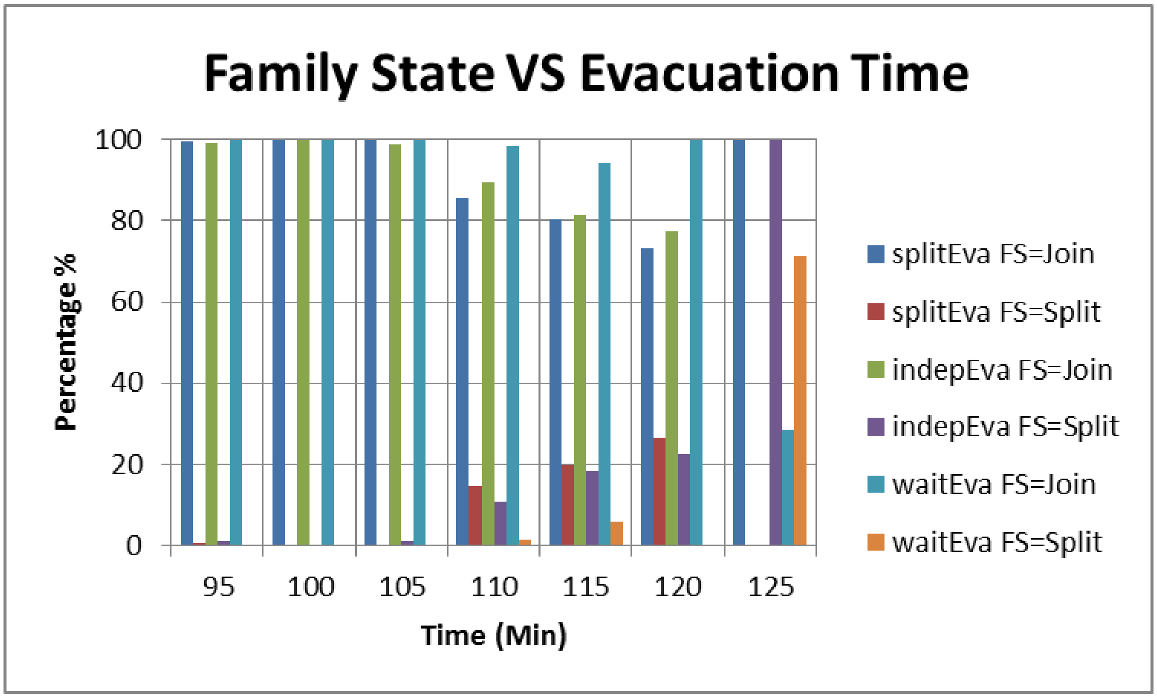


Figure 20: Family state effect on the evacuation time

During the first fifteen minutes of the evacuation process, for the period [90-105], it can be seen that all the evacuated families in the three adopted behaviors were joined. This affects the waitEva behavior, as there are no subfamilies to approach each other (of the same family) before evacuating as a unit. Therefore, the family can evacuate immediately. Similarly, in the case of the indepEva behavior, the families act as the waitEva behavior in the evacuation process since they are joined. With the splitEva behavior, on the other hand, family members can still split from each other and approach the exits independently even if the family was joined.

Then, during the time period [105-120] of the evacuation process, the three adopted behaviors show close results, as during this time period, the families that were located at farther areas with respect to the exits start to approach (refer to Figures 18, 19). Therefore, they need more time to evacuate, even if they were joined prior to the existence of the emergency situation. This shows the advantage of the splitEva behavior in the worst situation, where the exits are on the opposite side of the current location. Finally, after the first thirty minutes of the evacuation process, the families that adopt the waitEva behavior evacuate, as they were split prior to the occurrence of the emergency and located farther from the exit gates.

B) Evacuation process of people

This subsection discusses the effect of the adopted behavior by families during the evacuation process on people that compose the crowd as individuals or family members.

Initially, as can be seen in Figure 21 for the evacuated individuals in the three adopted family behaviors, the evacuation process of the individuals is the same. This is because the movement and the evacuation process of the individual are independent from the behavior adopted by families.

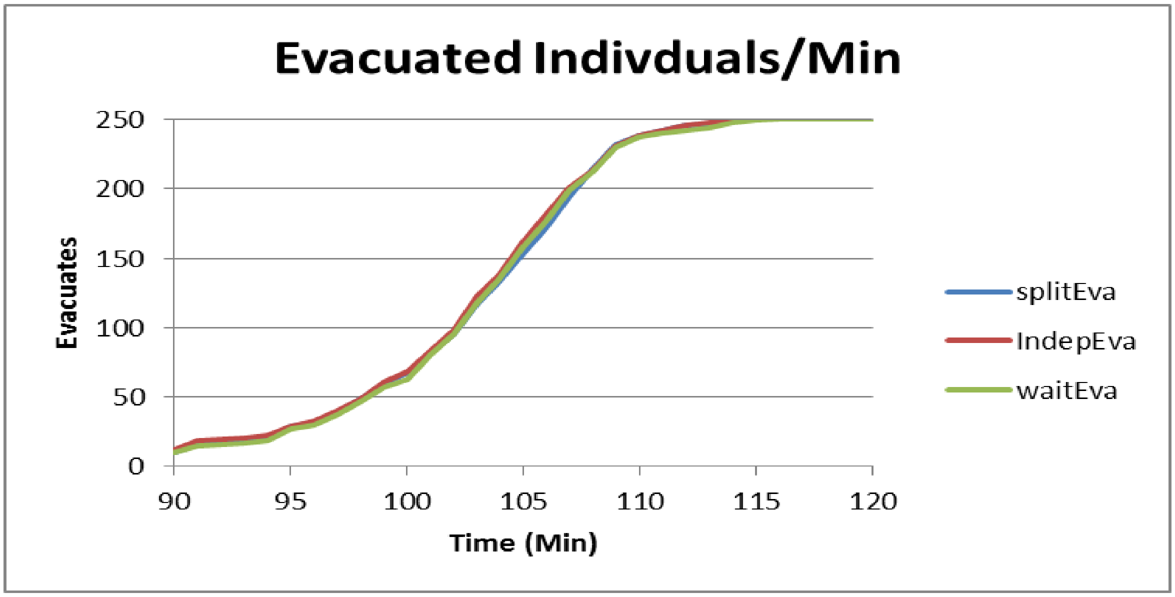


Figure 21: Number of evacuated individuals per minute

On the other hand, the behavior adopted by the families affect the evacuation process of their members. The evacuation rates of family members who belong to families that adopt certain behavior can be clearly noticed in Figure 22.

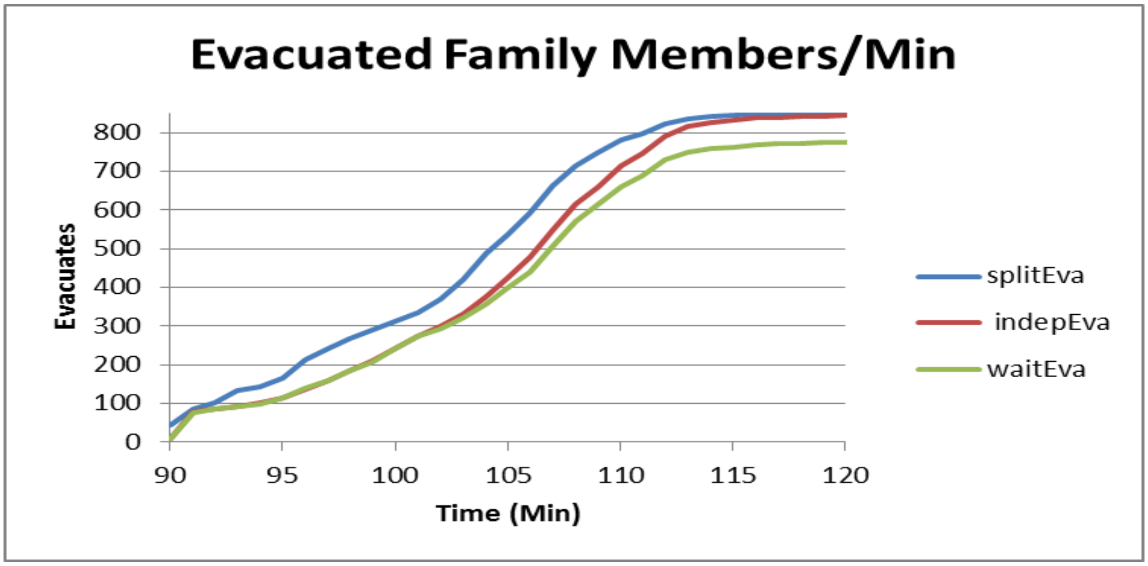


Figure 22: Number of evacuated family members per minute

As can be seen, families that adopted the splitEva behavior showed the highest evacuation rate compared to the other adopted behaviors. More specifically, as can be seen in Table 6, for the percentages of the evacuated family members during the first thirty minutes of the evacuation process time, it’s shown that, after around twenty minutes of the evacuation process, around 91% of the family members who belong to families that adopt the splitEva behavior were able to evacuate. For the families that adopt the indepEva behavior show close results (83%). On the other hand, for the same time period, around 76% of the family members who belong to families that adopt the waitEva behavior were able to evacuate. In fact, a percentage of 91% was reached by families that adopted the waitEva behavior after ten more minutes compared to the families that adopted the splitEva behavior.

At the end of the thirty minutes since the evacuation process started, the splitEva and indepEva behaviors almost converge to the same percentage, around 99%, while for the waitEva behavior, around 91% of the members were able to evacuate.

Table 6: Percentage of evacuated family members in first 30 minutes

Time	splitEva	indepEva	waitEva
95	19.32%	13.15%	13.15%
100	36.2%	27.94%	27.94%
105	62.4%	49.13%	46.22%
110	90.8%	83.12%	76.83%
115	98.37%	96.86%	88.71%
120	99.07%	98.25%	90.45%

Such differences in the percentages of the evacuated family members would have serious effects if a certain behavior is adopted with high percentages. More specifically, having high percentages of families that adopt the waitEva behavior during the evacuation process would increase the casualty rates of their members. This is discussed later in subsection C, where 64% of the families adopt the waitEva behavior based on the conducted survey results.

Figure 23 shows the distribution of the mean number of evacuees who belong to families of the ten runs at evacuation time equals to 105 for the three behaviors. It can be seen that the indepEva behavior has higher mean value compared to waitEva. However the difference is not statistically significant between them as their standard deviation bars overlap. For the splitEva behavior there is a significance difference in the number of evacuees compared to the two other behaviors.

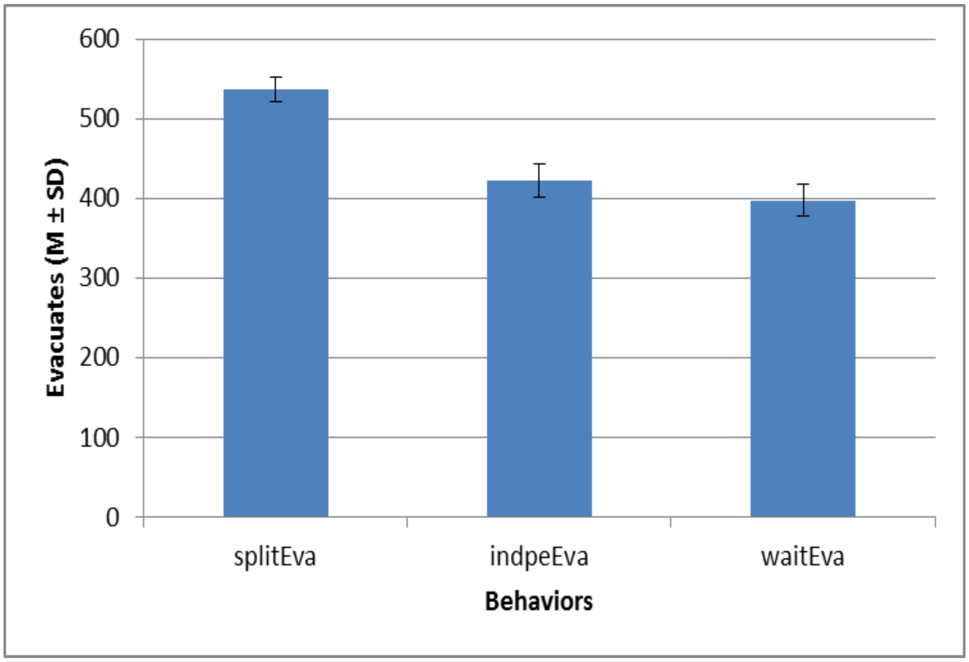


Figure 23: Mean and standard deviations of evacuated family members

The rest of this subsection discusses the decomposition of the family members who evacuated per minute of time.

The rates of the evacuated leaders, shown in

Figure 24, it can be seen that members belong to families that adopt the splitEva behavior score the highest number of the evacuated leaders compared to the indepEva or waitEva behaviors.

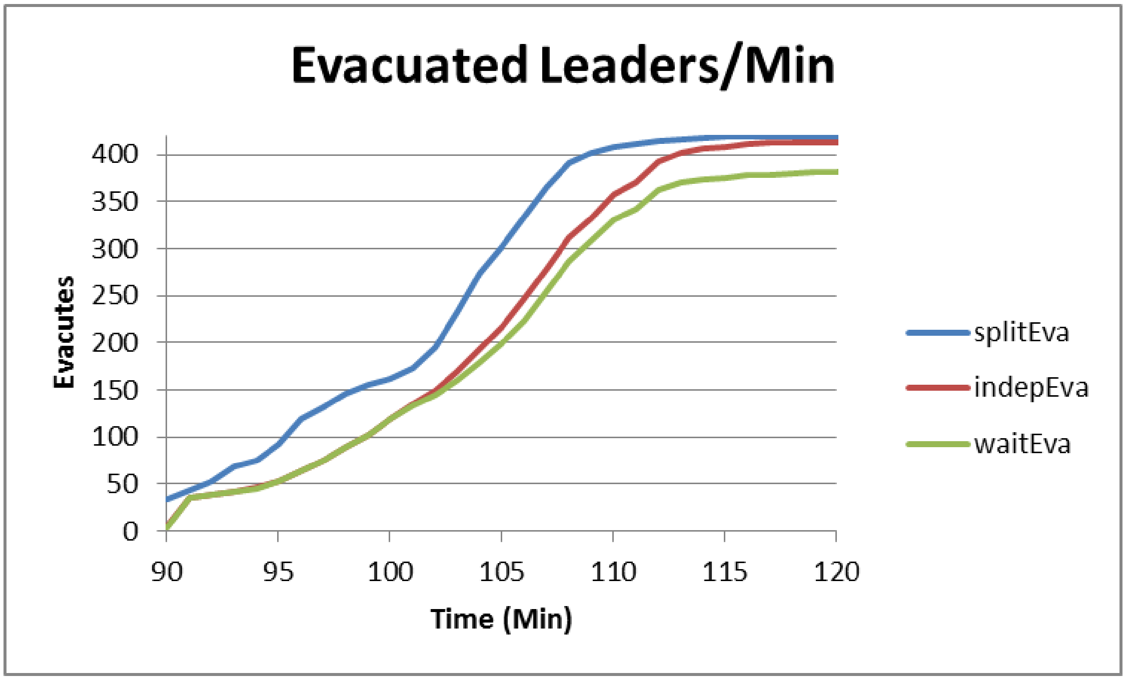


Figure 24: Number of evacuated leaders per minute

The reason for having such high evacuation rates of family leaders that adopt the splitEva behavior can be justified due to their independent movement of the family they belong to compared to the rest of the family members who are restricted to the movement of the family. More specifically, in such behavior, once the family is split, each possible leader carries the responsibly of evacuating itself, without the need to be further led by the main family leader. The rest of the family members, on the other hand, stay with the main leader, who in turn carries their evacuation responsibility along with maintaining their following behavior. These members could be elderlies, or could be children who couldn't be carried by the independent leaders. As discussed earlier in chapter 3, for the following behavior, having unfollowing members causes the family leader to wait or look for them. In the evacuation process, encountering such conditions causes delays to the whole family.

Considering the waitEva behavior, more delays are expected once the family is joined where all members move together as a unit. This can be justified due to the larger size of the moving unit means higher probabilities of having unfollowing members within the unit. Similar situations happen in the indepEva behavior for the joined families, while fewer delays are expected if the family is split up, as the moving unit size is smaller.

Since each leader that evacuates independently from the family in the splitEva behavior can carry a child, the rate of the evacuated children scores the highest compared to the families that adopt the waitEva or indepEva behaviors, as shown in Figure 25. It should be mentioned that the children are carried as well in the indepEva and waitEva behaviors during the evacuation process.

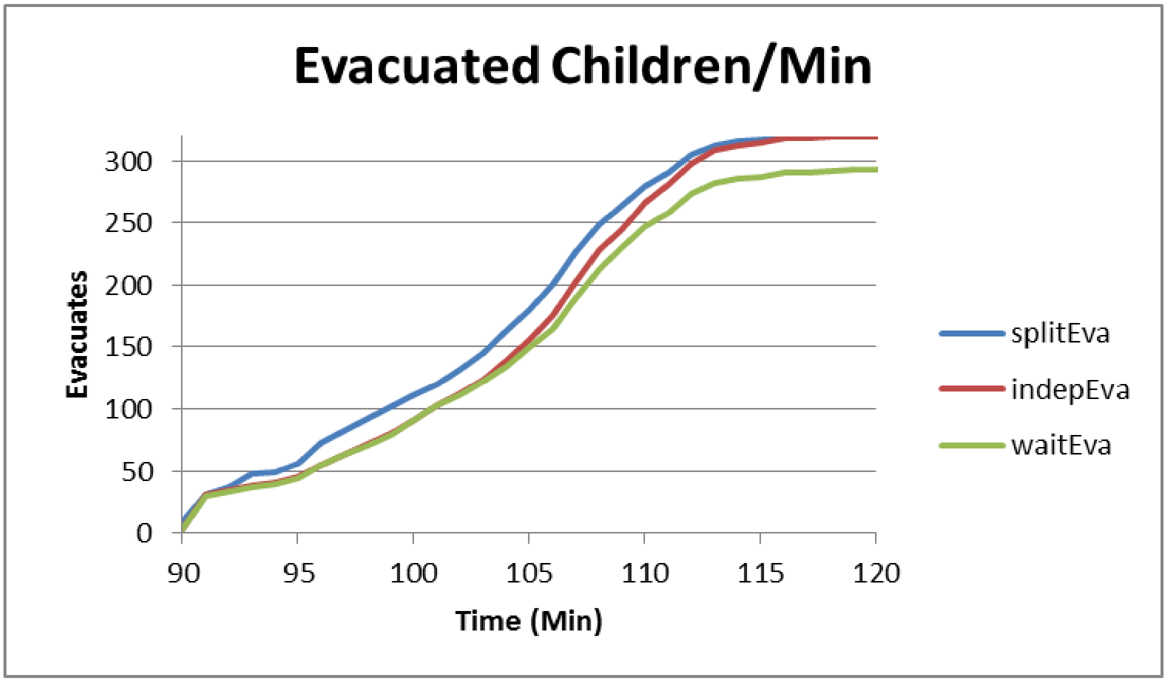


Figure 25: Number of evacuated children per minute

Figure 26 shows the evacuated elderlies over time. Similarly, the splitEva behavior shows the highest evacuation rates.

Figure 26: Number of evacuated elderlies per minute

This can be clarified based on the size of the family moving concept discussed earlier. That is, moving in a family of a smaller size makes its overall evacuation process faster. In the splitEva behavior, the family size becomes smaller, as all leaders who can are split from the family, carrying children, if possible. Therefore, the leader needs to manipulate fewer members, and the maximum number of unfollowing members would be less, causing fewer delays, hence, a shorter evacuation time.

C) Evacuation process of families with different behaviors

This section discusses the result of having crowd composed of families that adopt different behaviors each based on the conducted survey (refer to appendix). In this simulation set, 16% of the families adopt the splitEva behavior, while 20% adopt the indepEva behavior and the remaining 64% of the families adopt the waitEva behavior. The result of such composition is shown in Figure 27. Having such composition of the families results in evacuation rates of around 86% within the first thirty minutes of the evacuation process. Indeed, such composition mainly affects the people who belong to families, as the individuals are not affected by the behavior the families adopt, as discussed earlier.

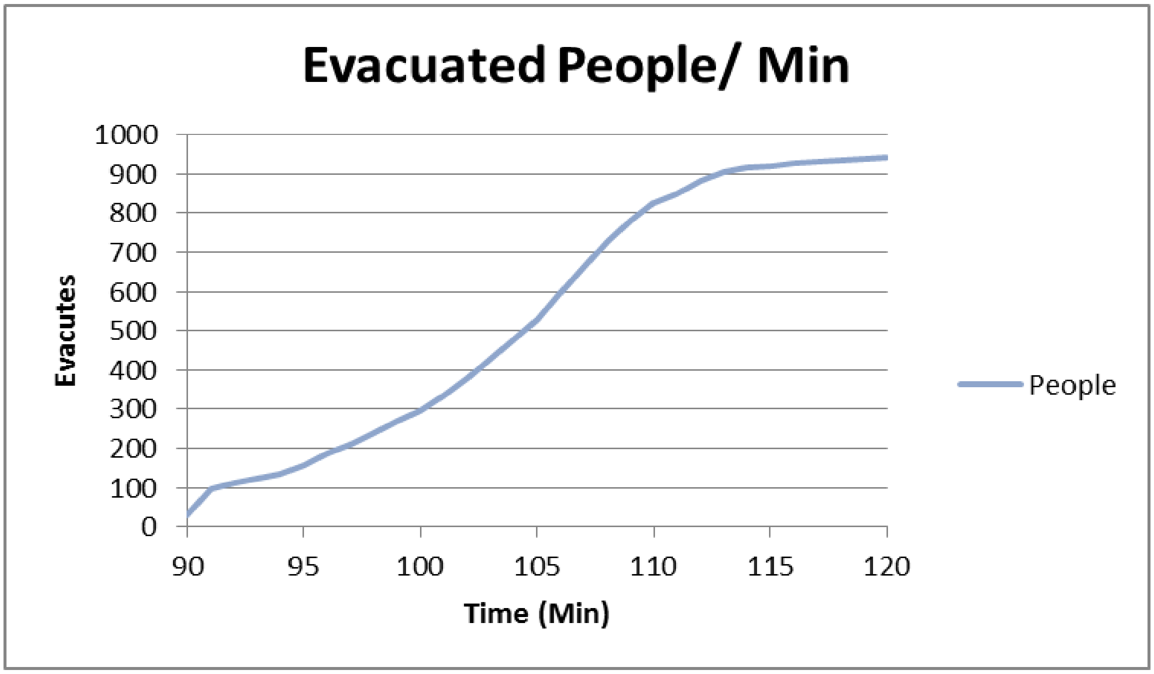


Figure 27: Evacuated people rate

4.2.1.2. Case Study Two

This section discusses the second case study related to testing in emergency situation. It studies the effect of modifying the layout settings on the evacuation process. The motivation behind this case study is that the human behavior in emergency situations depends on their psychological and social factors that cause them to behave in a certain way [100][107]. As discussed in the previous subsections, family members adopt kin behavior and delay their evacuation, which is represented as the waitEva behavior in this study. The results show that adopting such behavior results in the slowest evacuation rates. People can be educated about the consequences of adopting such behavior, but it’s not guaranteed that they wouldn’t adopt it in emergency situations, where their decisions might not be correct. Thus, this case study investigates the effect of modifying the layout on the evacuation process while having families adopt different behaviors based on the conducted survey results.

Case Study Description

This subsection discusses the case study description and the simulation setup.

Hypothesis

Having more exit gates at buildings improves the evacuation process by having lower evacuation times.

Research Questions

RQ1. Can the evacuation process be enhanced without alerting behavior adopted by families?

RQ2. Does the evacuation rate change when adding two more exits to the hall area of the Doha Exhibition Center?

Situation under Study

Crowds composed of individuals and families navigate the event by approaching different booths. These families act based on different behaviors with the percentages obtained from the conducted survey. This means, in the emergency situation, 16% of the families adopt the splitEva behavior, 20% adopt the indepEva behavior, and the remaining 64% adopt the waitEva behavior.

In order to study the effect of the layout properties on the evacuation process, the following simulation set is conducted, where each is set to run ten times.

a) Testing with the current layout settings that has two exit gates

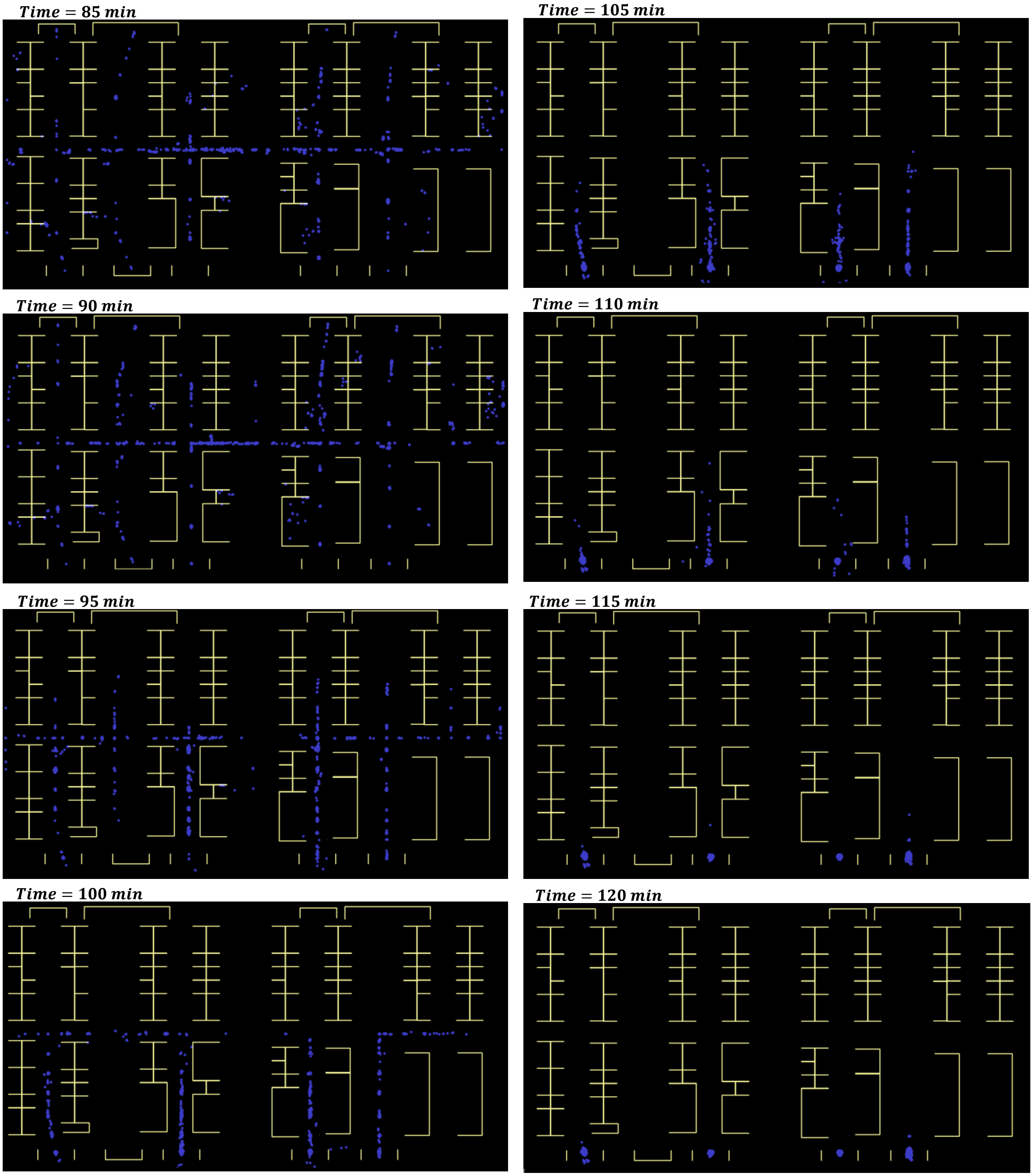
b) Adding two extra exits to the current layout of the event, in grids D and F (refer to Figure 19, which shows the grid areas of the layout).

Simulation setup

- Fire existence that triggers the evacuation process exists at minute 90—i.e., an hour and a half after the start of the event
- A time-controlled simulation, with a determined time window for agents to evacuate
- Fixed number of families, with the same structure

Case Study Results

Figure 28shows a snapshot of the evacuation process considering a layout of four exits. It can be seen how the evacuation process is enhanced by having more exits that leads to shorter travel times and in turn faster evacuation rates.



$Time = 85\ min$

$Time = 90\ min$

$Time = 95\ min$

$Time = 100\ min$

$Time = 105\ min$

$Time = 110\ min$

$Time = 115\ min$

$Time = 120\ min$

Figure 28: Evacuation process at different time stamps with four exits

The evacuation rate of people under the two settings of the layout is shown in Figure 29 shows. Similar to the previously discussed results, during the very first minutes of the evacuation process, the two situations show very close results. That is because of the existence of the crowd near the exits at the time of the emergency situation along with having joined families.

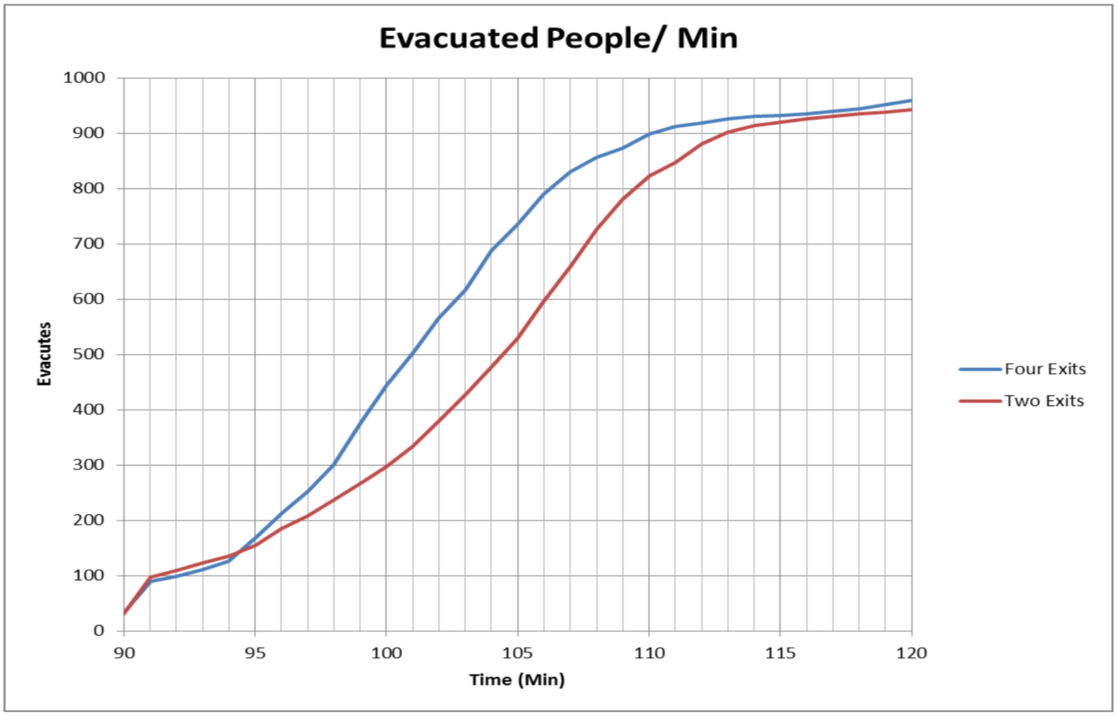


Figure 29: People evacuation rates under the two layout settings

The differences between the two settings start to increase after five minutes of the evacuation process. That is the time where the families that were located at the grid areas opposite to the exit gates are able to evacuate.

Table 7 shows the percentages of the evacuated people for both settings within certain time periods.

Table 7: Percentages of evacuated people within time under the two layout settings

Time (Min)	Four Exits	Two Exits
95	15%	14%
100	40%	27%
105	67%	48%
110	82%	75%
115	85%	84%
120	87%	86%

Considering the time for which around 85% of the people were able to evacuate under both settings, the results show that, for the case of having four exits, that percentage is reached around time =115 minutes. On the other hand, the same percentage is reached around time =119 for case of having two exits. Thus, the improvement of the evacuation process based on having four exits can be calculated as follows.

Considering the differences in start time between the two settings on time =95 minutes, then,

$$100 - \frac{100*10}{14} = 28.6\% \text{ Faster}$$

Figure 30 shows the mean values of evacuated people of the two layout settings of the ten experiments at time equals to 105 minutes. The mean value of the four exits case is higher compared to the two exits. Moreover, the standard deviation bars of both approaches don’t overlap indicating a significance difference statically between the two approaches.

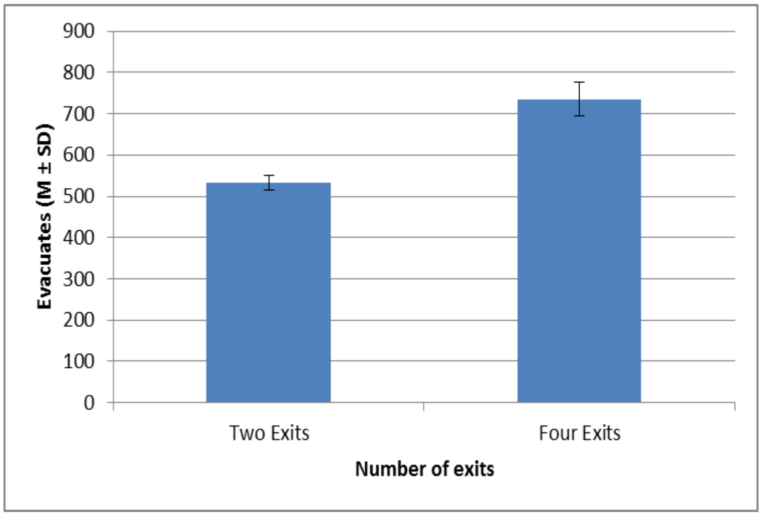


Figure 30: Mean and standard deviations of evacuated people in the two layout settings

Further investigations could be applied on adding extra exits in upper half grids of the layout as grids A, C, E, and G.

4.2.2. Normal Situation Case Study

This subsection presents a case study that studies the effect of family split on the level of satisfaction of its members in the normal scenario. The level of satisfaction is a measure of the number of achieved goals within certain period of time.

Case Study Description

Hypothesis

Having the family split in public events increases the satisfaction per family member by increasing the number of achieved goals that are pre-planned.

Research Question

RQ1. Does a family's splitting up increase the satisfaction factor?

Situation under Study

Families arrive to the event having their members pre-planned their goals based on interests. Up on arrival to the event, the families take certain decisions regarding keeping the unity, or split up in order to achieve more goals within certain time window. Based on the conducted survey (refer to appendix), who questions families' behavior at public events, equal percentages are found for families that don't split and prefer to navigate to the goals together, and for families that prefer to split up into smaller subfamilies that navigate independently to reach goals.

In order to study the effect of the decision to split up or not on the satisfaction factor of members, the following experiments are conducted, while the average family size is seven members.

a) Perform split at high rate, where the family can split up maximum of three subfamilies.

b) Have medium split rate, where the family can split up to maximum of two subfamilies

c) Have zero split rate, means families don't split

Simulations Setup:

- A time-controlled simulation
- Fixed number of families, with the same structure

Case Study Results

Figure 31 shows the average satisfaction level of the family members in the three decisions of splitting for their stay in the event of thirty minutes until ninety minutes.

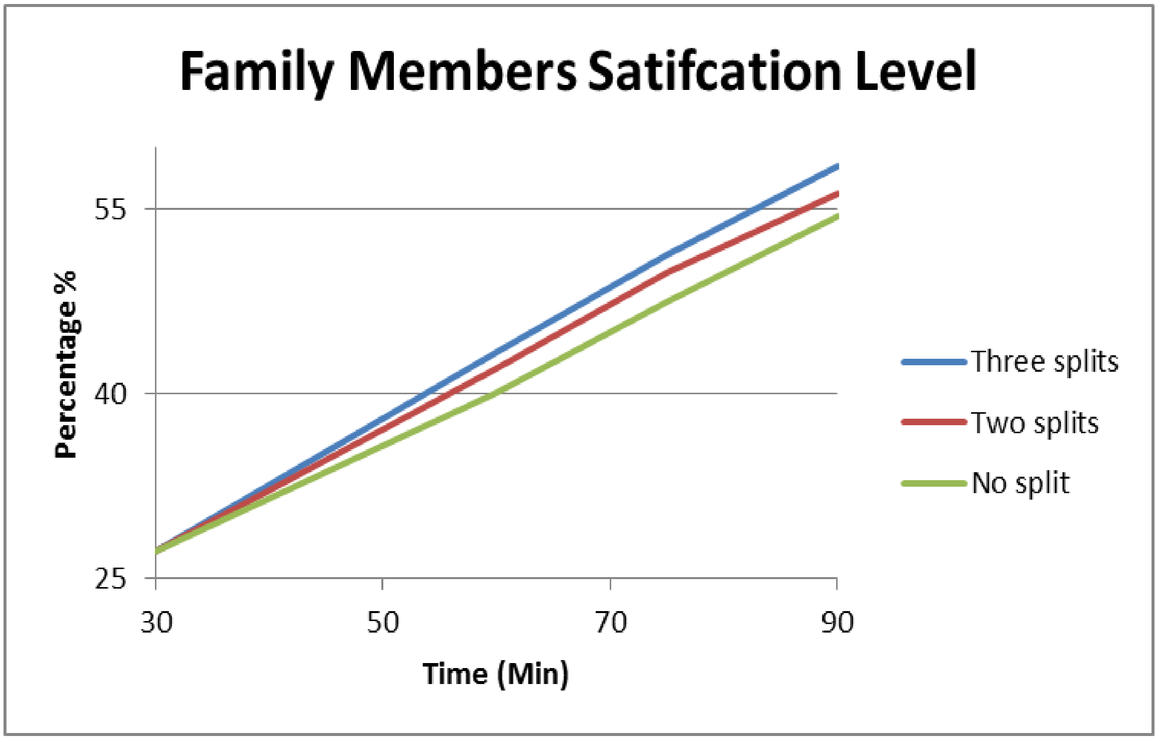


Figure 31: Average satisfaction level of the family members

The results show that deciding to split in general increases the satisfaction level of the family members compared to not split. Moreover, more splits within the family leads to higher satisfaction levels. This is because, once the family is split into smaller subfamilies, more goals can be achieved in parallel for the same time window.

In this case study, the three decisions on the split show close results in the satisfaction level. It's not always guaranteed that the family would split up to the maximum number of subfamilies all the time; it may not split up at all. This is because of number of reasons that are either related to the family constraints on the structure or the goals to be achieved. Constraints on the family structure that are defined in this model require that each subfamily to be formed should have a leader as disused in chapter 3. In some cases, the family may not have enough leaders to be assigned to the max number of subfamilies to be generated. Hence, the maximum number of splits is not always achieved. The other constraint is that, the children and elderlies should stay with a leader and are not allowed to navigate alone, therefore their satisfaction level might be lower compared to the leaders, which in turn affects the average satisfaction of the family.

The reasons that are related to the goals to be achieved, on the other hand, include matching of interests' factor and the number of goals to be achieved. The matching of interests' factor is defined as the percentage of matching goals between members. In this model, the subfamilies are formed based on having members who have the least conflict in interests between them. This means the more family members who could form subfamilies of distinct interests with respect to other subfamilies, the more subfamilies can be formed. Some cases occur as having a matching in interests between the family members; hence less subfamilies are formed. Finally, since the satisfaction level depends on the number of goals a member intends to achieve, having fewer goals would result in a higher satisfaction value within a certain time period compared to having more goals.

In this chapter, the family behavior in normal situations as well as in emergency situations is studied through conducting a set of simulations based on certain hypothesis to prove/disprove certain concepts.

In the emergency scenario, the evacuation process is studied under two case studies that include the effect of the family behavior, and the effect of the layout settings of the event. The effect of the family behavior on the evacuation process is analyzed for three behaviors and the consequence of each adopted behavior is presented. It’s found that splitting of the family into its leader while each leader can carry a child leads to the highest evacuation rates. On the other hand, adopting kin behavior leads to the lowest evacuation rates of the family members. Since people behavior during panic situation is affected by their psychological and social factors, means that high percentages would adopt the kin behavior, some recommendations can be provided to people that could enhance their evacuation process based on adopting such kin behavior. The first and could be the most important is to agree upon split about the behavior to adopt in case of an emergency situation occurred. This might save the time needed to evacuate as a family, and even would enhance the evacuation process as knowing that the other family split would adopt a certain behavior. On the other hand, not being able to know or predict how the rest of the family members would act, leads to dysfunctional behavior of the families [108]. A second recommendation could be to evacuate immediately if the family is split up since long time. Finally, agreeing on a join point upon deciding to split to be approached by the subfamilies in case of emergency situation might enhance the evacuation process. This is because, in emergency situations, subfamilies know that they need to approach a certain location, so it’s approached immediately, saving the time of communicating or looking for the other subfamilies. Indeed, this recommendation is set under the assumption that the join point is a safe area.

The other case study investigated the effect of adding extra exits on the overall evacuation process. It’s found that adding two extra exits to the layout results in an increase of the evacuation rate by around 29%. Finally, in normal scenarios, the effect of families’ splitting up on the satisfaction level of the members is studied. It’s found that having the family split up into more subfamilies increases the satisfaction level of the members

CHAPTER 5: CONCLUSION AND FUTURE WORK

This chapter discusses the main objectives that this work achieved, followed by some insights into future work based on the research.

5.1. Conclusion

The present research addressed the problem of molding family behavior in crowd simulations. The motivation for tackling such a problem is the analysis of family behavior in different contexts to predict the effects of behavior adopted during similar real-life situations.

Over the course of the present research, the following objectives are achieved:

- A model that describes family behavior in normal and emergency situations is created. That is achieved by designing a model that considers the contributions of multidisciplinary research and by conducting a survey of adopted behaviors in certain situations. Chapter 3 discusses how the considerations of multidisciplinary research are reflected in the model's design, while chapter 4, section 4.2, discusses other behavioral considerations in the model's design based on the results of the survey conducted.
- An implementation of the proposed model is undertaken by building the model on the top of a crowd simulation library. Then the model is validated through execution and by ensuring that it produced the outputs expected based on the input design. The implementation details and the high-level architecture of the model are discussed in chapter 3, section 3.3.

- A study of family behavior in normal and emergency situation is applied. This is achieved by conducting a set of case studies. The case studies are sought to investigate the effect of family behavior on certain parameters, including the evacuation process in emergency situations and the satisfaction level in normal situations. These case studies are discussed in detail in chapter 4, section 4.2.

Based on the study and the analysis of the family behavior applied in this work, the following findings are derived:

- Family behavior affects the family evacuation process in emergency situations. Each adopted behavior has certain consequences for family evacuation rates.
- Adopting kin behavior as a common during the emergency situation, leads to the lowest family evacuation rates.
- Family disunity in emergency situations affects the decisions made regarding which behavior to adopt, thus affecting the evacuation process.
- The family evacuation process is enhanced when the family splits during an emergency situation (as opposed to the process when family unity is conserved). The split could be total, leading to the highest evacuation rates, or could involve division into smaller subfamilies.
- The behavior that families adopt does not affect the process of evacuating individuals.

- The overall process of evacuating the people who make up a crowd is enhanced when extra exit gates are added to the layout where the crowd is gathered.
- Family splitting in public events increases the family members' satisfaction

5.2. Future Work

The following are proposed ideas for future research directions on family behavior:

- Applying the proposed family behavior model to studying family behavior in other contexts including emergency airplane disembarkation process.
- Using the proposed family behavior model to inspire a model for other specialized types of social groups such as friends' gatherings.
- Extending the adopted structure of the family in the proposed model to include members with special needs.
- Extend the proposed behavioral model and its decision-making process to consider emotions such as fear.
- Attempting to reinvent the decision-making process of the proposed model using fuzzy-logic or neural networks.
- Attempting visualization using a 3D environment.

REFERENCES

[1] Cabinet Office, *Understanding Crowd Behaviours*, vol. 59. 2009.

[2] M. W. Reid and H. M. Sandford, “Behaviour modification.,” *Aust. Fam. Physician*, vol. 6, no. 5, pp. 456–461, 1977.

[3] X. Zhao and Y. Son, “BDI-based human decision-making model in automated manufacturing systems,” *Int. J. Model. …*, vol. 28, no. 3, pp. 1–32, 2008.

[4] D. Thalmann and S. R. Musse, *Crowd Simulation*. 2013.

[5] M. Sung, M. Gleicher, and S. Chenney, “Scalable behaviors for crowd simulation,” *Comput. Graph. Forum*, vol. 23, no. 3 SPEC. ISS., pp. 519–528, 2004.

[6] C. Ren, C. Yang, and S. Jin, “A Multi-agent Simulation of Escape Panic,” *Comput. Sci. Optim. 2009. CSO 2009. Int. Jt. Conf.*, vol. 1, pp. 383–385, 2009.

[7] C. Rabiaa and C. Foudil, “Multi-layered framework for crowd microscopic simulation,” *2012 Int. Conf. Multimed. Comput. Syst.*, pp. 366–371, May 2012.

[8] L. Luo, S. Zhou, W. Cai, M. Lees, and M. Y. H. Low, “Modeling Human-Like Decision Making for Virtual Agents in Time-Critical Situations,” *2010 Int. Conf. Cyberworlds*, pp. 360–367, Oct. 2010.

[9] M. L. Chu, X. Pan, and K. Law, “Incorporating Social Behaviors in Egress Simulation,” in *Computing in Civil Engineering (2011)*, 2011, pp. 544–551.

[10] T. Giitsidis and G. C. Sirakoulis, “Simulation of Aircraft Disembarking and Emergency Evacuation,” *2014 22nd Euromicro Int. Conf. Parallel, Distrib. Network-Based Process.*, pp. 372–379, Feb. 2014.

[11] L. Zhang, Y. Song, J. Zhou, J. Gong, and W. Li, “The framework of crowd simulation modeling with social network,” *2010 Int. Conf. Comput. Appl. Syst. Model. (ICCASM 2010)*, no. Iccasm, pp. V3-437-V3-441, Oct. 2010.

[12] A. Shendarkar, K. Vasudevan, S. Lee, and Y.-J. Son, “Crowd simulation for emergency response using BDI agents based on immersive virtual reality,” *Simul. Model. Pract. Theory*, vol. 16, no. 9, pp. 1415–1429, 2008.

[13] N. Wagner and V. Agrawal, “An agent-based simulation system for concert venue crowd evacuation modeling in the presence of a fire disaster,” *Expert Syst. Appl.*, vol. 41, no. 6, pp. 2807–2815, 2014.

[14] J. Tsai, N. Fridman, E. Bowring, M. Brown, S. Epstein, G. Kaminka, S. Marsella, A. Ogden, I. Rika, A. Sheel, M. E. Taylor, X. Wang, A. Zilka, and M. Tambe, “ESCAPES -Evacuation Simulation with Children, Authorities, Parents, Emotions, and Social comparison,” 2011.

[15] C. Bian, D. Chen, and S. Wang, “Velocity Field Based Modelling and Simulation of Crowd in Confrontation Operations,” *2010 IEEE 16th Int. Conf. Parallel Distrib. Syst.*, pp. 646–651, Dec. 2010.

[16] L. Luo, S. Zhou, W. Cai, M. Y. H. Low, and M. Lees, “Toward a Generic Framework for Modeling Human Behaviors in Crowd Simulation,” *2009 IEEE/WIC/ACM Int. Jt. Conf. Web Intell. Intell. Agent Technol.*, pp. 275–278, 2009.

[17] J. Chang, “Simulation of Personnel Evacuation Based on Cellular Automata: To Consider Individual Character and Following Behavior,” *2013 Sixth Int. Symp. Comput. Intell. Des.*, pp. 403–405, Oct. 2013.

[18] J. Li-jun, C. Jin-chang, and Z. Wei-jie, “A crowd evacuation simulation model based on 2.5-dimension cellular automaton,” *2009 IEEE Int. Conf. Virtual Environ. Human-Computer Interfaces Meas. Syst.*, pp. 90–95, May 2009.

[19] A. Templeton, J. Drury, and A. Philippides, “From mindless masses to small groups: Conceptualising collective behaviour in crowd modelling,” vol. 19, no. 3, pp. 215–229, 2015.

[20] O. Beltaief and E. Beltaiefolfagmailcom, “Multi-Agent Simulation model of Pedestrians crowd based on Psychological theories,” pp. 150–156, 2011.

[21] J. Milazzo, N. Rouphail, J. Hummer, and D. Allen, “Effect of Pedestrians on Capacity of Signalized Intersections,” *Transp. Res. Rec.*, vol. 1646, no. 1, pp. 37–46, 1998.

[22] D. Helbing, C. J. Twining, a Bulsari, S. Oliker, M. Furst, and O. Maimon, “A Fluid-Dynamic Model for the Movement of Pedestrians,” *Complex Syst.*, vol. 6, pp. 391–415, 1993.

[23] G. C. Sirakoulis, “Cellular automata for crowd dynamics,” *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 8587 LNCS, pp. 58–69, 2014.

[24] D. Helbing and P. Molnár, “Social force model for pedestrian dynamics,” *Phys. Rev. E*, vol. 51, no. 5, pp. 4282–4286, 1995.

[25] C. W. Reynolds, “Flocks, herds and schools: A distributed behavioral model,” *ACM SIGGRAPH Comput. Graph.*, vol. 21, no. 4, pp. 25–34, 1987.

[26] A. Sud, R. Gayle, E. Andersen, S. Guy, M. Lin, and D. Manocha, “Real-time navigation of independent agents using adaptive roadmaps,” *ACM SIGGRAPH*

2008 classes - SIGGRAPH '08, vol. 1, no. 212, p. 1, 2008.

[27] J. E. Almeida, R. Rosseti, and A. L. Coelho, "Crowd Simulation Modeling Applied to Emergency and Evacuation Simulations using Multi-Agent Systems."

[28] A. Kirchner, H. Kl Upfel, K. Nishinari, A. Schadschneider, and M. Schreckenberg, "Simulation of competitive egress behavior: comparison with aircraft evacuation data," *Physica A*, vol. 324, pp. 689–697, 2003.

[29] S. Ó. Murphy, K. N. Brown, and C. Sreenan, "The EvacSim Pedestrian Evacuation Agent Model: Development and Validation."

[30] N. Pelechano and A. Malkawi, "Evacuation simulation models: Challenges in modeling high rise building evacuation with cellular automata approaches."

[31] N. Pelechano, J. M. Allbeck, N. I. Badler, N. Pelechano, J. M. Allbeck, and N. I. Badler, "Controlling Individual Agents in High-Density Crowd Simulation," pp. 99–108, 2007.

[32] D. Helbing, I. Farkas, and T. Vicsek, "Simulating dynamical features of escape panic.," *Nature*, vol. 407, no. 6803, pp. 487–490, 2000.

[33] A. Braun, S. R. Musse, L. P. L. De Oliveira, B. E. J. Bodmann, A. Unisinos, and S. Leopoldo, "Modeling Individual Behaviors in Crowd Simulation," no. 6, 2003.

[34] C. M. Henein and T. White, "Macroscopic effects of microscopic forces between agents in crowd models."

[35] C. M. Henein and T. White, "Agent-Based Modelling of Forces in Crowds," Springer Berlin Heidelberg, 2005, pp. 173–184.

[36] A. Lerner, Y. Chrysanthou, and D. Lischinski, "Crowds by Example," *EUROGRAPHICS*, vol. 26, no. 3, 2007.

[37] C. W. Reynolds, “Steering behaviors for autonomous characters,” *Game Dev. Conf.*, pp. 763–782, 1999.

[38] X. Liu, Xiaoyou.Zhu, and S. Zhou, “Modeling Crowd Behavior in Emergency Evacuation,” 2013. [Online]. Available: http://webcache.googleusercontent.com/search?q=cache:http://www.aicit.org/AISS/ppl/AISS3574PPL.pdf. [Accessed: 09-Dec-2015].

[39] E. Bonabeau, “Agent-based modeling: Methods and techniques for simulating human systems.”

[40] S. Goldenstein, M. Karavelas, D. Metaxas, L. Guibas, E. Aaron, and A. Goswami, “Scalable nonlinear dynamical systems for agent steering and crowd simulation,” *Comput. Graph.*, vol. 25, pp. 983–998, 2001.

[41] X. Pan, C. S. Han, K. Dauber, and K. H. Law, “A multi-agent based framework for the simulation of human and social behaviors during emergency evacuations,” *Ai Soc.*, vol. 22, no. 2, pp. 113–132, 2007.

[42] A. G. Bruzzone, E. Briano, E. Bocca, and M. Massei, “Evaluation of the impact of different human factor models on industrial and business processes,” *Simul. Model. Pract. Theory*, vol. 15, no. 2, pp. 199–218, Feb. 2007.

[43] M. E. Bratman and J. Seidman, *Intention, Practical Rationality, and Self-Governance*. Harvard University Press: Cambridge, MA, 1987.

[44] M. Georgeff, B. Pell, M. Pollack, M. Tambe, and M. Wooldridge, “The Belief-Desire-Intention Model of Agency.”

[45] M. WOOLDRIDG, *An Introduction to MultiAgent Systems*. Library of Congress Cataloging-in-Publication Data, 2002.

[46] S. Lee and Y. Son, "Integrated Human Decision Making Model Under Belief-Desire-Intention Framework For Crowd Simulation," no. Norling 2004, pp. 886–894, 2008.

[47] A. Shendarkar, K. Vasudevan, S. Lee, and Y.-J. Son, "Crowd Simulation for Emergency Response Using BDI Agent Based on Virtual Reality," *Proc. 2006 Winter Simul. Conf.*, pp. 545–553, 2006.

[48] G. Klein, *Sources of Power: How People Make Decisions.* MIT Press, 1998.

[49] J. So, C. Achar, D. Han, N. Agrawal, A. Duhachek, and D. Maheswaran, "The Psychology of Appraisal: Specific Emotions and Decision-Making," *J. Consum. Psychol.*, vol. 25, no. 3, pp. 359–371, 2015.

[50] L. Sun and W. Qin, "Simulation of crowd behaviors based on event reaction," *2011 IEEE Int. Conf. Comput. Sci. Autom. Eng.*, pp. 163–167, Jun. 2011.

[51] N. Hempe, "A flexible model for real-time crowd simulation," no. October, pp. 2085–2090, 2009.

[52] I. Von Sivers, A. Templeton, F. Künzner, G. Köster, J. Drury, A. Philippides, T. Neckel, and H.-J. Bungartz, "Modelling social identification and helping in evacuation simulation," *Saf. Sci.*, vol. 89, pp. 288–300, 2016.

[53] J. Turner, "Social categorization and the self-concept: A social cognitive theory of group behavior," *Adv. Gr. Process.*, 1985.

[54] H. Tajfel and J. Turner, *An integrative theory of intergroup conflict*. 1979.

[55] L. S. Poon ', "EvacSim: A Simulation Model of Occupants with Behavioural Attributes in Emergency Evacuation of High-Rise Building Fires."

[56] "Exodus." [Online]. Available: http://fseg.gre.ac.uk/exodus/. [Accessed: 31-Dec-

2016].

[57] "SIMULEX." [Online]. Available: https://www.iesve.com/software/ve-for-engineers/module/Simulex/480#technical-detail. [Accessed: 31-Dec-2016].

[58] P. A. Thompson and E. W. Marchant, "Simulex; Developing New Computer Modelling Techniques for Evaluation."

[59] S. Jafer and R. Lawler, "Emergency crowd evacuation modeling and simulation framework with cellular discrete event systems," *Model. Simul. Int.*, vol. 92, no. 8, pp. 795–817, 2016.

[60] T. Bosse, V. Chandra, E. Mitleton-Kelly, and N. Van Der Wal, "Analysis of Beliefs of Survivors of the 7/7 London Bombings: Application of a Formal Model for Contagion of Mental States," *LNCS*, vol. 7062, pp. 423–434, 2011.

[61] J. Saunier and H. Jones, "Mixed Agent/Social Dynamics for Emotion Computation," in *Proceedings of the 13th Inter- national Conference on Autonomous Agents and Multiagent Systems (AAMAS 2014).*, 2014.

[62] A. F. Aveni, "The Not-So-Lonely Crowd: Friendship Groups in Collective Behavior," *Sociometry*, vol. 40, no. 1, p. 96, 1977.

[63] J. R. G. Dyer, C. C. Ioannou, L. J. Morrell, D. P. Croft, I. D. Couzin, D. A. Waters, and J. Krause, "Consensus decision making in human crowds."

[64] V. Reuter, B. S. Bergner, G. Köster, M. Seitz, F. Treml, and D. Hartmann, "On Modeling Groups in Crowds: Empirical Evidence and Simulation Results Including Large Groups," 2012.

[65] M. Moussaïd, N. Perozo, S. Garnier, and D. Helbing, "The walking behaviour of pedestrian social groups and its impact on crowd dynamics," pp. 1–18, 2010.

[66] A. Kamphuis and M. H. Overmars, “Finding paths for coherent groups using clearance,” *ACM SIGGRAPH / Eurographics Symp. Comput. Animat.*, pp. 19–28, 2004.

[67] V. Kountouriotis, S. C. A. Thomopoulos, and Y. Papelis, “An agent-based crowd behaviour model for real time crowd behaviour simulation,” *Pattern Recognit. Lett.*, vol. 44, pp. 30–38, 2014.

[68] N. Jaklin, A. Kremyzas, and R. Geraerts, “Adding Sociality to Virtual Pedestrian Groups,” 2015.

[69] A. Kremyzas, N. Jaklin, and R. Geraerts, “Towards social behavior in virtual-agent navigation,” *Sci China Inf Sci*, vol. 59, no. 11210211, 2016.

[70] C. Loscos, D. Marchal, and a. Meyer, “Intuitive crowd behavior in dense urban environments using local laws,” *Proc. Theory Pract. Comput. Graph. 2003.*, pp. 0–7, 2003.

[71] S. R. Musse and D. Thalmann, “A Model of Human Crowd Behavior : Group Inter-Relationship and Collision Detection Analysis,” *Comput. Animat. Simulations*, pp. 39–51, 1997.

[72] I. Karamouzas and M. Overmars, “Simulating and evaluating the local behavior of small pedestrian groups.,” *IEEE Trans. Vis. Comput. Graph.*, vol. 18, no. 3, pp. 394–406, 2012.

[73] Z. Ren, P. Charalambous, J. Bruneau, Q. Peng, and J. Pettré, “Group Modeling: a Unified Velocity-based Approach,” *Comput. Graph.* , vol. xx, pp. 1–11, 2016.

[74] S. I. Park, F. Quek, and Y. Cao, “Modeling Social Groups in Crowds Using Common Ground Theory,” *Winter Simul. Conf.*, 2012.

[75] H. Clark, *Herbert H . Clark , Using language . Cambridge : Cambridge University Press ,*. Cambridge University Press, 1996.

[76] B. SUSAN and H. Clark, *Grounding in communication*. American Psychological Association, 1991.

[77] S. I. Park, F. Quek, and Y. Cao, “Modeling agent social joint actions via micro and macro coordination strategies,” *Web Intell. Intell. Agent Technol. (WI-IAT), 2012 IEEE/WIC/ACM Int. Conf.*, vol. 2, pp. 180–187, 2012.

[78] J. Šochman and D. C. Hogg, “Who knows who-Inverting the Social Force Model for finding groups,” *IEEE Int. Conf. Comput. Vis.*, pp. 830–837, 2011.

[79] F. Qiu and X. Hu, “Modeling dynamic groups for agent-based pedestrian crowd simulations,” *Proc. - 2010 IEEE/WIC/ACM Int. Conf. Intell. Agent Technol. IAT 2010*, vol. 2, pp. 461–464, 2010.

[80] M. Alexander, “Non-Adaptive Group Behavior,” *J. Abnorm. Soc. Psychol.*, vol. 40, pp. 150–159, 1951.

[81] L. Festinger, “‘A theory of social comparison processes,’” *Hum. Relations*, pp. 117–140, 1954.

[82] J. L. Bryan, “A selected historical review of human behavior in fire,” *J. Fire Prot. Eng.*, 2002.

[83] D. Tong and D. Canter, “The Decision to Evacuate: a Study of the Motivations which Contribute to Evacuation in the Event of Fire*,” *Fire Saf. J.*, vol. 9, pp. 257–265, 1985.

[84] A. R. Mawson, “Understanding Mass Panic and Other Collective Responses to Threat and Disaster,” 2005.

[85] G. Köster, M. Seitz, F. Treml, D. Hartmann, and W. Klein, “On modelling the influence of group formations in a crowd,” *Contemp. Soc. Sci.*, 2011.

[86] N. Pelechano and N. I. Badler, “Modeling crowd and trained leader behavior during building evacuation,” *IEEE Comput. Graph. Appl.*, vol. 26, no. 6, pp. 80–86, 2006.

[87] M. Okaya and T. Takahashi, “Human Relationship Modeling in Agent-Based Crowd Evacuation Simulation,” 2011.

[88] M. Ling Chu, P. Parigi, J.-C. Latombe, and K. H. Law, “Simulating effects of signage, groups, and crowds on emergent evacuation patterns,” *AI Soc.*, 2014.

[89] R. Xie, Z. Yang, Y. Niu, and Y. Zhang, “Simulation of Small Social Group Behaviors in Emergency Evacuation,” in *Proceedings of the 29th International Conference on Computer Animation and Social Agents*, 2016.

[90] J. Fang, ; S El-Tawil, F. Asce, and B. Aguirre, “New Agent-Based Egress Model Allowing for Social Relationships,” *J. Comput. Civ. Eng.*, vol. 30, no. 4, 2016.

[91] M. Kyžňanský and P. Lacko, “Crowd Evacuation with Family Scenario Expansion,” pp. 263–266, 2014.

[92] D. M. Bramble and D. E. Lieberman, “Endurance running and the evolution of Homo,” *Nature*, vol. 432, no. 7015, pp. 345–352, Nov. 2004.

[93] “Height to Weight Ratio Chart.” [Online]. Available: http://www.disabled-world.com/artman/publish/height_weight.shtml.

[94] “Resting Heart Rate Chart.” [Online]. Available: http://www.topendsports.com/testing/heart-rate-resting-chart.htm.

[95] “Pediatric Vital Signs Reference Chart | PedsCases.” [Online]. Available:

http://www.pedscases.com/pediatric-vital-signs-reference-chart.

[96] D. Merwe and V. Der Merwe, “Prediction of energy expenditure from heart rate monitoring during submaximal exercise .,” *J. Sports Sci.*, 2005.

[97] “Minimum Amount of Calories Needed Per Day to Survive | LIVESTRONG.COM.” [Online]. Available: http://www.livestrong.com/article/310517-minimum-amount-of-calories-needed-per-day-to-survive/.

[98] B. Latané, K. Williams, and S. Harkins, “Many hands make light the work: The causes and consequences of social loafing.,” *J. Pers. Soc. Psychol.*, vol. 37, no. 6, pp. 822–832, 1979.

[99] G. ZIPF, “Human Behavior and the Principle of Least EJort,” pp. 268–270, 1949.

[100] B. E. Aguirre, D. Wenger, and G. Vigo, “A Test of the Emergent Norm Theory of Collective Behavior,” vol. 13, no. 2, 1998.

[101] A. R. Mawson, “Understanding Mass Panic and Other Collective Responses to Threat and Disaster,” vol. 68, no. 2, 2005.

[102] J. D. Sime, “Affiliative Behaviour During Escape To Building Exits,” *J. Environ. Psychol.*, vol. 3, pp. 21–41, 1983.

[103] J. Snape, S. J. Guy, D. Vembar, A. Lake, and M. C. Lin, “Reciprocal Collision Avoidance and Navigation for Video Games,” *Intel Softw. Netw.*, vol. 27599, pp. 1–14, 2012.

[104] J. Snape, J. Van Den Berg, S. J. Guy, and D. Manocha, “The Hybrid Reciprocal Velocity Obstacle,” *IEEE Trans. Robot.*, vol. 27, no. 4, 2011.

[105] T. Gärling, A. Böök, and E. Lindberg, “Spatial Orientation and Wayfinding in The

Designed Environment: A Conceptual Analysis and Some Suggestions for Post occupancy Evaluation," *Source J. Archit. Plan. Res. J. Archit. Plan. Res. J ARCH PLAN RES*, vol. 3, no. 3, pp. 55–6455, 1986.

[106] "The Ministry of Culture and Sports| Doha International Book Fair." [Online]. Available: http://www.dohabookfair.com/#/. [Accessed: 16-Jan-2017].

[107] H. Winter, "Modelling Crowd Dynamics During Evacuation Situations Using Simulation," 2012.

[108] N. J. Smelser, *Theory of collective behavior*. Routledge & Kegan Paul, 1962.

APPENDIX: SURVEY ABOUT FAMILY BEHAVIOR

This survey is intended to analyze family behavior in family gatherings. It aims at studying behavior in normal as well as emergency situation.

1. How many members are in your family?

2. How many kids are in your family (below 12 years)?

3. How many adults and teenagers are in your family?

4. You are attending with your family an event of different interests; how does your family usually behave in the event?

○ All family members hang around together always to visit different areas of interest

○ Family is divided into smaller groups to visit different areas of interest

○ Other (please specify)

5. When hanging around with family, usually after how many minutes do you get bored?

6. Why do you get Bored?

○ Not visiting areas of interests you intended to visit within certain time

○ Family is favoring other members' needs than visiting your areas

○ Other (please specify)

7. When hanging around in an event, usually after how many minutes do you go to restroom?

8. When hanging around in an event, usually after how many minutes do you go to restaurant?

9. When you are in an event and you are with your family at the same place, suddenly, a fire evacuation alert started. How will you first react?

○ Evacuate yourself first

○ Evacuate with other family members together

○ Other (please specify)

10. When you are in an event and you are apart from your family, suddenly, a fire evacuation alert started. How will you first react?

○ Evacuate yourself first

○ Try to approach other family members then evacuate together

○ You will evacuate with the a group, If you are in a group of family members

○ Other (please specify)

☐

11. Do you expect less causalities if your family groups waited for each other before evacuating?

○ Yes

○ No

12. Do you expect less causalities if each member of your family evacuated by himself regardless of other members?

○ Yes

○ No

13. Do you expect less causalities when each family group evacuate by itself regardless of the other groups, if the family was split in groups?

○ Yes

○ No

14. When you were moving around in an open event with your family, you noticed that one of your children or an elderly person is not around (he/she has no cell phone) how will your family react?

○ All family members will look for him together as a unit

○ Your family members will split to look for him in different possible areas

○ One family member will be looking for him, and others will wait, in case the family cannot split

○ Some of the family members will look for him and the others resume movement

○ Other (please specify)

☐

15. When you were moving around in an open event with your family, you noticed that one of your family members who is an adult or a teenager is not around (he/she has no cell phone) how will your family react?

○ All family members will look for him together as a unit

○ Your family members will split to look for him in different possible areas

○ One family member will be looking for him, and others will wait, in case the family cannot split

○ Some of the family members will look for him and the others resume movement

○ Other (please specify)