A PARTICLE SWARM OPTIMIZATION BASED BEHAVIORAL AND PROBABILISTIC FIRE EVACUATION MODEL INCORPORATING FIRE HAZARDS AND HUMAN BEHAVIORS

by

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Dedication

This thesis is dedicated to my parents, Zhirong and Rongying, my uncle, Jin Xue, and my grandmother, Fengjin Zhen.
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Abstract

Many fire safety engineers use computer models to test various designs as a part of the decision-making of the building construction plan. Currently, there are two principal types of computer models: hydraulic (or network flow models) and behavioral models. Although hydraulic or network flow models are generally inexpensive to purchase and easy to run, they have drawbacks such as rarely including an appreciation of human behaviors, which play a critical role in the performance of occupants in real fire evacuations. In contrast, behavioral models attempt to realistically simulate the actions and decisions made by occupants during an evacuation, which comply with the performance-based codes to generate performance-based design solutions.

This thesis focuses on simulation of human behaviors under the emergency of building fires using a behavioral model called *Vacate*. Many types of behaviors are included in this research such as automatically detecting the fire hazards, random walking behaviors in pre-evacuation time, wandering behaviors when occupants are in the environment of heavy smoke, wall-following behaviors in the event of heavy smoke, group evacuation behaviors when evacuation leaders are present, and passive evacuation behaviors, such as turning back to the previous room or other rooms to gather belongings or seek refuge. All of these behaviors are based on the heuristic optimization technique of Particle Swarm Optimization (PSO), which originates from simulating a flock of birds.
This thesis includes the simulation of the decision-making process of the occupants’ response to fire. Probabilistic factors are considered while the decisions are mainly based on the combined effects of environment, configuration, procedure, and behaviors.

This thesis also focuses on improving the current fire hazard model by combining the hazard effects of smoke, heat, and toxicity. The hazard information of fire is calculated by the Fire Dynamics Simulator (FDS), which is a Computational Fluid Dynamics (CFD) model of fire driven fluid flow developed by the National Institute of Standards and Technology (NIST). This is incorporated into the Vacate model.

The proposed PSO-based algorithm has been successfully tested and verified in a variety of floor plans and in a mixture of populations with different occupant characteristics. Although a larger number of verification cases are required to justify the effectiveness of this method, this thesis has demonstrated the important role of fire data and human behaviors in the performance-based design of fire safety engineering. In the future, behaviors such as automatically avoiding the smoke barrier, looking for friends, and interactions between occupants and the fire environment (e.g. the fire fighting behavior) will be incorporated into the current evacuation model.
Chapter 1

Introduction

1.1 Overview

This thesis incorporates an upgraded fire hazard model into the current building fire evacuation program *Vacate* [1], and investigates various human behaviors [2] in building fire in this model. With the integration model of fire hazards, human behaviors and layout of building environment, the research simulates and validates building fire evacuation with numerous test cases.

1.2 Motivation

Based on data from the National Fire Protection Association, there were 1,550,500 fires reported by fire departments in the United States in 2004, resulting in approximately 3,900 civilian deaths, 17,785 injuries, and $9,794,000,000 in property damage [3]. Approximately 85% of the properties loss was from structure fires. Due to inadequate evacuation procedures and evacuation infrastructure, a great number of deaths and injuries occur each year.

Life Safety Codes [4] for building design have been designed to ensure the safety of the occupants by making sure buildings comply with some prescriptive rules [1]. The
prescriptive rules inflexibly specify the precise minimum requirements for buildings. Improvements to prescriptive codes occur incrementally and are often based on incidents that provide evidence that exiting provisions are based on faulty assumptions [5]. For example, Research on movement down stairs revealed that code assumptions relating stairway width to flow rates were faulty [5]. One of the drawbacks of prescriptive codes is that they do not consider psychological and physiological behaviors of humans in the event of fire [1]. However, these behaviors are critical to the variation of the evacuation results because the occupants’ movement is not simply analogous to water flowing through pipes or balls moving on a pool table. Instead, to accurately represent evacuation scenarios, models should considerably include, for example, the possibility of movement in a familiar direction, turning back, moving toward the fire to get out faster and moving at different speeds [6].

From the 1990s to 2000s (identified as the “Performance Code Incentive Years”), the worldwide movement toward performance codes created a demand for intensive research on human behaviors. Recent research on human behaviors in the case of fire has provided the theoretic basis for the behavior-based evacuation computer models used here, which demonstrate certain improved accuracy on evaluation of various architectural plans with the help of visualization techniques. The potential advantage of the development of these computer models is they can be used to spare the implementation of expensive and dangerous full-scale evacuation drills. For example, between 1969 and 1993, more than 20 full-scale evacuation certification demonstrations were performed for aircraft design involving over 7000 volunteers, with each trial costing approximately $2 million dollars.
Numerous injuries (even permanent paralysis in one case) have resulted from such trials [7].

Many computer evacuation models have been developed, and can be categorized into three categories [4]: single-parameter estimation methods; movement models; and behavioral simulation models. Single-parameter estimation methods are simple evacuation time calculations generally calculated using equations derived from data collected in evacuation drills of non-emergency situations [1]. Movement models are commonly referred to as “ball bearing” models simulating evacuation as water flowing in pipes or ball bearing in chutes [1]. The lack of psychological and social aspects in these models treats occupants as mindless subjects. Behavioral simulation models consider occupants as single entities with individual characteristics such as age, gender, disability, familiarity to building enclosure, etc. These individual characteristics influence and contribute to occupants’ decision-making, movement and behavior during the evacuation simulation [1]. A detailed review can be found in reference [1].

A behavior-based computer evacuation simulation model named *Vacate* was developed in 2004, based on Particle Swarm Optimization [1]. *Vacate* can simulate the basic human behaviors in the event of fire, such as pre-evacuation time, speed fluctuations, overtaking, queuing, helping disabled occupants, taking alternate exits in case of overcrowding, avoiding obstacles and walls, etc. This model also includes a simple human tenability assessment model based on the Fractional Effective Dose Method which was developed by Purser [9]. In *Vacate*, the movement simulation method of the occupants is based on
the heuristic optimization technique of PSO [10-12] which originated from the simulation of flocking birds [13]. The most attractive attribute of using the PSO method is that it recognizes the coordinate-based crowd movement governed by various human behaviors, which substantially outperforms various network-flow computer models available on the market. Most of these models are grid-based in that the entire enclosure is divided into small grids and occupants move from one node to another according to some rules. The state-of-the-art behavioral model EXODUS [14-18] is also based on the grid–based movement algorithm. One of the disadvantages of such an algorithm is that it is usually computationally expensive to lay out fine enough grids for large enclosures. Hence, this limits the area of the floor plan and the total number of people that can be modeled with available desktop computer systems. More detailed discussion can be found in reference [1].

Although Vacate has substantial potential to simulate evacuation that considers human behaviors, it is still a primitive model. The objective of this thesis work is to focus on two critical areas: first, to incorporate the fire spread, smoke transportation, and combined heat and toxicity hazard generated from combustion into this model to represent their potential influence on the occupants’ evacuation. For example, during a fire, smoke usually spreads from the sources of the fires to the rest of the building. During the process, it may obstruct some of the existing fire exits [19]. Also, visual obscuration and irritancy of smoke impedes escape efficiency, affecting escape behavior and slowing travel speeds. This may be followed by incapacitation primarily due to exposure to asphyxiating gases (mainly carbon monoxide [CO] and hydrogen cyanide [HCN]), and
death [9]. Second, more human behaviors are incorporated into *Vacate* such as automatically detecting the time-dependent fire hazard information, walking randomly in a pre-evacuation period, wandering in the heavy smoke, following the walls in the heavy smoke, group evacuation by following a trained evacuation leader, following crowds, redirecting to other exits, returning to previous or other rooms to seek refuge or gather belongings. Combinations of these behaviors with basic behaviors generate an updated model which results in a more accurate and realistic fire scenario simulation.

1.3 Organization of Thesis

In this chapter, a brief discussion on the need to develop a more sophisticated behavioral computer evacuation model is presented. In Chapter 2, the related work which has been done in this field is reviewed. In Chapter 3, details on how to incorporate the fire hazard model into *Vacate* are described. Chapter 4 shows the development of algorithms of that capture the various human behaviors. Chapter 5 presents the implementation of the developed methodology with extending the functionalities of *Vacate* (which is a Windows–based MFC application). In Chapter 6, validation cases and results are discussed. Conclusions and suggestions on future research are described in Chapter 7.
Chapter 2

Background

2.1 Overview

This chapter provides the critical review of current computer evacuation models for building enclosure evacuation under fire. Models are classified into three categories according to different modeling methods [20]:

- Movement models (no behavioral capabilities);
- Partial-behavioral models (implicit behavior is simulated [21]); and
- Behavioral models (occupant decision-making and behavior are simulated).

Because the aim of this thesis is to focus on incorporating the fire hazard model and more human behaviors into Vacate, the review emphasizes methods for simulating behaviors and the use of fire data \(i.e.\) the incorporation of fire hazard models. Excellent reviews on different methods of occupant movement \(e.g.\) coarse network approach, fine network approach, continuous network approach) and other features can be found in reference [1], [8] and [25]. Also, since this work is focusing on improving the current behavioral model used in Vacate, several other state-of-the-art behavioral models are reviewed in detail.
2.2 Background on pedestrian planning and design

Fruin [22], and Predtechenskii and Milinskii [23] have done numerous studies to quantify and analyze crowd movement under non-emergency situations. They quantified pedestrian movement with two relationships: (1) the velocity (ft/min) of pedestrians as a function of density (area/person); and (2) flow rate (people/unit length of walkway, stair or exit/min) as a function of density (area/person) [1]. The diagrams associated with this data and more details can be found in references [1], [22], and [23]. Although the maximum crowd flow rate presented in these studies does not represent the crowd flow rate observed during real emergency situations [24], these relationships still serve as the basic validation proof for results from any computer simulation model due to the lack of more complete validation data.

2.3 Fire hazard data

For behavioral models, there are two critical reasons about why we should include the fire hazard data. First, the fire environment interacts with occupants’ decision-making process and behavior with the generated hazards of heat, smoke, asphyxiant and irritant gases. For example, when an occupant is faced with a smoke barrier walking toward the exit, he most likely would not go through the smoke if there is any other alternative exit available. The second issue (or the ultimate issue) is that these data are needed to assess the safety of the occupants who travel through such conditions [25]. Purser [9] developed a model to calculate a fractional incapacitating dose for individuals exposed to asphyxiant gases such as CO, HCN, CO₂, and reduced O₂. Purser also developed models to calculate certain effects due to smoke, heat and irritant gases. However, he did not consider the
combined hazard effects of the smoke, heat and asphixiant gases on the escaping occupants. Further discussion on this is presented in Chapter 3.

The fire data mentioned here are generated by various computer fire models. A computer fire model is a model that simulates the fire growth, fire spread, and smoke movement in a certain simulation environment according to users’ inputs, and then generates fire hazard information as the outputs. Olenick [30] et al. classified the fire models into 6 categories originated from Friedman’s survey [29]: zone models; field models; detector response models; fire endurance models; egress models and miscellaneous models. The zone models and field models are used to model fire development inside a compartment or a series of compartments. The detector response models predict primarily the time to activate an initiating device, such as the thermal detector, sprinkler, or fusible link to a fire-induced flow and smoke detector. Fire endurance models simulate the response of building structural elements to fire exposure which concentrates on determining when the structure will fail. Egress models predict the time for occupants of a structure to evacuate, which falls into the scope of this thesis. Miscellaneous models are those models not appreciate for one of the upper categories because these models are containing many sub-models and therefore can be used for several of the categories listed above [30]. In fact, the detector response models, fire endurance models, egress models and miscellaneous models all are derived from the two basic fire models (zone models and field models) and then became more specific. In this thesis work, the fire hazard model is to be selected from the category of zone models and field models. A more detailed description about zone models and field models is presented in Chapter 3.
2.4 Movement Models

Movement models are those models that focus on the movement of occupants from one point in the building to another (usually the exit or a position of safety). The main types of output include the total evacuation time, locations of bottlenecks inside the building, and flow through openings [25]. Some typical movement models are listed as the following: \textit{EVACNET4} [26-27], \textit{Magnetic Model} [54] and \textit{EgressPro} [28]. Unfortunately, none of these models allows for the inclusion of fire data, with the exception of \textit{EgressPro}. This unique model incorporates a limited amount of user-supplied fire data to the program to simulate the time of the alarm sounding [25].

Almost all the movement models listed above lack the high behavioral simulation capabilities that movement of occupants throughout the building is not simulated based on the theory of velocity \textit{vs.} speed correlations developed by Fruin [22], and Predtechenskii and Milinskii [23]. Only the \textit{Magnetic Model} [54] offers a complex queuing system with three types of behaviors, including queuing in front of a counter, queuing in front of a gate, and queuing in front of vehicles, such as a bus. However, this is far less than enough to generate the more realistic predicted evacuation time using such models.

2.5 Partial-behavioral Models

These models primarily calculate occupant movement, but begin to simulate behaviors. The pre-movement time distributions among the occupants, unique occupant characteristics, overtaking behavior, and the introduction of smoke or smoke effects to
the occupant implicitly represent many possible behaviors [25]. Two typical partial-behavioral models: EXIT89 include [31-34] and SIMULEX [35-37]. Only EXIT89 includes the fire hazard model CFAST [38], which is a two-zone fire model capable of predicting the environment in a multi-compartment structure subjected to a fire [38].

The main difference between this category and the behavioral category is that the “behaviors” in this category are implicitly modeled by providing inputs of body size, occupant characteristics, the inclusion of pre-evacuation times, and fire data [25]; whereas in the behavioral category, the “behaviors” are explicitly modeled by considering the occupants decision-making and human behaviors directly that are implemented due to environmental conditions of the building.

2.6 Behavioral Models

Behavioral models are those models that incorporate the occupants’ decisions and behaviors, in addition to movement toward a specified goal (exit) [25]. The typical models are: CRISP [39-42]; ASERI [43-44]; buildingEXODUS [45, 90-91]; EGRESS [46-47]; and MASCM [48]. All of the behavioral models (except MASCM) described in this section are capable of accepting some type of fire hazard data. These data along with some “rules”, such as “If the occupants are engulfed in the heavy smoke, the occupant will wander in the room if he can not find the wall and follow it”, simulate the decision-making process and human behaviors.
The model buildingEXODUS [45, 90-91], which is one of the sub-models of EXODUS, perhaps has the most complete set of social psychological attributes and characteristics for each agent. There are twenty-two in all, including age, name, sex, breathing rate, running speed, and dead/alive [8]. The model also accounts for the eventual cessation, delay, or movement due to the accumulated hazard effect of heat and toxic gases. The model as a whole is comprised of five interacting sub-models: movement; behavior; passenger (agent); hazard; and toxicity. For a more critical review on the movement method and other features about this sophisticated model, please refer to references [1] and [8]. These features make EXODUS an outstanding behavioral model on the current market. However, this model still has some big disadvantages including: (1) the computer power is highly related to the overload of the layout of the grid; (2) the movement method generates jagged or unrealistic movement of occupants (e.g., like moving the chess on the chessboard); and (3) EXODUS assumes a linear relationship between width and flow rate which is not always true in that high flow rates are possible for high density crowd in real emergency situations. These three disadvantages are avoided by applying a modified PSO [11-13] algorithm to obtain the most realistic movement of the occupants. PSO is a coordinate-based (not grid-based) algorithm which is designed for simulating social behaviors. It is very flexible and can be modified easily. Thus with PSO it is easy to incorporate fire hazard data and various human behaviors into the simulation model. Some human behaviors have already been incorporated into Vacate [1], such as speed fluctuations, overtaking, queuing, helping the disabled, taking alternative exits in case of overcrowding, and avoiding obstacles and walls. However, more accurate fire model and human behaviors are incorporated in this work to make Vacate even more realistic.
In the next sections, four behavioral models are introduced in detail. They are *MASCM* [48], *ASERI* [43-44] [49], *CRISP* [39-42], and *Measured Response* [100-102].

### 2.7 MASCM

*Muti-Agent Simulation for Crisis Management (MASCM)* [48] is a behavioral model which emphasizes the presence of leadership in fire evacuation. Murakami et al. [48] recognized that leaders are key players in a variety of scenarios, which includes police officers, fire fighters, security guards, and ushers. These researchers developed *MASCM* to overcome the assumptions that are usually made by the traditional simulation tools, which include group homogeneity, unidirectional movement, and insignificance of social interaction. They consider the pivotal role of leaders, especially in relation to dynamic choices of an evacuation route. This feature extends the possibility of choosing the shortest path (or alternatively using a familiar route) to the case where a leader may lead a group through a path that is neither the shortest nor the familiar path, but is the only available path considering the location of the fire threat [8]. Murakami et al. [48] use the a real-world experiment conducted by Sugiman in 1988 [51] to serve as benchmarks for the simulation results. Prior to the development of the model, the researchers explored the impact of social interaction simulated in 3D virtual spaces, which enabled identification of the subtleties attending the interaction of evacuees and leaders in order to develop an accurate interaction language (named Q). This language serves as the base of two simple multi-agent simulators, *FlatWalk* and *FreeWalk* [48]. *FreeWalk* generates a 3-dimensional environment that produces agents that may interact with each other verbally and perform visual gestures, such as pointing. *FlatWalk* produces a two-dimensional
“aerial” image whereby the entire group can be monitored during evacuation and the user can track the state of the individual occupants [48]. By using these two sub-models, this model produces significant improvements since it enables the user to develop a distinct scenario for each evacuee. These researchers extracted the evacuating rules from Sugiman’s research to govern the behavior of occupants [51]. Applying these rules to FlatWalk and FreeWalk, MASCM generates “guarded commands” and other special forms of notation which produce five simultaneous actions, including: (1) telling the occupant to “please follow me”; (2) starting to walk along the evacuation route; (3) seeing an occupant at a distance; (4) waiting for the occupant to approach; and (5) listening to an occupant speak. Murakami et al. [48] also developed two sets of rules and scenarios for leaders: one set for the “Follow-direction Method” and the other set for the “Follow-me Method.” The former involves verbally directing evacuees to an exit, while the latter involves physically leading evacuees to an exit without any appreciable verbal explanation of the route. The researchers attempt to compare the evacuation time after applying these two different approaches. The results are presented in reference [48].

There are three main disadvantages associated with MASCM. First, although fairly accurate and diverse rules are applied to evacuation leaders, there is no set of methods to simulate the group decision-making processes, such as selecting a leader when evacuation leaders or trained occupants are not available. However, it is often the case that in evacuation situations there are no official leaders. Second, despite the fact Murakami et al. [48] recognize the importance of adherence to some group during evacuation, they failed to pinpoint the nature of the relationships between the occupants
and how these would be likely to affect the rate and nature of the evacuation behavior [8].
For example, the rules direct an occupant during egress to move to the nearest group. However, Johnson and Feinberg et al. [52] suggest that such an action typically involves various social factors including the character of the relationship between occupants, and with whom they were staying with before the emergency event. If the occupants are with friends, work associates, and family members, and are separated from them during the course of egress, there are high possibilities that the occupants would search for those persons before fully exiting or would even return to the building after exiting [8]. Thus, occupants do not always stick to nearby groups, unless their primary group is not present. The third disadvantage is that MASCM doesn’t include any fire hazard data, which is critical to the decision-marking process and human behaviors. Thus, MASCM is not appropriate to be used for simulations of real fire evacuation scenarios except for the evacuation drills.

2.8 ASERI

ASERI [62 – 63] [49] is an individual-based modeling of egress movement in complex geometries, including behavioral response to smoke and fire spread. In this model, each occupant is treated as an individual person, moving inside the building or whatever other geometrical scenarios may be amenable to egress movement [49]. The external stimuli and limitations due to the movement of other occupants trigger certain behavioral aspects and then govern the individual egress movement. Individual decisions and corresponding behavior may contribute to a delay in starting the evacuation or interrupts, especially in the initial phase of the evacuation process. Furthermore, the choice of the egress path is
strongly influenced by individual characteristics, such as knowledge of the building layout and smoke tolerance.

An attractive feature of ASERI is that the behavioral response can be modeled in a statistical way [49] by performing Monte-Carlo simulations [50]. A number of replicate runs with identical input data are performed and statistically analyzed, yielding not only mean values of egress times but also standard deviations and confidence limits [49]. A similar probabilistic-based feature is also included in this thesis work to accommodate the uncertainty and lack of experimental data on human information processing in fire emergency.

ASERI can calculate the time-dependent temperatures and concentrations of smoke, carbon monoxide (CO), carbon dioxide (CO₂), oxygen (O₂) and hydrogen cyanide (HCN) related to each unit. The ASERI model also calculates the incapacitating effects of exposure to asphyxiating gases and heat using the FED model developed by Purser [9]. The synergetic effects, especially hyperventilation caused by the presence of CO₂, are considered in Purser’s model. In addition, critical concentration thresholds of toxic fire effluents and oxygen are included in ASERI [49]. Considering that short exposure to a high temperature is more incapacitating than a longer exposure to a lower temperature, thermal stress caused by radiated or convected heat can also be expressed in terms of an effective dose [49]. ASERI assigns a time-dependent visibility to each geometry unit to consider the obscuring effects of smoke. Behavioral responses such as reduction of walking speed and certain other attributes are reflected in ASERI. The basic frame of
ASERI for the fire hazard model and behavioral model shows that many behaviors and fire hazard data are easy to incorporate.

The occupants’ movement is defined by the individual walking speed and the orientation of the corresponding velocity vector. The movement algorithm of ASERI ensures that no conflict with walls, obstacles or the movement of other occupants occurs [49]. A continuous network applies a 2-D (continuous) space to the floor plans of the structure, allowing the occupants to walk from one point in space to the other throughout the building. This attribute overcomes the chessboard moving behaviors as EXODUS presents.

The disadvantages of ASERI are: 1) the number of specified levels (floors), units, passages, and obstacles is limited by computer memory; 2) the fire data used for human tenability analysis is not produced by any fire models. Instead, it is defined by users; and 3) although ASERI uses no grid on movement calculation, occupants move sequentially with certain priority rules rather than move simultaneously which a PSO-based movement model is able to achieve.

2.9 CRISP

CRISP is a Monte-Carlo model of entire fire scenarios [42]. The basic structure of CRISP is a two-layer zone model of smoke flow for multiple rooms, coupled with a detailed model of human behavior and movement. CRISP focuses more on Monte-Carlo Simulation for Risk Assessment than modeling the occupants’ evacuation behaviors. The
simulation of the occupants’ movement is captured by applying the fine network model, which divides a floor plan into a number of small grid cells that the occupants move to and from.

The most attractive feature is that this model uses a Monte-Carlo controller to supervise all the physical objects (such as rooms, doors, windows, detectors and alarms, items of furniture, hot smoke layers, and people) for each time step. The Monte-Carlo controller also handles all the inputs and outputs, initialization for each run, and starts each run automatically.

*CRISP* uses a two-layer zone model to simulate the flame spread and smoke movement. The FED [9] hazard assessment is applied as the occupants move around the floor plan. The total risk is expressed simply in terms of the fraction of occupants who end up with the individual FED reaches 1. Then it averages the fraction over a sufficiently large Monte-Carlo sample.

Occupants are assumed to adopt distinct behavioral roles either naturally or due to training. Their behaviors may be abandoned and substituted by new ones, depending on the state of the environment. Rational decisions are made based on current knowledge [42]. In *CRISP*, occupants are able to perform a number of actions (e.g. investigate, warning others, or just staying there) before actually starting to escape.
Thus the best advantage of CRISP is it uses Monte-Carlo controller to handle the potentially complicated features of human behaviors although human decision-making process is not developed. A big disadvantage is CRISP is also using a network model to do the movement calculation, which shows the chess-moving behavior and requires huge calculations when handling large floor plans.

### 2.10 Measured Response

Measured Response is a homeland security exercise scenario, which simulates the effects of a terrorist attack on our critical infrastructure using a weapon of mass destruction, disruption, or effect, and the ability of our government to respond to such an attack [100]. By taking human-agent inputs in response to simulated threats and incidents, Measured Response is able to model a realistic, albeit synthetic, critical incident on a national scale [100]. Measured Response is based on the platform called SEAS, the Synthetic Environment for Analysis and Simulations, is the engine that enables researchers and organizations to experiment with models or techniques in a publicly known, realistically-detailed environment, without the logistical problems associated with actual installation [100].

Based from the SEAS, there are three independent simulations (Fire, Structure, and Agent). The Fire and Structure simulations are based on FDS, the Agent simulation is written in Java [101]. The Agent simulation is directly affected by the results of the fire simulation, and then output to the 3D visualization model. The structure model takes over when the fire has reached the point at which the building will collapse and the agents left
behind are assumed to have perished in the collapse. The Fire simulation uses a 3D city created from 3ds max 6 by discreet company. It takes fire and structure data along with agent locations [100].

The Three independent simulations are combined by a Dynamic Data Driven Application System (DDDAS) [102]. DDDAS consists of three components: the shared reality, the bridges between the members and the members (i.e., the three independent simulations) themselves [102]. DDDAS uses the shared reality engine to exchange information form one simulation to another.

The most attractive feature of Measured Response is it demonstrated vivid 3D visualization of the emergency evacuation simulation scenarios, which intuitively tells users how serious the emergency is and how agents react to the emergency. Inclusion of fire propagation and smoke transportation is another attractive feature. Three critical human behaviors such as avoiding the obstacle, selecting shortest path to the nearest exit, or selecting alternate exits (if the nearest exit is blocked by the fire) are developed by using the two dimensional A* algorithm (shortest path algorithm) [103]. Another good feature is the human tenability analysis is also performed to track the agent’s health declination based on the temperature, carbon monoxide, and carbon dioxide. These advantages make Measured Response a powerful emergency evacuation simulation tool that has great potential.
However, numerous disadvantages have been observed. First, *Measured Response* applies the A* algorithm to calculate movement of agents. This algorithm is also grid-based (or network-based) and thus it has the same advantages as those network-based models such as chess-moving behavior and high computation overhead. Second, although numerous human behaviors are simulated, agents are fed information telling them to do some actions or not to do some actions. I.e., no sophisticated human decision-making analysis is applied to make agents make their decisions (i.e., what action to take) adaptively based on the dynamic emergency environment. Third, agents started moving towards the exits at the time fire started which means the factor of the pre-evacuation time including alarm issues is not taken account. Fourth, due to the nature of the A* algorithm, the distance between the position of an agent and the exit can only be estimated since the exact distance can only be achieved in coordinate-based movement calculation algorithm. Thus the estimation may need modification when a large and complicated floor plan is under investigation due to the accumulated errors.

### 2.11 Summary

In these four state-of-the-art behavioral models discussed above, *MASCM* shows a strong manipulation on simulating group evacuation with evacuation leaders. This feature is usually neglected by most of the advanced evacuation models. Unfortunately, *MASCM* lacks the ability to handle the interaction between the fire environment and the occupants, which invalidates the incorporation of the interactive decision-making process that relates to fire hazards. *EXODUS* demonstrates comprehensive consideration of fire environment, human behaviors and human decision-making. However, *EXODUS* uses the grid-based
movement calculation algorithm which demonstrates unrealistic chess-moving behavior and requires huge calculations based on the size of the grids. The most attractive feature of *ASERI* and *CRISP* is that they incorporate Monte-Carlo simulation to address the randomness in simulation, and perform the statistical analyses for the results to provide a comprehensive perspective on the nature of evacuations. However, *ASERI* does not include any fire models to simulate the physical phenomenon of fire emergency; instead, the fire information is defined by users. Thus the entire simulation results may be easily biased by the defined fire information. *CRISP* has no human decision-making process included. *Measured Response* demonstrated outstanding visualization strength of the simulation results. However, using the grid-based movement calculation algorithm, primitive human behaviors and lack of human decision-making shows a long way ahead for it to go.

Thus, a model which overcomes these listed disadvantages needs to be developed, which will demonstrate attractive features on occupants’ movement method, decision-making process, fire hazard model and human behaviors in fire.
Chapter 3

**Incorporating the Updated Fire Hazard Model into Vacate**

This chapter discusses the methodology developed here to incorporate all updated fire hazard model into *Vacate*. An overview of the current fire hazard model is first presented with a discussion of different aspects of zone fire models and field models, followed by descriptions of some typical models. The differences between zone and field models are also presented. *FDS* [67-68] is selected as the fire model to be used in this research to generate the fire hazard data for *Vacate*. The fire data are loaded into *Vacate* by first converting the fire data saved in slice files format [67] into comma delimited files format [67] using a converter *FRNEW4.exe* written in Fortran 90 [98], then calling MATLAB [99] functions to read the data into *Vacate*. Purser’s [9] Fractional Effective Dose (FED) method is used to assess the human tenability of occupants. Combined hazard effects on occupants of the smoke, heat and toxicity are then considered.

### 3.1 Overview of Current Fire Hazard Models

Fire modeling of a compartment (or one of the rooms of a building under investigation) can be achieved either using empirical equations based on observations from experiments...
or mathematical methods that are commonly divided into two groups: stochastic (probabilistic) and deterministic models [54]. The deterministic models use physical and chemical principles involved in fires. The stochastic models do not make direct use of physical and chemical principles involved in fires, but make statistical predictions about the transition from one stage of fire growth to another [55]. Since in most of the fire evacuation simulation models the fire hazard data are collected from solutions to mathematical equations that describe the physical and chemical behavior of a fire, the deterministic models will be emphasized here.

For simulating the transport of smoke and heat in encloses, there are normally two types of deterministic models: zone models and field models [56]. These models are discussed in details in following sections.

3.1.1 Zone Model

A zone model is a computer model that divides the room(s) in question into different control volumes (or zones) and, for each zone, the physical parameters, such as gas temperature and species concentrations, are assumed to be uniform [56]. Zone models may be grouped into two types based on the number of control volumes (zones) in each compartment: one-zone and two-zone models. The major difference between these models is that the two-zone models split the room(s) into two zones, named an upper hot zone and a lower cold zone, while the one-zone models take the room(s) as one zone. One-zone and two-zone models are widely used in the analysis of post- and pre-flashover
fires, respectively [57]. The one zone modeling concept is developed by Kawagoe [58], who introduced a single-zone approach for analyzing a post-flashover fire. The NRC-fire growth model [59] and the Ozone model are examples of one-zone models [60]. Two-zone models are based on the principle of the conservation of mass and energy as well as the ideal gas law and a set of ordinary differential equations (ODE) were derived [61]. Typical two-zone models for a single compartment include FIRST [62] and ASET [63]. For multi-compartments, CFAST [64] and FIRM [65] are typical models.

The most important advantage of zone models is that they are relatively easy to use and efficient with respect to computer time, in that most models take only several minutes to compute compared with several hours for field models.

One of the disadvantages of zone models is that they cannot accurately take into account re-radiation from the surroundings. The heat release rate is not an output, so tests must be done to quantify the size of the fire that engineers consider adequate for what they want to model.

3.1.2 Field Model

The most sophisticated deterministic models for simulating enclosure fires are termed “field models” or “CFD models” (computational fluid dynamics models) [55]. The rapid growth of computing power and the corresponding maturing of computational fluid dynamics (CFD), has led to the development of CFD-based filed models. The CFD models apply a 3-dimentional grid of elementary control volumes to the enclosure (like
the zone models dividing the enclosure into one zone or two zones), but might have hundreds of thousands of control volumes. CFD models then solve time-dependent differential equations (known as the Navier-Stokes equations [66]), which are based on basic laws of mass, momentum, and energy conservation, for each control volume. The Navier-Stokes equations are only constrained by the boundary surface of the problem, which allows few assumptions and more complex room geometries compared to zone models [56]. Example field models used are: FDS [67-68], JASMINE [70], and CFX [71]. FDS will be described in details later in this chapter, as it has been implemented in this work.

One of the most attractive features of CFD models is that they can be used for such complex geometry as curved walls and unusually shaped buildings. This feature overcomes the need to simplify the building geometry as is usually done in zone models. The other attractive feature of CFD models is that they have a great potential to demonstrate more accurate results with more efficiency, provided that computer power is not a roadblock. Additionally, CFD models are used extensively in other fields such as mechanical and aerospace engineering, which suggests CFD codes might be much more widely tested, developed and verified than the codes for zone models.

There are also several disadvantages of CFD models. First, CFD models usually require a large amount of computing time which is highly related to the number of control volumes. A small increase in the number of the control volumes may lead to a large increase of computing time. Second, although CFD models avoid some major naïve
assumptions made in zone models (e.g., the properties of the upper and lower zones for two-zone models) are assumed to be spatially uniform but vary with time. So, for example, the temperature and mass fraction of species are homogenously distributed in each of the same layer), a certain number of parameters are still based on assumptions. Thus, CFD models must be validated. In the next section, the CFD model *FDS* is described in detail.

### 3.1.3 *FDS*

The *Fire Dynamics Simulator (FDS)* is a fire model that uses the Large Eddy Simulation (LES) technique [68]. *FDS* has been under development for almost 25 years in various forms [67]. *FDS* numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires [67]. *FDS* computes the density, velocity, temperature, pressure and species concentration of the gas in each computational cell (i.e., called small rectangular control volumes) based on the conservation laws of mass, momentum, and energy, to model the movement of fire gases. *FDS* utilizes material properties of the furnishings, walls, floors, and ceilings to simulate fire spread.

The inputs of *FDS* include: the geometry of the building compartments being modeled; computational cell size; location of the ignition source; ignition source; thermal properties of the walls; furnishings and the size and location; and timing of vent openings to the outside which critically influence fire growth; and spread. All the input data is prescribed by writing a small file that uses the *namelist formatted* records [67].
The *FDS* outputs include density, temperature, U-velocity, V-velocity, W-velocity, pressure, heat release per unit volume, mixture fraction, divergence, water mass per unit volume, water vapor, oxygen volume fraction, fuel volume fraction, nitrogen volume fraction, carbon dioxide volume fraction, carbon monoxide volume fraction, soot volume fraction, smoke particulate concentration, extinction coefficient, visibility distance, water mass flux, net radiative flux; convective flux, net heat flux, wall temperature, inner wall temperature, mass loss rate per unit area, pressure coefficient, and water mass per unit area. The outputs can be visualized by *Smokeview* [69], which is also developed by the National Institute of Standards and Technology (NIST). Readers can refer to some figures in reference [69] for more details.

### 3.2 Selecting *FDS* as the Fire Hazard Model for *Vacate*

In this thesis work, more sophisticated human behaviors are simulated in *Vacate*. These include automatically detecting the fire hazards, following the wall in very heavy smoke, heading to other rooms for refuge or gathering personal belongs, etc. Zone models usually require much less computing time while compared to CFD models. However, the major assumption that zone models make (*i.e.*, assuming the fire hazard data to be homogenous in the same layer), is not good enough to simulate the fire hazard environment which is the input to the human tenability assessment model (more specifically, Purser [9]’s FED method). Also, no smoke transportation can be simulated to generate an input for the decision-making process to predict human behaviors such as dodging the smoke barrier. CFD models usually take large amount of computing time,
which makes it almost impossible to generate the fire hazard data on real simulation time steps applied by evacuation programs. For example, ASERI advances the discrete time step by 0.5 second [49] for each simulation. Time is advanced by every 0.05 seconds in Vacate for a much smoother simulation of the occupants’ movement [1]. Thus, the only practical method to incorporate the CFD fire model into the evacuation model is: first, to run the CFD model after setting up the input data according to the evacuation scenario under investigation, and then to input the calculated fire data from the CFD model to Vacate.

In this thesis work, FDS is selected as the fire model used to generate the fire hazard data for Vacate. Comparing FDS with other CFD models, this model has numerous impressive advantages, including: sophisticated CFD codes; comprehensive inputs and outputs; an intuitive visualization tool, and the fact that it is free for downloading from the website of NIST. In human tenability assessment models, since the toxicity gases near the head height of a standing occupant are usually the most dangerous, the slice files that contain the time-dependent fire hazard data (such as the concentration of CO and CO2 at head height) are inputted into Vacate. To minimize the file-loading overhead, only one slice file for each of the fire hazard data categories (e.g., the soot density, temperature, asphyxiant gases and visibility) are inputted into Vacate. Obviously, loading more slice files into Vacate supplies more information to generate more accurate results. However, this impacts the trade-off between accuracy and efficiency of the evacuation simulation due to the limitations on current computer power. In the next section, a brief description of slice files is presented.
3.3 FDS Slice Files

A “slice” refers to a subset of the entire computational domain. It can be a line, plane, or volume [67]. Slice files are one of the FDS output file formats that records the various gas phase quantities for each time step. A complete list of the gas phase quantities can be found in reference [67]. This file format is written out unformatted by a FORTRAN routine dump.f [67], which is programmed to dump the FDS output files into certain formats, such as slice files, PLOT3D files, Boundary files, etc [67]. Since the files are written in an unformatted way to save storage overhead, they are usually difficult to directly read into other software packages. NIST developed a Fortran 90 program called fds2ascii.exe, which can convert slice files into text files (called comma delimited files). These files can be read into a variety of graphics packages [67]. However, fds2ascii.exe can only output the time-averaged data at each grid point rather than output the data at each simulation time step which is considered more useful for Vacate. Thus, the source code of fds2ascii.exe has modified and compiled into frnew4.exe. Features of the outputs of frnew4.exe are explained in the next section.

3.4 Inputting output data from FDS into Vacate

As stated in section 3.2, the approach of inputting the output data from FDS to Vacate can be summarized in two steps: (1) Convert the slice files into text files; and (2) read the text files into Vacate. Obviously, there exists a more efficient way to do the conversion which is to read the slice files into Vacate directly. However, since the slice files are generated by the FORTRAN/Write command, it is then mandatory to use the FORTRAN/Read command to parse the slice files in Visual C++, since Vacate is coded
in Visual C++. Here then comes the problem of mixing FORTRAN code with Visual C++, which could create non-trivial compiling problems. Thus, a feasible approach is to convert the slice files into text files by using the FORTRAN/Read/Write command in a single FORTRAN routine, and then calling the MATLAB [99] built-in function \texttt{csvread()} to read the outputted text files from the FORTRAN routine into \textit{Vacate}. This approach is implemented in this work.

3.4.1 Converting slice files into text files (*.csv files)

This work is done by the program \texttt{frnew4.exe} which is modified from the converter \texttt{fds2ascii.f}. The major task of this program is to parse all the required fire hazard data at desired time step in the format of slice files to text files (which have the extension .csv and can be read by many spreadsheet software packages). The information to be parsed is listed in Table 3.4.1.1 shown as following.
Table 3.4.1.1: Description on information to be parsed

<table>
<thead>
<tr>
<th>Key Items</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slice plane</td>
<td>The slice plane which the sliced file lies on in FDS. There are three basic planes: X-Y, Y-Z, and X-Z in Cartesian coordinates. In this thesis work, the X-Y plane is used as default.</td>
</tr>
<tr>
<td>Size of the time step in the fire model</td>
<td>The size of the time step outputted by FDS (due to the solving mechanism of the time-dependent differential equations, the size of the time step is not constant).</td>
</tr>
<tr>
<td>Number of time steps</td>
<td>The number of time steps in the fire model.</td>
</tr>
<tr>
<td>Total number of array cells</td>
<td>The product of the number of time steps and the grid number in the X coordinate and the grid number in the Y coordinate.</td>
</tr>
<tr>
<td>Sampling factor</td>
<td>Sample the fire data by the specified sampling factor. For example, if 1, input all the data; if 2, sample the data by every two grids, etc.</td>
</tr>
<tr>
<td>Grid number along each coordinate (X or Y)</td>
<td>This parameter is specified by the user as an input of FDS.</td>
</tr>
<tr>
<td>Starting coordinate</td>
<td>Starting coordinate of the computational domain along the current coordinate (X or Y or Z).</td>
</tr>
<tr>
<td>Ending coordinate</td>
<td>Ending coordinate of the computational domain along the current coordinate (X or Y or Z).</td>
</tr>
<tr>
<td>Parsed fire data for each time step</td>
<td>The current solution value at each grid point at each time step of current slice file.</td>
</tr>
<tr>
<td>Maximum value</td>
<td>The maximum value among the current parsed fire data of the current slice file.</td>
</tr>
</tbody>
</table>

To simplify the operation of these parsed data, before they are read into Vacate, the data are listed in the form of a one-dimensional array. The sequence of the time-dependent data (which is in ASCII format) is illustrated in Table 3.4.1.2:

Table 3.4.1.2: The sequence of the time-dependent data for the parsed slice file

<table>
<thead>
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<th>Sampled X-direction Coordinate</th>
<th>Time Step 1</th>
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Time Step n
The fire data of the grid points for each time step are saved into a large array in the sequence shown in Table 3.4.1.2. To save the storage overhead, the coordinates of the sampled data are not read into the *Vacate* but are rather generated by Equation 3.4.1.1 and 3.4.1.2:

\[
X_m = X_1 + m \cdot \left( \frac{X_n - X_1}{TGNX} \right) \quad 3.4.1.1
\]
\[
Y_m = Y_1 + m \cdot \left( \frac{Y_n - Y_1}{TGNY} \right) \quad 3.4.1.2
\]

where:

\(m=\text{Sampling factor}, \ m>2;\)

\(TGNX=\text{Grid number along X coordinate}; \ \text{and}\)

\(TGNY=\text{Grid number along Y coordinate}.\)

### 3.4.2 Reading the *.csv files into *Vacate*

The text files (i.e., comma delimited files) are read into *Vacate* by calling the MATLAB functions in Visual C++ [88]. MATLAB developed a framework that serves as a template [93] for users who are interested in mixing MATLAB with FORTRAN or C++. In the template, the MATLAB built-in function, *csvread()*, actually loads the comma delimited data into memory.

The data are used to assess the time-dependent fire hazard. However, since the data are usually sampled sparsely due to the trade-off between running efficiently and analysis fidelity, the loaded data are not good enough to reflect the fire hazards. To improve this situation as well as to save computational expense, bilinear interpolation [79] of the fire hazard data for each occupant at each desired time step is performed to obtain the
interpolated fire hazard data for each occupant at any arbitrary position in the entire computational domain. A more detailed discussion of Bilinear Interpolation is presented in section 3.6.1. Before performing the Bilinear Interpolation, all the required parameters of the Bilinear Interpolation are prepared from the loaded fire data.

There are two ways to the sampling points by equations 3.4.1.1-3.4.1.2. One way is that the boundaries of the computational domain can be sampled. Thus, the fire hazard data of any points in the domain can be achieved either directly by taking the value of the sampling points or by performing the bilinear interpolation (this case is illustrated in Figure 3.1). The other way is that the boundaries of the computational domain can not be sampled if and only if Equations 3.4.2.1 and 3.4.2.2 are NOT satisfied. This case is illustrated in Figures 3.2 and 3.3. This leads to the Equations 3.4.2.1 and 3.4.2.2, which are shown as following:

\[
TGNX/NSAM = \text{floor} \left( \frac{TGNX}{NSAM} \right); \quad (3.4.2.1)
\]

\[
TGNY/NSAM = \text{floor} \left( \frac{TGNY}{NSAM} \right); \quad (3.4.2.2)
\]

where:

*NSAM*-sampling factor;

*floor (X)*-rounds the elements of $X$ to the nearest integers towards minus infinity; and

All definitions of the other parameters are the same as before.
Figure 3.1: considering the sampling factor (2 here) and boundaries are included

Figure 3.2: considering the sampling factor (2 here) without “boundary correction”
The second case is called the “computational domain lost” in this thesis. The simplest way to solve it is to always include the last points on both the X and Y coordinates, as in the second case illustrated in Figure 3.3 while in the first case, the last points are automatically included. With this approach, in the second case, the size of the last grids of the computational domain will be smaller than the size of the other regular grids, but this is not a problem.

### 3.4.3 Matching the time step in fire model *FDS* with the time step from *Vacate*

The size of the time steps (i.e., the length of each time step) in the *FDS* calculation is constrained by the convective and diffusive transport speeds of fluids via two conditions [68]. The first is known as the Courant-Friedrichs-Lewy (CFL) condition. The second is known as the Von Neumann criterion. The initial time step is normally set automatically by dividing the size of a grid cell by the characteristic velocity of the flow. During the calculation, the time step is adjusted automatically so that the CFL condition is always satisfied. The CFL condition asserts that the solution of the equations can not be updated...
with a time step larger than that allowing a parcel of fluid to cross a grid cell [67]. For more details about the time step configurations, please refer to reference [67]. Thus, the time steps cannot be manipulated as part of the inputs (i.e., the steps are usually not constant). In Vacate, the time step is forwarded every 0.05 seconds. Only if the difference between the two categories of time steps is within a predefined value, then is considered that the time step in Vacate matches the time step in FDS. Vacate uses the matched fire hazard data to assess the human tenability, which is discussed in the next section.

3.5 Human tenability

Human tenability in a fire depends upon the mix of heat and asphyxiant gases to which occupants are exposed, the concentration (or intensity-time curves) for the gases, and the effects upon the occupants. Tenability depends not just on whether an exposure is lethal, but also the extent to which the exposure affects the ability of the occupants to perform those actions necessary for their survival [72]. These exposure effects are also called sub-lethal effects and include:

- Incapacitation (inability to effect one’s own escape);
- Reduced egress speed due to, for example, sensory (eye, lung) irritation, heat or radiation injury, reduced motor capability, and visual obscuration; and
- Choice of a longer egress path due to, for example, decreased mental acuity and visual obscuration [73].
Thus, the hazard effects impact the occupants’ movements both psychologically and physiologically. In this chapter, the physiological effects are discussed. The psychological effects are generally reflected in the decision-making process. This issue will be discussed in Chapter 4.

Purser [9, 72] shows that the hazard effects are generated from the radiant heat, exposure to hot fire effluent (convected heat), optically dense and irritant smoke, and asphyxiant gases. Based on this category, there are four sub models to assess the fire hazards separately: the heat hazard model, the irritant the gas model, the asphyxiant gas model and the smoke obscuration model [74]. The mathematical equations for each of these four models can be found in references [9], [72] and [74]. Since few sets of yield data for large-scale fire tests are available for irritant gases and although smoke and irritant gases are likely to delay and inhibit escape attempts they are unlikely to be the main cause of collapse or death during a fire [9]. In the current thesis work, therefore, the effects of irritant gases are not considered.

3.5.1 Heat hazard model

Exposure to heat may lead to life threat in three ways: hyperthermia; body surface burns; and respiratory tract burns. The respiratory tract burns do not occur from air containing less than 10% by volume water vapor. The respiratory tract burns may occur upon inhalation of air above only 60°C when saturated with water vapor, as may occur when water is used for fire extinguishment [72]. Thus, it is necessary to input the data of temperature and water vapor as well as consider two criteria—the threshold of burning of the skin, and the exposure where hyperthermia is sufficient to cause mental deterioration.
and, therefore, threaten survival. According to Purser’s previous research [9, 72], the respiratory tract burns are considered to happen randomly in the simulation only if the temperature is above 60°C and the air around the occupant is saturated with water vapor. Generally, the tenability limit for the exposure of skin to radiant heat is approximately 2.5 $\text{kw/m}^2$. Below this incident heat flux level, exposure can be tolerated for 30 minutes or longer without significantly affecting the time available for escape [74]. Above the threshold, the time to burning of the skin (assuming it leads to incapacitation) due to radiant heat is given by Equation 3.5.1.1 [9].

$$t_{\text{rad}} = \frac{1.33}{q^{1.33}}$$  \hspace{1cm} (3.5.1.1)

Where

$$t_{\text{rad}} = \text{Incapacitation time (unit: minute)};$$

$q = \text{the radiant heat flux in kw/m}^2 \text{which is calculated by Equation 3.10.2 in reference [1]; and}$

If $q<2.5\text{kw/m}^2$, $t_{\text{rad}}$ tends to be zero.

For exposures to convected heat from air containing less than 10% by volume of water vapor and for unclothed or lightly clothed subjects, the time to incapacitation, $t_{\text{conv}}$, at a temperature, $T$, is given by Equation 3.5.1.2 [75]:

$$t_{\text{conv}} = \frac{5 \times 10^7}{T^{3.4}}$$  \hspace{1cm} (3.5.1.2)

where

$t_{\text{conv}} = \text{the incapacitation time (unit: minute); and}$

$T=\text{temperature in °C which is calculated in FDS}$
The Fractional Effective Dose (FED) method [9] is used to calculate the accumulated “dose” of heat over a period of time during exposure. The FED method can also calculate the fraction of fire hazards such as asphyxiant gases and smoke. The FED value varies from 0 to 1. When the value reaches unity, incapacitation is considered to occur. Considering that the value of \( t_{\text{rad}} \) and \( t_{\text{conv}} \) are time and location dependent, the total fractional effective dose of heat acquired during an exposure can be calculated using Equation 3.5.1.3.

\[
FED_{\text{rad}} = \sum_{k=1}^{n} \left( \frac{1}{t_{\text{rad},k}} + \frac{1}{t_{\text{conv},k}} \right) \Delta t_k
\]  

(3.5.1.3)

where

\[
\Delta t_k = \frac{t_2 - t_1}{n};
\]

\( t_1 = \text{starting time of the simulation, is usually zero; } \)

\( t_2 = \text{ending time of the simulation;} \)

\( \Delta t_k = k^{th} \text{ exposure time increment;} \)

\( n = \text{number of total time steps for the time interval (} t_2 - t_1); \)

\( t_{\text{rad},k} = \text{incapacitation time for heat radiation in } k^{th} \text{ time increment; and } \)

\( t_{\text{conv},k} = \text{incapacitation time for heat convection in } k^{th} \text{ time increment. } \)

### 3.5.2 Asphyxiant gas model

The asphyxiant gases are the main agents responsible for causing intoxication and loss of consciousness in a fire [9]. According to fire history, the best known of the asphyxiant fire gases is CO and is a major reason of incapacitation in many fires. It is also the major
cause of fire deaths, as well as a major cause of long post-exposure neurological health effects [9]. Based on numerous laboratory-scale experiments on materials and on full-scale fire tests, other important asphyxiant gases are hydrogen cyanide (HCN), carbon dioxide (CO₂), and reduced oxygen [9]. They all cause hypoxia of the nervous and cardiovascular systems, resulting in confusion, followed by loss of consciousness, then ultimately by death from asphyxiation [75].

As asphyxiant gases are inhaled during a fire, an accumulated dose builds up in the body. Thus, the FED method again is applied here to assess the hazards from asphyxiant gases. The simplest form is given by Equation 3.5.2.1 [74]:

\[
FED = \sum_{i=1}^{m} \sum_{k=1}^{n} \frac{C_i \cdot \Delta t_k}{(C \cdot t)_i} \quad (3.5.2.1)
\]

Where,

\(C_i=\text{the average concentration in ppm of an asphyxiant gas “i” over the chosen time increment } \Delta t_k;\)

\((C \cdot t)_i=\text{the specific exposure dose in ppm·min that would prevent occupants’ safe escape; and}\)

\(m=\text{number of asphyxiant gas species.}\)

As with heat effects, when the FED value reaches unity, incapacitation is considered to occur. Among the four asphyxiant gases, CO and HCN are the only two asphyxiant gases that play a significant role on the time available for escape. The reduced oxygen can also produce asphyxiation, but its consideration is not required as long as O₂ concentrations do
not fall below 13% [9]. The CO₂ does not have significant narcotic effect until its concentration exceeds 2% by volume [74]. Since the concentration of HCN cannot be calculated by FDS, it is not included in this thesis work. Therefore, a detailed form of Equation 3.5.2.1 is shown as Equation 3.5.2.2 [74]:

\[
FED = \sum_{k=1}^{n} \frac{[CO]_k}{35000 \text{ ppm} \cdot \text{min}} \Delta t_k \quad (3.5.2.2)
\]

Where,

\([CO]_k = \text{the CO concentration (ppm) in } k^{th} \text{ time increment } \Delta t_k\).

In cases where the CO₂ concentration exceeds 2% by volume, the concentration term, [CO] in Equation 3.5.2.2 at each time increment, shall be multiplied by a frequency factor, \(V_{CO_2}\), to allow for the increased rate of asphyxiating uptake due to hyperventilation [75]. The equation is given as shown below [75].

\[
V_{CO_2} = \exp\left[\frac{\%CO_2}{5}\right] \quad (3.5.2.3)
\]

If the O₂ concentrations fall below 13%, the fraction of an incapacitating dose of low oxygen hypoxia is given by Equation 3.5.2.4 [75].

\[
FED_{IO} = \sum_{k=1}^{n} \frac{\Delta t_k}{\exp[8.13 - 0.54 \cdot (20.9 - \%O_2)]_k} \quad (3.5.2.4)
\]

The term \(FED_{IO}\) is added to Equation 3.5.2.2, for a total FED

3.5.3 Smoke obscuration model

The fundamental research on smoke effects was done by Jin [76]. The research shows that optically dense smoke affects exit choice and escape decisions, as well as wayfinding ability and the speed of movement of the occupants. These effects depend upon the
smoke density, light extinction coefficient [67], irritancy to the eyes, and upper respiratory tract [9]. The detailed psychological effects, such as the wayfinding ability, exit choice, and escape decisions due to the smoke, will be discussed in the decision-making part of chapter 4. The physiological effects are reflected on the speed of movement of occupants only in this thesis work. Purser [9, 75] realized the complications of setting up the tenability limits of smoke, and suggested the appropriate limits will depend on the building and occupant characteristics [9]. For example, for small spaces with short travel distances to exits, it may be possible to set less stringent tenability limits if the occupants are familiar with the building. For large spaces, it may be necessary to set more stringent tenability limits, particularly if occupants are likely to be unfamiliar with the building and need to be able to see much further in order to orient themselves to find exits [9]. Other factors to be taken into consideration would be the complexity of the space, the lighting, and the visibility of the signage [9]. Although these considerations are correct, no quantitative relationships between the tenability limits and these various factors are available due to lack of large amount of relative experiments. Purser [9] developed a concept of the Fractional Effective Concentration (FEC) method to assess the visual obscuration effects of smoke. Similar to the FED method, if the total FEC value reaches unity, then the effect of the visual obscuration would be sufficient to seriously impact escape attempts which means the moving speed of the occupants starts decreasing. The FEC relationship is given by Equations 3.5.3.1 and 3.5.3.2[9]:

\[
FEC_{smoke} = \frac{[OD \ m^{-1}]}{0.2}
\]

(3.5.3.1)

\[
FEC_{smoke} = \frac{[OD \ m^{-1}]}{0.1}
\]

(3.5.3.2)

where,
$[OD \ m^{-1}] = \text{the concentration (optical density) of the smoke;}$

*Equation 3.5.3.1 is for small enclosures; and*

*Equation 3.5.3.2 is for large enclosures.*

*FDS* calculates the visibility distance by Equation 3.5.3.3:

$$S = \frac{C}{K} \quad (3.5.3.3)$$

where,

$C = \text{a non-dimensional constant characteristic of the type of object being viewed through the smoke, i.e. } C = 8 \text{ for a light-emitting sign and } C = 3 \text{ for a light-reflecting sign} [77]$;

$K = \text{the light extinction coefficient, is a product of the density of smoke particulate, } \rho \ Y_s, \text{ and a mass specific extinction coefficient, } K_m, \text{ that is fuel dependent; and}$

$S = \text{the visibility distance in unit: m.}$

According to Purser’s research [9], the tenability limit of 0.2 m$^{-1}$ in quantity of optical density is equivalent to 5 meters in quantity of visibility distance. Since the enclosures investigated in *FDS* are usually small, Equation 3.5.3.1 is modified to Equation 3.5.3.4, which is used in *Vacate*, as follows:

$$FEV_{\text{smoke}} = 1 - S / 5, \text{ when } s \leq 5 \quad (3.5.3.4)$$

where,

$FEV_{\text{smoke}} = \text{Fractional Effective Visibility.}$

Thus, if $FEV_{\text{smoke}}$ reaches unity (i.e., the occupant can hardly see anything around) he will move very slowly. However, as illustrated above, the real fire scenario is usually much more complicated and this tenability limit has very limited accuracy. To overcome this
problem, one practical way is to introduce probabilistic factors into Equation 3.5.3.4. For example, when $FEV_{\text{smoke}}$ reaches unity, $\text{rand}(\ )$ can be used to generate a random number $r$ between 0 and 1. If the number is less than a threshold (in the current thesis work, the value is 0.15), the occupants would not move very slowly. On the contrary, if the number is between 0.15 and 1, people would move very slowly. If occupants see other occupants, they could communicate with them, follow them, and are more likely to keep the current moving speed unchanged. Thus, the final effect from the obscuration by smoke should be decided by considering if occupants detect other occupants nearby or not. In the current thesis work, if there is any occupant within a distance of 2 meters away from the occupant, the smoke is assumed to have no effects on him.

3.5.4 Combined hazard effects of the smoke, heat and asphyxiant gases

The hazard effects of the smoke, heat, and asphyxiant gases produced from the fire are modeled separately in all previous research. However, it is obvious that in a real fire environment, the hazard effects act on occupants simultaneously and would have come combined effect. Certain interactions among these hazard effects may exist. For example, if the smoke is irritant as well as with obscuration, this may disturb breathing patterns and cause bronchoconstriction and alteration of lung ventilation/perfusion ratios [75]. These effects can impair gas exchange in the lungs, resulting in further asphyxiant effects that might be considered potentially additive with the effects of inhaled asphyxiant gases. On the other hand, effects of irritants on respiration may also reduce the rate of uptake of inhaled asphyxiant gases [74]. The heat effects can also interact with the asphyxiant effects in a similar way. The ISO/DTS 13571 [74] declares that these interactions are
considered to be relatively minor compared to the primary effects of the individual components. However, the reality is there is insufficient research investigating the potential relationships within the fire hazard interactions. Hence, this issue is an important one that may bring the computer fire evacuation simulation models into the next generation. Similarly, Purser [9, 75] considers the smoke, heat, and asphyxiant effects individually when assessing if the conditions that lead to incapacitation are satisfied. These three kinds of hazard effects are assessed in parallel to see which one reaches unity first when analyzing a particular simulation case. This approach has two disadvantages. First, the predicted results may deviate from the reality severely because of not considering the combined effects of heat, smoke and asphyxiant gases. Second, if the entire evacuation process is to be simulated (which is the objective of this thesis research), rather than obtaining only the final solution, then the combined hazard effects on occupants at interim time steps can not be achieved. To be more specific, if all three hazard effects can impact the moving speed of occupants in the fire environment, what is the overall impairment to the moving speed? Similarly, what is the overall effect on the occupants’ exit choices and the human information process during the evacuation?

In the current thesis work, the physiological effects from combined fire hazards are modeled to reflect impact on the variation of the moving speed of the occupants. The impairment to the moving speed is given by Equation 3.5.4.1—3.5.4.4 [1] as follows:

\[
FED_{overall} = \sum_{k=1}^{n} \left( \frac{1}{t_{rad,k}} + \frac{1}{t_{conv,k}} + \frac{[CO]_k \cdot \exp \left( \frac{\%CO_2}_k \right)}{35000 \text{ ppm} \cdot \text{min}} \right) \Delta t_k + FED_{IO} + FEV_{smoke}
\]

(3.5.4.1)
\[ FEV_{\text{smoke}} = (1 - S_t / 5) \quad (S_t \leq 5) \]  \hspace{1cm} (3.5.4.2)

\[ \text{Occupant}.v_x = (1 - \text{FED}_{\text{overall}}) \times \text{occupant}.v_{\text{max}} \times x_t \]  \hspace{1cm} (3.5.4.3)

\[ \text{Occupant}.v_y = (1 - \text{FED}_{\text{overall}}) \times \text{occupant}.v_{\text{max}} \times y_t \]  \hspace{1cm} (3.5.4.4)

where,

35000 ppm·min = the incapacitation dose for CO;

\( S_t \) = the visibility distance in unit: m for each time step to read in the fire data;

If \( S_t > 5 \), or a random number \( r_t \) is less than 0.15, or there is any other occupant within 2 meters away from the current one, \( FEV_{\text{smoke}} = 0 \), the movement speed is assumed not impaired although s/he is surrounded by heavy smoke;

If the CO2 concentration does not exceed 2% by volume, the term of \( \exp \left( \frac{\%CO_2}{5} \right) \) is 1;

\( \text{FED}_{\text{IO}} = 0 \) if the O2 concentrations do not fall below 13% during the certain exposure time \( \Delta t_k \);

\( \text{Occupant}.v_x = \) x component of the final velocity of the occupant;

\( \text{Occupant}.v_y = \) y component of the final velocity of the occupant;

\( \text{Occupant}.v_{\text{max}} = \) maximum unimpeded velocity of the occupant;

\( x_t = \) x-component of the resultant drive;

\( y_t = \) y-component of the resultant drive; and

The definitions of other symbols remain unchanged as before.

The means of deriving a realistic model of the combined hazard effects, rather than using simple superposition subjects, is a critical research topic, but is quite beyond the current scope of this thesis work. The threshold of \( r_t \) (0.15 is in this research) must also be
investigated. At this point, however, these models developed in this work represent greater sophistication than all others presently in use.

The psychological effects due to the combined fire hazards are reflected on the variation of the decision-making process and human behaviors which will be discussed in chapter 4.

3.6 Getting the fire data for any occupant at the arbitrary position

The loaded time-dependent fire data, \textit{i.e.} the density, temperature, concentration of CO, CO$_2$, etc. are node values for each of the sampling points. If the position of an occupant does not match the position of a sampling point, the fire data at that position is not available. However, it is necessary to have the fire hazard information for each occupant at any arbitrary positions during the simulation. The easiest approach is to apply the fire solution value of the nearest sampling point around the current position on the current position. Figure 3.4 shows this approach. However, if the grids are very sparse, the approximation may be not suitable. Another disadvantage is that by doing this approximation we lost the information of other vicinal sampling points. For example, since the \textit{FDS} lays 2-D rectangular grids for the entire computational domain, if only the nearest sampling point is used, fire data of other three sampling points are lost.
Alternatively, bilinear interpolation can be used, which takes advantage of multiple data to obtain more accurate fire data, as shown in Figure 3.5.
Figure 3.5: Evaluating the fire hazard data based on the nearest 4 sampling points or 2 points (in case if the arbitrary point is right on the boundary)

The selected sampling points serve as the inputs of the bilinear interpolation to generate more reasonable fire data. Bilinear interpolation is discussed in details in next section.

3.6.1 Bilinear interpolation

Linear Interpolation [78-79] is the simplest way among numerical interpolation methods of getting values at positions between sampling points. Comparing to other interpolation methods, such as the Cubic Spline Interpolation method or Polynomial Interpolation method, it has the lowest fidelity of the interpolated data. However, while doing the fire hazard assessment, high fidelity of the fire data is not required. Thus, for the slice files generated by *FDS*, bilinear interpolation (also called Linear Interpolation for 2-D space)
is applied. The mathematical model for bilinear interpolation is given by equation 3.6.1.1-3.6.1.7 as follows:

\[ L(u,v) = \sum_{i,j} f(u_i,v_j) \cdot B(u-u_i) \cdot B(v-v_j) \]  \hspace{1cm} (3.6.1.1)

\[ B(u-u_i) = (1 - \frac{|u-u_i|}{d_u}) \]  \hspace{1cm} (3.6.1.2)

\[ B(v-v_i) = (1 - \frac{|v-v_i|}{d_v}) \]  \hspace{1cm} (3.6.1.3)

\[ d_u = u_i - u_{i-1} \hspace{1cm} (u_{i-1} < u < u_i) \]  \hspace{1cm} (3.6.1.4)

\[ d_u = u_{i+1} - u_i \hspace{1cm} (u_i < u < u_{i+1}) \]  \hspace{1cm} (3.6.1.5)

\[ d_v = v_i - v_{i-1} \hspace{1cm} (v_{i-1} < v < v_i) \]  \hspace{1cm} (3.6.1.6)

\[ d_v = v_{i+1} - v_i \hspace{1cm} (v_i < v < v_{i+1}) \]  \hspace{1cm} (3.6.1.7)

where,

- \( L(u,v) \) = the interpolated fire solution value which has the coordinate \((u,v)\);
- \( f(u_i,v_j) \) = the fire hazard value at the sampling point (or called control point) which has the coordinate \((u_i,v_j)\), serves as the weight parameter of the interpolation;
- \( B(u-u_i) \) = the basic function on X coordinate;
- \( B(v-v_i) \) = the basic function on Y coordinate;
- \( d_u \) = the distance of two control points next to each other along X coordinate;
- \( d_u > 0 \);
- \( d_v \) = the distance of two control points next to each other along Y coordinate; and
Based on these equations, at every simulation time step in Vacate, the nearest control points around the location of the occupant are detected and, if necessary (i.e., the position of the occupant is not right on one of the sampling points or boundaries), bilinear Interpolation is performed.

However, one thing we should be careful about is when some of the sampling points are out of the current region where the occupant is. Values at those sampling points should be set to zero because regions (or rooms) are separated by walls which create the discontinuity of the fire data.

In the next chapter, critical human behaviors observed in real fire scenarios will be discussed in detail.
Chapter 4

*Human behavior in fire*

The modeling of human behavior and prediction of human responses in a fire situation is one of the most complex areas of fire protection engineering [2]. Incomplete or cursory attention to the human behavior in an evacuation scenario can result in misleading, overestimated, or underestimated evacuation times, which is obviously the primary goal of an evacuation simulation [2]. There is limited understanding and acknowledged uncertainty related to human behavior, which is affected by many factors including occupant characteristics, the fire environment, and building characteristics. Furthermore, the interactions between these factors, such as the fire fighting behavior changing the fire environment, fire blocking the exits, and the case of an alarm system waking up some sleeping occupants, that make human behavior more unpredictable. Thus, to precisely simulate the human response and behavior in evacuation scenarios at this stage is almost impossible. However, existing literatures and research results have identified some human behaviors that have critical effects on the evacuation times (such as following the evacuation leader, heading back to a previous region, wandering in heavy smoke, etc.) and are therefore mandatory to be represented even though the precise solutions may never be achieved.
The entire simulation process of human behaviors in fire can be illustrated as a multi-input, multi-output system. The inputs are occupants’ characteristics, building characteristics, and the fire environment. The outputs are the human response to cues (or the pre-evacuation time), evacuation modes (e.g., group evacuation, single evacuation, or stay in the region, etc.), behaviors (e.g., the wall-following behavior in heavy smoke, helping others, etc.), and the moving speed of the occupants. Inputs are processed by the Information Processing Model to get the outputs. Outputs are then visually presented by Vacate. The system is illustrated briefly in Figure 4.1.

The Information Processing Model includes 3 sub-models as follows: 1) the pre-evacuation time calculation; 2) the decision-making; and 3) the moving-speed calculation. The decision-making is called at each decision-making time step, which is different from the simulation time step (\(\Delta t = 0.05\) second). The moving-speed calculation model is called at each simulation time step to generate three outputs.

![Figure 4.1: the Human Behavior System](image-url)
(Evacuation modes and Critical human behaviors and Moving speed) separately. The pre-evacuation time calculation is only evaluated once to get the calculated pre-evacuation time for each occupant before the start of the evacuation simulation. In next sections, the inputs, information processing model and outputs will be discussed in detail.

4.1 Input of the Human Behavior System

The inputs are occupants’ characteristics, building characteristics, and the fire environment, which are considered to be the critical factors that influence the simulation results [2]. Detailed information regarding these factors is provided in the following subsections.

4.1.1 Occupants’ characteristics

Occupant characteristics includes, but are not limited to, gender, age, physical capabilities, sensory capabilities, familiarity with the building, past experience and knowledge of fire emergencies, social and cultural roles, presence of others, and commitment to activities [2]. As demonstrated before, in the real fire scenarios, maybe there are more occupants’ characteristics involved and the interactions between these characteristics are rather complicated. Also, since two different characteristics may affect the same behavior, it is difficult to develop a precise mathematical model to describe the relationship between characteristics and the affected behaviors. For example, with respect to gender difference, many researchers [80-83] have pointed out that in a fire emergency, females are more likely to alert or warn others, gather family members, take protective
actions and evacuate in response to fire cues than males, while males are more likely to fight the fire, and take a re-entry behavior in residential fires to serve in the role of the protectors of the families. However, these studies also found these gender differences may actually be due to the different social roles. In the Project People II final report [84], the study group was largely made up of women, and the predominant occupation among the participants was nursing. The protective actions taken by the women in the study may have been a reflection of their role as nurses (and caregivers) rather than their gender. This shows the effects of gender and social roles can be mixed in real fire scenarios. Future studies are needed to help differentiate the influence of gender and social roles.

Therefore, in the current work, only critical characteristics are selected and some relatively less important characteristics are not included. Table 4.1.1.1 summarizes the critical occupant characteristics and the affected outputs.
Table 4.1.1: the Critical Occupant Characteristics & the Affected Outputs

<table>
<thead>
<tr>
<th>Occupant Characteristics</th>
<th>Affected Outputs and factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population number, density Location and distribution</td>
<td>1. moving speed (this is incorporated in PSO)</td>
</tr>
<tr>
<td></td>
<td>1. possibility of returning (entering other rooms) or continue heading to the exit</td>
</tr>
<tr>
<td></td>
<td>2. possibility of following the crowd or taking the route with minimum fire hazards</td>
</tr>
<tr>
<td></td>
<td>3. possibility of taking the group evacuation or being the leader in group evacuation</td>
</tr>
<tr>
<td>Familiarity with the building</td>
<td>1. possibility of taking the group evacuation or being the leader in group evacuation</td>
</tr>
<tr>
<td></td>
<td>2. pre-evacuation time</td>
</tr>
<tr>
<td>Activity (or alertness)</td>
<td>1. pre-evacuation time</td>
</tr>
<tr>
<td>Commitment role and responsibility (e.g., staff or not staff)</td>
<td>1. possibility of taking the group evacuation or being the leader in group evacuation</td>
</tr>
<tr>
<td></td>
<td>2. pre-evacuation time</td>
</tr>
<tr>
<td>Physical ability (non-disabled or disabled)</td>
<td>1. moving speed</td>
</tr>
<tr>
<td></td>
<td>2. pre-evacuation time</td>
</tr>
<tr>
<td>Social affiliation</td>
<td>1. possibility of taking the group evacuation</td>
</tr>
<tr>
<td></td>
<td>2. moving speed (in group evacuation, need to consider other occupants’ moving speed in the same group)</td>
</tr>
<tr>
<td>Occupants’ health condition (changes dynamically due to the fire hazard effects)</td>
<td>1. moving speed</td>
</tr>
<tr>
<td>Gender</td>
<td>1. moving speed</td>
</tr>
<tr>
<td></td>
<td>2. possibility of returning (entering other rooms) or continue heading to the exit</td>
</tr>
<tr>
<td>Age</td>
<td>1. moving speed</td>
</tr>
<tr>
<td></td>
<td>2. ability to withstand the exposure to fire byproducts (toxicity gases)</td>
</tr>
</tbody>
</table>

4.1.2 Building characteristics

The responses and behaviors of occupants during fire emergencies can be influenced to a small or great extent by the various building characteristics [2]. In Vacate, the number and location of exits are already quantified and their effects on occupants’ behavior (or specifically, the behavior of selecting evacuation exits) are reflected in the objective functions [1]. In the current work, to generate the average pre-evacuation time, the
building type—public (i.e., school, mall, office, etc) or private (i.e., apartment, townhouse, etc), is predefined before the simulation. The activation time for the alarm is also predefined with either a fixed or random value (detailed information provided in Section 4.3.1). Other building characteristics, such as the exit facilities, signs, and lighting system, can also be quantified. However the effects of these characteristics are difficult to be evaluated. For example, each occupant has his own understanding of the signs (although the signs are usually marked intuitively) and the brightness of the building lights in fire scenarios differs, so each occupant will respond to the hazards differently. Because the relevant experimental data are not available currently, only building types and alarm are included in this thesis work.

4.1.3 Fire environment

The fire environment actually has a tremendous impact on different evacuation modes and human behaviors. For example, it is more likely that the occupant returns to the previous region (or room) in a heavy fire hazard than in a light fire. The human tenability assessment of the occupants was made in Chapter 3 by using the FED method, and its effect is reflected on the moving speed of occupants. Based on the severity of the fire hazards, there are four categories: 1) no fire hazard, 2) small fire hazard, 3) medium fire hazard, and 4) severe fire hazard. These are used as the inputs to the decision-making process. Three physical quantities, (heat flux, temperature, and visibility) are used to classify the four different fire hazard severities. Three thresholds for each physical quantity are defined as the criteria for classifying the fire hazards.
For the quantity of heat flux, there are 3 thresholds: 2.5 \( \text{[9]} \), 1.5, and 0.5 \( \text{kw/m}^2 \). The severity of heat flux is classified as follows:

- Severe heat flux (the heat flux is over 2.5\( \text{kw/m}^2 \));
- Medium heat flux (the heat flux is less than 2.5\( \text{kw/m}^2 \), but larger than 1.5\( \text{kw/m}^2 \));
- Small heat flux (the heat flux is less than 1.5\( \text{kw/m}^2 \), but larger than 0.5\( \text{kw/m}^2 \)); and
- Effect of heat flux is negligible (the heat flux is less than 0.5\( \text{kw/m}^2 \)).

For the quantity of temperature, there are 3 thresholds (37, 40, \( 45^\circ \text{C} \)) which are summarized and modified from reference [96]. Different temperatures are classified as follows:

- Very high temperature (the temperature is over \( 45^\circ \text{C} \));
- High temperature (the temperature is less than \( 45^\circ \text{C} \), but larger than \( 40^\circ \text{C} \));
- Non-comfortable temperature (the temperature is less than \( 40^\circ \text{C} \), but larger than \( 37^\circ \text{C} \)); and
- Proper temperature (the temperature is less than \( 37^\circ \text{C} \)).

For the quantity of visibility, there are 3 thresholds (5, 10, 15 meters) that are summarized and modified from references [2], and [81]. Different visibilities are classified as follows:

- Very bad visibility (the visible distance is less than 5 meters);
- Bad visibility (the visible distance is less than 10 meters, but greater than 5 meters);
• Impaired visibility (the visible distance is less than 15 meters, but greater than 10 meters); and

• Unimpaired visibility (the visible distance is greater than 15 meters).

With these thresholds, Table 4.1.3.1 shows the conditions used to classify the fire hazard severity:

Table 4.1.3.1: the classified fire hazard

<table>
<thead>
<tr>
<th>Conditions to assess the hazard severity</th>
<th>Fire hazard severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>If the occupant meets very bad visibility, or very high temperature, or severe heat flux, or detects the fire pool directly</td>
<td>4—strong fire hazards</td>
</tr>
<tr>
<td>If the occupant meets bad visibility, or high temperature, or medium heat flux</td>
<td>3—medium fire hazards</td>
</tr>
<tr>
<td>If the occupant meets impaired visibility, or non-comfortable temperature, or small heat flux</td>
<td>2—small fire hazards</td>
</tr>
<tr>
<td>otherwise</td>
<td>1—no fire hazards</td>
</tr>
</tbody>
</table>

The function of assessing the fire hazard severity is called at each simulation time step to get the updated results ready to be inputted into the Information Process Model.
4.2 Output of the Human Behavior System

Three main outputs are shown in Figure 4.1 including Human response to fire, Evacuation modes and critical human behaviors, and Moving speed. The Human response to fire is quantified by the pre-evacuation time. The Moving speed itself is the output. The Evacuation modes and critical human behaviors include:

1) 3 basic evacuation modes:
   - Staying in the current region, which is represented by random walking behavior;
   - Taking single evacuation (**i.e.**, not following a leader);
   - Taking group evacuation (**i.e.**, following a leader);

2) 6 Critical human behaviors:
   - Heading to other rooms for refuge;
   - Going back to the previous region;
   - Taking the route with the minimum fire hazards when the occupant is familiar with the current building environment;
   - Following the crowd when the occupant is not familiar with the current building environment;
   - Wandering around in the extreme heavy smoke;
   - Heading to the wall and moving along it in the extreme heavy smoke.

Several basic human behaviors such as obstacle avoidance, separation, queuing and overtaking behavior, avoiding fire source, staying within walls, helping disabled occupants are also simulated based upon our previous work [1].
4.3 Information Processing Model

This model functions to predict the pre-evacuation time, evacuation modes and human behaviors and the dynamic moving speed of occupants in the fire emergency based on the input of the occupants’ characteristics, building characteristics, and the fire environment. All three sub-models (the pre-evacuation time calculation, the decision-making, and the moving-speed calculation) are constructed by applying the *if-then-else* rational analysis. Since there is high uncertainty or randomness in the information processing (especially decision-making) of occupants while the fire hazard is not apparent (*e.g.*, either a small fire hazard or medium fire hazard), the probability of taking different evacuation modes or alternate human behaviors should be considered. For example, assume there are two exits for a room, where one is a regular exit and the other one is an emergency exit. When an occupant sees the smoke is coming into the room via the most familiar exit, the occupant may still want to evacuate from the familiar exit instead of the emergency one, but with a less probability than in the scenario in which no fire hazards are present around the regular exit. In the same case, if the fire hazard is heavy and the regular exit is blocked, then the occupants must evacuate from the emergency exit, which means the probability of heading to the regular exits is zero. By applying a probability method in the current model, more dispersed simulation results can be generated with more runs of the current simulations. The distribution pattern of the evacuation time can be statistically evaluated. This approach will be presented in detail in Chapter 6.
4.3.1 The pre-evacuation time calculation model

This model calculates the pre-evacuation time at the beginning of the simulation. The pre-evacuation time is the time period before the occupants start to evacuate from the current region when hearing the alarm signal or perceiving some smoke. This time period includes the alarm activation time, the fire hazards detection time, and investigation time. Some references [83, 85-86] have shown that there are usually delays (also called the summation of the fire hazards detection time and investigation time) before deciding to evacuate, the time is spent on looking for others of gathering personal items, as well as in attempts made to move toward the fire and fire fighting, which have been observed repeatedly. In current thesis work, all of these behaviors associated with pre-evacuation time are represented by random walking behavior, which is described in details in section 4.3.2.2. The total evacuation time for each occupant is calculated as follows:

\[ t_{\text{evac}} = t_{\text{pre-evac}} + t_{\text{travel}} \]  

(4.3.1.1)

where,

\( t_{\text{evac}} \) = total evacuation time;

\( t_{\text{pre-evac}} \) = pre-evacuation time; and

\( t_{\text{travel}} \) = travel time.

The pre-evacuation time is defined as follows:

\[ t_{\text{pre-evac}} = t_{\text{alarm}} + t_{\text{fd}} + t_{\text{inv}} \]  

(4.3.1.2)

where,

\( t_{\text{alarm}} \) = alarm activation time;
$t_{fd} =$ fire hazard detection time; and $t_{inv} =$ investigation time.

For convenience and simplification, we define the summation of $t_{fd} + t_{inv}$ as $t_{delay}$, the delay time.

The delay time is affected by the occupants' characteristics, building characteristics, and fire hazards. Table 4.1.1 lists the occupants’ characteristics affecting the delay time. These are activity, commitment (or role or responsibility), and physical ability. To simplify the model, only one of the building characteristics is considered to affect the pre-evacuation time. This is the type of buildings that is on fire—a public place (mall, museum, factory, etc) or a private place (house, apartment, etc). In a public building, visitors do not assume the responsibility to initiate adaptive behavior when the fire alarm is activated; they expect that they will receive information from staff or a figure of authority if the alarm is for a valid threat. In a single-family house, occupants tend to respond right away when the smoke alarm activates because they know they are responsible to investigate and initiate adaptive action [2]. The impact from fire hazards, however, is the most important one since it terminates the pre-evacuation time and most effectively triggers the evacuation. Thus, if the occupant detects any fire hazards, he starts evacuate immediately.

The probability method is applied here to accommodate the essential complication and uncertainty of estimating the delay time. This is given by Equation 4.3.1.3 as follows:

$$t_{delay} = t_{av} + \Delta t_{ac} + \Delta t_{ph} \quad (4.3.1.3)$$
where,

\[ t_{av} = \text{the average pre-evacuation time according to building type (public or private)}; \]

\[ \Delta t_{ac} = \text{the effect of activity (or alertness) on pre-evacuation time}; \]

\[ \Delta t_{ph} = \text{the effect of physical ability on pre-evacuation time}; \]

And all of these parameters are in unit: second

Note that the delay time is defined randomly from 0-2 seconds instead of using Equation 4.3.1.3 in the following situations: \( t_{delay} < 0 \), or the occupant detects any fire hazards, or the occupant is an evacuation leader, or s/he’s in an evacuation group.

Parameters \( t_{av} \), \( \Delta t_{ac} \), and \( \Delta t_{ph} \) are determined with pre-defined values with randomness. Due to the lack of experimental data, these values are empirical. They could be replaced if more experimental data are available in the future. Tables 4.3.1.1-4.3.1.3 show the values of various parameters with the corresponding probabilities.

### Table 4.3.1.1: The average delay time

<table>
<thead>
<tr>
<th>Building Type</th>
<th>( t_{av} ) (unit: second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public</td>
<td>40 or defined by user</td>
</tr>
<tr>
<td>Private</td>
<td>20 or defined by user</td>
</tr>
</tbody>
</table>

As illustrated above, the occupants are assumed to respond faster to the fire emergency when they are in private buildings (such as a house, apartment rooms, etc.) than in public buildings.
Table 4.3.1.2: The effect of activity (or alertness) on delay time

<table>
<thead>
<tr>
<th>Activities</th>
<th>Threshold $T_{ac}$</th>
<th>Random Number $r_{ac}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r_{ac} \leq T_{ac}$</td>
<td>$r_{ac} &gt; T_{ac}$</td>
</tr>
<tr>
<td></td>
<td>$\Delta t_{ac}$ (unit: second)</td>
<td></td>
</tr>
<tr>
<td>Sleeping (and there are no other occupants in the same region)</td>
<td>0.20</td>
<td>0</td>
</tr>
<tr>
<td>Sleeping (and there are other occupants in the same region)</td>
<td>0.50</td>
<td>+10</td>
</tr>
<tr>
<td>Non-sleeping</td>
<td>0.50</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.3.1.3: The effect of physical ability on delay time

<table>
<thead>
<tr>
<th>Physical ability</th>
<th>Threshold $T_{ph}$</th>
<th>Random Number $r_{ph}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r_{ph} \leq T_{ph}$</td>
<td>$r_{ph} &gt; T_{ph}$</td>
</tr>
<tr>
<td></td>
<td>$\Delta t_{ph}$ (unit: second)</td>
<td></td>
</tr>
<tr>
<td>Non-disabled</td>
<td>0.10</td>
<td>+10</td>
</tr>
<tr>
<td>Disabled</td>
<td>0.10</td>
<td>+10</td>
</tr>
</tbody>
</table>

In Table 4.3.1.2, we assume that if the occupant is not the only person in the room, and he is sleeping, other occupants around are supposed to wake him up (with randomness applied, the pre-defined values are 10 or 20 seconds, respectively). Again, these pre-defined values are subjected to further research and could be changed if they are found to be not practical.

4.3.2 The decision-making model

This model is used to simulate the human decision-making process in fire scenarios. The decision-making process happens during the pre-evacuation time as the cues for the fire hazards have been detected and validated. This process is also difficult to be simulated...
since it is essentially a complicated psychological process subject to the inputs of the occupant characteristics, building characteristics and the fire environment. The \textit{if-then-else} approach is applied here to serve as the routine to predict the evacuation modes and behaviors. To accommodate the randomness and uncertainty of the process, the probability factors are also included. The decision-making process includes two parts: 1) to predict three basic evacuation modes (listed in Section 4.1); 2) to predict six critical human behaviors (listed in Section 4.1).

\subsection*{4.3.2.1 Predicting basic evacuation modes}

The three basic evacuation modes are as follows:

\begin{itemize}
  \item Staying in the current region, which is presented by random walking behavior;
  \item Taking single evacuation (\textit{i.e.}, evacuating alone); and
  \item Taking group evacuation (\textit{i.e.}, following the leader).
\end{itemize}

In \textit{Vacate}, before calling the functions for predicting the single/group evacuation, or predicting if the occupant is going to stay in the current region or not, the information about the occupants’ characteristics, building characteristics, and the fire environment is introduced with randomness and serves as the inputs for the decision-making model. The fire hazards detecting model is discussed later in this chapter. The predicting process is illustrated with flowcharts shown in Figures 4.2-4.4.
Figure 4.2: Predicting to take the group/single evacuation
Figure 4.2 shows the process required to obtain the predicted results for each occupant on its decision to engage in group evacuation or single evacuation. Two thresholds $T_1$, and $T_2$, are shown as in Table 4.3.2.1.1.

*Table 4.3.2.1.1: Four possible values of $T_1$ and $T_2$ according to the severity of the fire hazards*

<table>
<thead>
<tr>
<th>Severity of fire hazards</th>
<th>$T_1$</th>
<th>$T_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No fire hazards</td>
<td>0.99</td>
<td>0.85</td>
</tr>
<tr>
<td>Small fire hazard</td>
<td>0.90</td>
<td>0.70</td>
</tr>
<tr>
<td>Medium fire hazard</td>
<td>0.80</td>
<td>0.60</td>
</tr>
<tr>
<td>Strong fire hazard</td>
<td>0.50</td>
<td>0.10</td>
</tr>
</tbody>
</table>

However, who will follow whom (i.e., how the occupants select the evacuation leader) has not been discussed yet. This is realized in Figure 4.3:
Counter the number of leaders in the current region (or room)

Is there a fire pool on the way of the current occupant heading to the leader?

- y: Don't consider to follow this leader
- n: Take this leader as one of the candidates to be followed

Does the current occupant have social affiliation? (e.g., have family member around, or close friends)

- y: randomly follow a qualified leader
- n: Are there too many followers are following the randomly selected leader the current occupant wants to follow?

- y: Are all the leaders having the same problem?
  - y: change to single evacuation
  - n: randomly select and follow another qualified leader
- n: follow this qualified leader

Figure 4.3: Selecting the group evacuation leader
In figure 4.3, the first assumption is that the social affiliation of the occupant is the most important factor in deciding whether the occupant takes the group evacuation or not. The number of occupants in a group is also restricted in Vacate (10 occupants by default) based on the concept that in a real fire scenario, it is not likely that groups get very large since this would cause an evacuation jam.

The second assumption is that the occupants would follow the leader all the time during the evacuation after they decided to follow a leader (which is based on the fact the group members usually want to stick with each other following the leader during the evacuation, especially when the group is a family or some other organization where the members in it are all very close to each other) [53]. If incapacitation impacts to the evacuation leader, a new leader would be selected to lead the group.

In the pre-evacuation time, fire hazard cues and the alarm are two critical factors that have the strongest impact on the occupants’ decision of whether to stay in the current region (or room) or start moving out. In Vacate, it is assumed that in most cases the occupants would move out immediately after the alarm goes off, except for some special case such as when the occupant is sleeping or disabled, which may cause some delay. The method to calculate the delay time is presented in Section 4.3.1. The action in the delay time is simplified to staying in the current region (or room) and is demonstrated by the random walking behavior in Vacate. When the delay time is over (i.e., the pre-evacuation time is over), the occupant may start evacuating or may continue staying in the current region (or room). This mainly depends on the severity of the fire hazards
environment. Figures 4.4-4.7 demonstrates the if-then-else structure of predicting whether the occupant is staying or not.

Figure 4.4: Deciding if the pre-evacuation time for the current occupant is over or not—part1
Did the occupant detect any fire hazards?

- y: His/her pre-evacuation time is terminated in advance
- n: Randomly generate a random number $R$

- If $R < 50$?
  - y: His/her pre-evacuation time is terminated in advance
  - n: Is any other occupant around evacuating?

- n: Is any other occupant around evacuating?

Figure 4.5: Deciding if the pre-evacuation time for the current occupant is over or not—part 2
Is this correct that the current occupant did not evacuate and now his/her pre-evacuation time is over (NOT terminated in advance?

- y: His/her pre-evacuation time is over
- n: S/he is still in the pre-evacuation time

Figure 4.6: Deciding if the pre-evacuation time for the current occupant is over or not—part3
Is the current occupant's pre-evacuation time over or terminated in advance?

Generate 4 different Threshold values $T^*$ for 4 different fire hazards

Is the current occupant an evacuation leader or is s/he following the leader?

If yes, s/he doesn't stay in the current region.

If no, generate a random number $R$ (between 0-1).

If yes, $R < T^*$?

If yes, s/he stays in the current region.

If no, s/he doesn't stay in the current region.

Figure 4.7: Deciding if the occupant wants to stay in the current region or not
In figure 4.7, $T^*$ is assumed to have 4 possible values according to the severity of the fire hazards. Table 4.3.2.1.2 lists these values.

*Table 4.3.2.1.2: four possible $T^*$ values according to the severity of the fire hazards*

<table>
<thead>
<tr>
<th>Severity of fire hazards</th>
<th>Value of $T^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No fire hazards</td>
<td>0.10</td>
</tr>
<tr>
<td>Small fire hazard</td>
<td>0.05</td>
</tr>
<tr>
<td>Medium fire hazard</td>
<td>0.01</td>
</tr>
<tr>
<td>Strong fire hazard</td>
<td>0.0</td>
</tr>
</tbody>
</table>

4.3.2.2 Predicting critical human behaviors

The critical human behaviors in a fire emergency evacuation that can be predicted are the following:

- Heading to other rooms for refuge;
- Going back to the previous region;
- Taking the route with the minimum fire hazards when the occupant is familiar with the current building environment;
- Following the crowd when the occupant is not familiar with the current building environment;
- Wandering around in the extreme heavy smoke; and
- Heading to the wall and moving along it in the extreme heavy smoke.

Predicting these behaviors in *Vacate* is also realized by the *if-then-else* approach (i.e., to predict the possible behaviors by going through a series of flowcharts) In *Vacate*, this
predicting process is called every 20 simulation seconds. The entire process is demonstrated in Figure 4.8:
For every 20 simulation seconds

Is the current occupant engulfed in the heavy smoke? or did the fire hazard degree for her (him) change a lot?

Is the s/he engulfed in the heavy smoke?

Generate 3 different thresholds $T^*$ to help predict the wall-following behavior and wandering behavior

Generate 12 different thresholds $T^{**}$ to help predict the passive and active evacuation behavior

Generate a random number $R_1$ between 0 and 1

$R_1 < T^*$?

S/he is going to follow the wall in the heavy smoke

S/he is going to be wandering around the current region

$s$/he is going to take the passive evacuation behavior like heading back to the previous region (or room)

S/he is going to take the active evacuation behavior (i.e., get out of the current building)

Generate a random number $R_2$ between 0 and 1

$R_2 < T^{**}$?

No prediction is updated in this time period

Figure 4.8: Predicting 6 critical human behaviors
The thresholds $T^*$ is determined also by going through a series of if-then-else’s as shown in the flowchart in Figure 4.9.

![Flowchart](image)

*Figure 4.9: 3 possible $T^*$ values according to 3 different occupant characteristics*

The twelve thresholds for $T^{**}$ in Figure 4.8 are also determined by going through a flowchart based on the *if-then-else* structure. However, for convenience, a table instead of the flowchart is presented in Table 4.3.2.2.1. As with other threshold values, these could easily be changed if better values were identified through experiments or experience.
Table 4.3.2.2.1: All possible thresholds for $T**$

<table>
<thead>
<tr>
<th>Severity of fire hazards</th>
<th>Possible Values of $T**$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group leader</td>
</tr>
<tr>
<td>No fire hazards</td>
<td>0.00</td>
</tr>
<tr>
<td>Small fire hazard</td>
<td>0.00</td>
</tr>
<tr>
<td>Medium fire hazard</td>
<td>0.00</td>
</tr>
<tr>
<td>Strong fire hazard</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The predicting process is called every 20 simulation seconds and works only if the severity of the fire hazards increases. The underlying assumption for this process is that during the evacuation, occupants are unlikely to change their decisions very often unless the fire hazards become more dangerous. For example, if the occupants see that the fire hazards are extreme and therefore keep them from heading to the exit, they may decide to head back to the previous region or enter another room to take a refuge instead of heading to that dangerous exit.

Familiarity of the building environment is a critical factor to the prediction of whether the occupant is going to follow the route with the minimum fire hazards (regardless of the traveling distance) or is going to follow the crowd. In *Vacate*, the difference originated by familiarity is included in the objective functions, which are used to select the evacuation exits for occupants. The method to realize the difference is to consider the occupant density near each potential exit. The details about the modified objective functions are discussed in Section 4.3.3. A simple flowchart for predicting the difference is shown in Figure 4.10:
Is the current occupant familiar with the building environment?

The factor is assumed not working because of the strong fire hazards.

Figure 4.10: predicting if the occupant is going to follow the route with the minimum fire hazards or following the crowd

This Figure shows that if occupants encounter strong fire hazards, the effect from the fire hazards is assumed to be overwhelming and thus dominates the effect of familiarity.

As these behaviors are predictable, to realize them is either by modifying the objective functions or modifying the steering drives (or called steering forces) [1] and [87], which are discussed in detail in the following sections.
4.3.3 Simulating predicted human behaviors with modified PSO and steering behaviors for autonomous characters

In the former sections, the decision-making processes are used to predict the human behaviors to be simulated in Vacate. The general idea for this simulation is to find the objective function for each identified human behavior of each occupant, then optimize the objective functions (which usually it means to minimize the distance between the occupant and the selected objective, including exits, leaders, or disabled occupants) at each simulation time step for each occupant. This produces the effect of moving toward the exits (if the exits are the objectives), moving along the wall (if an offset point that is ahead of the occupant and along the wall is the objective), following the leader, etc. Reynolds [87] developed simple steering behaviors such as seek, flee, and obstacle avoidance, as well as more complex steering behaviors such as wander, path following, wall following, and leader following, by generating different steering forces or blending simple steering behaviors. Based on Reynolds’ framework, the update of the position of each occupant is realized by applying a weighted combination of normalized steering forces [1] (or called steering locomotion, steering drives) to the occupant, which drives the occupant to an updated location at each simulation time step. In the next sections, the methodology for simulating each of the predicted behaviors is presented in detail.

4.3.3.1 Staying in the current region

To stay in the current region (or room) means the occupant does not want to get out of the building for some reason (e.g., the occupant is in the pre-evacuation time, he did not hear the alarm, he just do not want to react to the alarm, he is collecting some personal items
before evacuation, etc). The easiest way to simulate this is to kill the objective and steering drives on the current occupant for some number of time steps. However, in the real life, occupants may randomly walk around instead of just staying still without any movement. Therefore, random walking behavior is introduced here to present a more reasonable simulation when occupants stay in the current region (or room). There are four steps to realize this behavior; which are outlined below.

- Generate a random objective in the current region (or room), which produces a steering drive for an occupant. Equations 4.3.3.1.1-4.3.3.1.2 show the details:

\[
\text{occupant}.randomx = \text{region}.lower\_cornerx + 1 + r_1 \ast (\text{region}.upper\_cornerx - \text{region}.lower\_cornerx - 2) \tag{4.3.3.1.1}
\]

\[
\text{occupant}.randomy = \text{region}.lower\_cornery + 1 + r_2 \ast (\text{region}.upper\_cornery - \text{region}.lower\_cornery - 2) \tag{4.3.3.1.2}
\]

where,

\text{occupant}.randomx = the randomly generated x-coordinate of the objective;

\text{occupant}.randomy = the randomly generated y-coordinate of the objective;

\text{region}.lower\_cornerx = the lower-left side x-coordinate of the current region (or room);

\text{region}.upper\_cornerx = the upper-right side x-coordinate of the current region (or room);

\text{region}.lower\_cornery = the lower-left side x-coordinate of the current region (or room);

\[r_1, r_2= \text{random numbers between 0 and 1}; \text{ and}\]
The values 1 and 2 in Equations 4.3.3.1.1-4.3.3.1.2 are used to avoid generating a random objective right on the walls of the current region (or room), which would not be meaningful.

- Generate the steer drives from the randomly generated objective as in Equations 4.3.3.1.3-4.3.3.1.4:

\[ x_p = \text{occupant[k].randomx - occupant[k].x} \]  \hspace{1cm} (4.3.3.1.3)

\[ y_p = \text{occupant[k].randomy - occupant[k].y} \]  \hspace{1cm} (4.3.3.1.4)

where,

\[ x_p = \text{x-component of the un-normalized forward drive from PSO; and} \]

\[ y_p = \text{y-component of the un-normalized forward drive from PSO.} \]

Here, the forward drives \( x_p \) and \( y_p \) must be normalized to ensure that an occupant cannot travel at speeds higher than his maximum unimpeded travel velocity [1]. In the behaviors we will discuss later the normalization applies if \( \text{mag} > 1 \). The normalization is implemented as follows:

If \( \text{mag} = \sqrt{(x_p)^2 + (y_p)^2} > 1 \), then

\[ x_p = \frac{x_p}{\text{mag}} \]  \hspace{1cm} (4.3.3.1.5)


\[ y_p = \frac{y_p}{mag} \] (4.3.3.1.6)

- Generate some “still-standing” time for the occupant if he reaches his objective (as in real life, occupants would not keep walking without stopping). The method is shown by Equation 4.3.3.1.7-4.3.3.1.8.

\[ x_p = 0 \] (4.3.3.1.7)

\[ y_p = 0 \] (4.3.3.1.8)

- Generating random numbers to control the switching of the “still-standing” behavior and walking behavior. Figure 4.11 shows how to achieve the control by using a random number.
Did the occupant reach the random objective?

- **Y**: Generate a random number $R$ between 0 and 1
- **N**: continue walking to the random objective

- **Y**: $R>0.5$? or has the occupant stopped moving for a short while?
  - **Y**: Generate a new random objective and walk to it
  - **N**: don't move

- **N**: simulation time step increases 1

**Figure 4.11: Controlling the random switch of the “still-standing” and walking behavior to produce a natural-look random walking behavior**

### 4.3.3.2 Group evacuation behavior by following a leader

The method demonstrated here is to simulate that in some fire scenarios, occupants desire to follow an evacuation authority (i.e., trained evacuation leader, staff member, etc.) or stay with someone who has strong social affiliation with them. This behavior is simulated
by combining separation behavior [1], [87] among occupants, arrival behavior about a follower heading to a target (or focal point) slightly behind the leader, moving out of the way if a follower finds himself on the near future path of the leader, and waiting for the followers if the leader finds that he is too far away from the followers to allow them to catch up. The mathematical models to accomplish all these behaviors are discussed next.

- **Separation** behavior between occupants to avoid collision

This mathematical model was developed by Tyagi [1] in his thesis work. The separation drive can be calculated from the relations:

\[
x_s = \text{occupant}[\text{x}] - \text{Obs\_occupant}[\text{x}] \\
x_s = \text{occupant}[\text{x}] - \text{Obs\_occupant}[\text{x}]
\]

where,

\[\text{Obs\_occupant}[\text{x}] = \text{x-coordinate of the obstructing occupant}\]

\[\text{Obs\_occupant}[\text{y}] = \text{y-coordinate of the obstructing occupant}\]

More detailed descriptions on this topic can be found in section 3.9 in reference [1].

- **Arrival** behavior concerning a follower heading to a target (or focal point) slightly behind the leader

This behavior is identical to seek behavior [87] while the occupant is far from his leader. However, based on the observation of real life scenarios, followers tend to slow down their walking speed as they approach the leader instead of maintaining a full speed (which is represented by the seek behavior). Thus, arrival behavior is used here. The
forward drives, $x_p$ and $y_p$, of the follower are then directed to an offset target slightly behind the leader by using Equations 4.3.3.2.3-4.3.3.2.4:

$$x_p = leader.offset\_x - follower.x$$ \hspace{1cm} (4.3.3.2.3)

$$y_p = leader.offset\_y - follower.y$$ \hspace{1cm} (4.3.3.2.4)

where,

$leader.offset\_x =$ the x-coordinate of the offset target of the leader

$leader.offset\_y =$ the y-coordinate of the offset target of the leader

$follower.x =$ the x-coordinate of the follower

$follower.y =$ the y-coordinate of the follower

If the follower is close to the leader, they slow down the walking speed “linearly” realized by Equation 4.3.3.2.5.

$$agent.v_{weighted} = agent.v_{max} \times \frac{leader\_follower\_dis}{slow\_down\_dis}$$ \hspace{1cm} (4.3.3.2.5)

where,

$agent.v_{weighted} =$ the weighted velocity;

$agent.v_{max} =$ the maximum unimpeded velocity of the agent;

$leader\_follower\_dis =$ the current distance between the leader and the follower; and

$slow\_down\_dis =$ the threshold distance which activates the “slowing down”

(Equation 4.3.3.2.5) if the current distance is less than this threshold, in current thesis work, this threshold is 0.5 feet.

- Moving out of the way if a follower finds himself on the near future path of a leader
This behavior includes two sub-behaviors: 1) the follower detects if he is in the way of a leader’s near future path; and 2) the follower moves to a proper direction to get out of the way of the leader. Figure 4.12 illustrates the first sub-behavior.

Figure 4.12: the follower detects if s/he is on the way of a leader’s near future path

In figure 4.12, the following distances are shown:

$D1=$ the distance between the mid-point $m$ and the leader;

$D2=$ the distance between the follower and the line from the leader to the exit potential;
\( D3 = \) the projected distance between the leader and the follower; and

\( D4 = \) the distance between the leader and the follower.

In *Vacate*, at each simulation time step, if the conditions of \( D4 < 4 \) (feet), \( D2 < 2 \) (feet), and \( D3 < D1 \) are all true, it is assumed the follower is in the way of the near future path of a leader.

After the follower detects himself is on the way of the leader, he would move to a position offset from the leader. This is illustrated in Figure 4.13.
In Figure 4.13, the directions of arrow 1 and arrow 2 are both parallel with line 1. The follower is expected to move to either offset position 1 or offset position 2 depending on which direction is further away from the leader. Also, if one of the offset positions is outside the current region, Vacate is able to detect this “fake” offset position and discard it. Equations 4.3.3.2.4-4.3.3.2.7 show how to generate the two offset positions.

\[ \text{offset \_ postion \_1} \_x = \text{agent}\_x + 5 \times \cos \theta_1 \]  

(4.3.3.2.4)
Here, a 5 feet offset distance along the direction of arrow 1 and arrow 2 is used. The forward drive, $x_p$ and $y_p$, of the follower are temporarily modified as shown in Equations 4.3.3.2.7-4.3.3.2.8:

\[
\begin{align*}
x_p &= \text{offset}_x - \text{agent}_x \\
y_p &= \text{offset}_y - \text{agent}_y
\end{align*}
\]  

(4.3.3.2.8)

(4.3.3.2.9)

where,

$\text{offset}_x$ = the x-coordinate of the selected offset position; and

$\text{offset}_y$ = the y-coordinate of the selected offset position.

- **The leader waits for the followers if the leader finds him/herself is too far away from the followers to allow them to catch up.**

This behavior is often observed in the real life evacuation. For example, a father would wait for his son who is not around or go back to look for his son. The latter behavior is not simulated in *Vacate* at present but will be a topic for future work.

This behavior is simulated in the following way: first, calculate the average position from all the positions of the current followers of the leader; and second, if the distance between the average position and the leader is too far, the leader starts to decrease his walking speed to wait for the followers to catch up. To quantify this process, a “maximum
velocity” circle and an “almost-zero velocity” circle are defined to judge if followers are too far away from the leader. Figure 4.14 shows the details for this.

Figure 4.14: “maximum velocity” circle and “almost-zero velocity” circle
In figure 4.14, the radius of the “maximum velocity” circle and “almost-zero velocity” circle serve as the thresholds for deciding the leader’s walking velocity. That is, if the average position of the followers (see Figure 4.14) is within the “maximum velocity” circle, the walking speed of the leader is assumed to be unimpeded. If the average position of the followers is within the “almost-zero velocity” circle but not the “maximum velocity” circle, the walking speed of the leader is impeded linearly as shown in Equation 4.3.3.2.10:

\[
leader.v = \frac{(ag\_leader\_dis - zero\_vradius)}{(max\_vradius - zero\_vradius)} \times (leader.v_{max} - leader.lowest\_speed) + leader.lowest\_speed
\]

(4.3.3.2.10)

where,

- \(leader.v\) = leader’s impeded velocity due to waiting for the followers;
- \(ag\_leader\_dis\) = the current distance between the follower and the leader;
- \(zero\_vradius\) = the radius of the “almost-zero velocity” circle, it’s defined as 8 feet in Vacate;
- \(max\_vradius\) = the radius of the “maximum velocity” circle, it’s defined as 4.5 feet in Vacate;
- \(leader.v_{max}\) = leader’s unimpeded velocity; and
- \(leader.lowest\_speed\) = the lowest walking speed of the leader when the average position of the followers are larger than the \(zero\_vradius\).
When the distance between the leader and the average position of the followers is larger than the value of \texttt{zero\_vradius}, the walking speed of the leader is always assigned with the lowest walking speed, (which in \textit{Vacate} is predefined as 0.1 feet/second).

The combination of these behaviors results in a complete simulation of the group evacuation behavior as shown in Figure 4.15:

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4_15.png}
\caption{the group evacuation simulation}
\end{figure}

In this figure, blue dots represent male occupants, magenta dots represent female occupants, brown dots represent disabled occupants, red rectangles represent obstacles, green dots represent group evacuation leaders, and the blue line connects the group evacuation leader and his followers.
4.3.3.3 Wandering around in the extreme heavy smoke

Although the term “wandering” suggests, a random steering force at each time step, this would produce a “twitchy” behavior, which would look very unnatural because the steering force is randomly changed with high frequency (in Vacate, the steering force is changed every 0.05 seconds). A better approach is to maintain the steering force for a certain number of time steps, then update it randomly, and maintain it for another certain number of time steps, and so on. As a result, the simulation looks like a random walking behavior since the steering force takes a “random walk” from one direction to another. However, this still does not look natural enough either as a wandering behavior in the extreme heavy smoke. In the heavy smoke, occupants are unlikely to switch to completely different directions because some weak visual cues give them a little exposure to a short distance ahead which would cause them to only slightly adjust their direction. Reynolds [87] suggests a method to constrain the steering force to the surface of a sphere located slight ahead of the occupant. Figure 4.16 illustrates the basic idea as following.
Figure 4.16: the mechanism on wandering behavior

Figure 4.16 shows a randomly generated steering drive at some simulation time step. At the first simulation time step, the initial random steering drive is produced by doing the following: the biggest circle with radius $r_1$ determines the maximum wandering “strength” (or range) and the initial direction of the wandering behavior is generated by a random $\theta_1$ in $[-\pi, \pi]$. The parameter $\theta_1$ is only generated once at the first time step.
which ensures no “twitchy” behavior occurs. Then the position of point D is generated as an initial drive supplied by Equations 4.3.3.3.1-4.3.3.3.2 as following:

\[
\begin{align*}
\text{Initial \_ drive \_ } x &= agent.x + r_1 \cos \theta_1 + r_2 \cos \theta_2 \\
\text{Initial \_ drive \_ } y &= agent.y + r_1 \sin \theta_1 + r_2 \sin \theta_2
\end{align*}
\]  

(4.3.3.3.1)  \hspace{1cm} (4.3.3.3.2)

At successive simulation time steps, each steering drive at the current time step is updated from the drive at the last time step. For example, in Figure 4.16, the steering drive point to B from the occupant is generated from the last one that points to D from the occupant. The basic idea is to generate an angle increment of \(\Delta \theta_1\) or \(\Delta \theta_2\) (marked as \text{Inr\_theta1} and \text{Inr\_theta2} in Figure 4.16) and add this to \(\theta_2\). \(\Delta \theta_1\) is equal to \(\Delta \theta_2\) except that it has an opposite signs which generates the left-offset move or right-offset move in the simulation. Whether to use \(\Delta \theta_1\) or \(\Delta \theta_2\) is also randomly decided by generating another random number \(R_0\). If \(R_0 < 0.5\), then \(\Delta \theta_1\) is selected, otherwise, \(\Delta \theta_2\) is selected.

Equations 4.3.3.3.3-4.3.3.3.4 show how to calculate the \(\Delta \theta_1\) and \(\Delta \theta_2\):

\[
\Delta \theta_1 = \cos^{-1}\left(\frac{2r_2^2 - (R \times s_3)^2}{2r_2^2}\right) \quad (4.3.3.3.3)
\]

\[
\Delta \theta_2 = -\Delta \theta_1 \quad (4.3.3.3.4)
\]

where,

\(R = a \text{ random number between } [0, 1]; \text{ and}\)

\(s_3 = \text{the length of line BC and CD (see figure 4.16), which is equal to } r_3.\)
From the Equation 4.3.3.3.3, it is shown that the magnitude of $r_2$ or $r_3$ controls the wander “rate” in the simulation. Thus, with the current approach of simulating of the wandering behavior, if we want to get different simulation results under a different fire hazards environment (which is based on the fact that the wandering behavior in an extreme heavy smoke environment is different from that in a less smoky smoke environment), we will only need to modify the $r_1$, $r_2$, and $r_3$.

The result steering drive is produced as equation 4.3.3.3.5-4.3.3.3.8 show:

$$drive_{-x} = agent.x + r_1 \cdot \cos \theta_i + r_2 \cdot \cos(\theta_2 + \Delta \theta_2)$$ (4.3.3.3.5)

$$drive_{-y} = agent.y + r_1 \cdot \sin \theta_i + r_2 \cdot \sin(\theta_2 + \Delta \theta_2)$$ (4.3.3.3.6)

Which would be written as follows if $\Delta \theta_1$ is used.

$$drive_{-x} = agent.x + r_1 \cdot \cos \theta_i + r_2 \cdot \cos(\theta_2 + \Delta \theta_1)$$ (4.3.3.3.7)

$$drive_{-y} = agent.y + r_1 \cdot \sin \theta_i + r_2 \cdot \sin(\theta_2 + \Delta \theta_1)$$ (4.3.3.3.8)

The forward drive is then generated as shown in Equations 4.3.3.3.9-4.3.3.3.10.

$$x_p = drive_{-x} - agent.x$$ (4.3.3.3.9)

$$y_p = drive_{-y} - agent.y$$ (4.3.3.3.10)

### 4.3.3.4 Heading to the wall and moving along it in the extreme heavy smoke

Instead of wandering in the smoke, moving along the wall is also a common behavior when the occupant encounters very heavy smoke. In *Vacate*, this behavior is simulated by combining three basic behaviors: 1) heading to the wall; 2) moving along the wall; and 3)
turning at the corner and following the next wall (or “cornering” behavior). To illustrate this wall-following behavior better, a flowchart is shown in Figure 4.17.
Find the nearest wall of the current room around the current occupant

Is the current occupant moving along the wall?

Is the current occupant heading to the wall?

Has the occupant found the nearest wall?

Find the nearest wall of the current room around the current occupant

Perform the cornering behavior

Moving along the wall

Has the occupant hit the wall?

update to next time step

Figure 4.17: Basic process of simulating the wall-following behavior
The simulation methods for each of these three basic behaviors are discussed below.

- **Heading to the wall**

It is possible that if an occupant is engulfed with very heavy smoke, he would like to head to the nearest wall if he sees the wall and then want to move along it. The first thing to do is to make the occupant detect the nearest wall around him. Figure 4.18 shows how this is implemented.

![Figure 4.18: detecting the nearest wall](image-url)
In Figure 4.18, occupant C is looking for the nearest wall that he could follow. Point P is a random spot the occupant can see in the heavy smoke. Point D, which generates the steering drive, is a perpendicular point of P on the line of the wall-following constraint distance. Equations 4.3.3.4.1-4.3.3.4.2 show how to calculate the location of point D:

\[
D_x = C_x + w_{fc} * \sin(\text{slopewall} \cdot \frac{3\pi}{2}) \tag{4.3.3.4.1}
\]

\[
D_y = C_y + w_{fc} * \cos(\text{slopewall} \cdot \frac{3\pi}{2}) \tag{4.3.3.4.2}
\]

where,

\[w_{fc}\] = the wall-following constraint distance, which is 1 feet;

\[D_x\] = the x-coordinate of the D point;

\[D_y\] = the y-coordinate of the D point;

\[\text{slopewall}\] = slope of the wall where has C point on;

\[C_x\] = the x-coordinate of the C point; and

\[C_y\] = the y-coordinate of the C point.

The coordinates of point C are generated by Equation 4.3.3.4.3-4.3.3.4.4 as follows:

\[
C_x = \frac{[\text{wall}.y1 - \text{wall}.x1 * \tan(\text{wall}.slope)] - [P_y + \frac{P_x}{\tan(\text{wall}.slope)}]}{\tan(\text{wall}.slope)} - \tan(\text{wall}.slope) \tag{4.3.3.4.3}
\]

\[
C_y = \tan(\text{wall}.slope) * C_x + [\text{wall}.y1 - \text{wall}.x1 * \tan(\text{wall}.slope)] \tag{4.3.3.4.4}
\]

where,
\( P_x = \) the x-coordinate of point \( P \);

\( P_y = \) the y-coordinate of point \( P \);

\( \text{wall}[]_{x1} = \) the x-coordinate of the starting point of the wall that the occupant is moving along with; and

\( \text{wall}[]_{y1} = \) the y-coordinate of the starting point of the wall that the occupant is moving along with.

It is worthwhile to mention that the slope of the wall could be infinite (i.e., \( \tan 90^\circ = \infty \)), which would result in a numerical error when using Equation 4.3.3.4.3. It is easy to solve this problem by applying a simple if-then-else structure to handle these special cases separately.

Here, for occupant B in Figure 4.18, point \( G \), which also produces the steering drive \( GB \) is on the left-side of point \( F \), while point \( D \) is on the right-side of point \( C \). Then, we use Equation 4.3.3.4.5-4.3.3.4.6 to calculate the position of point \( G \) as follows:

\[
\begin{align*}
xG &= F_x + w_c d \cdot \sin(\text{wall.slope} + \frac{\pi}{2}) \\
yG &= F_y + w_c d \cdot \cos(\text{wall.slope} + \frac{\pi}{2})
\end{align*}
\]

where,

\( xG = \) the x-coordinate of the \( G \) point;

\( yG = \) the y-coordinate of the \( G \) point;

\( \text{wall.slope} = \) slope of the wall where has \( F \) point on;

\( F_x = \) the x-coordinate of the \( F \) point; and
\( F_y \) = the y-coordinate of the F point.

The forward drive (steering drive CD in Figure 4.18) for occupant B is then produced by Equations 4.3.3.4.7-4.3.3.4.8 as shown below.

\[
x_p = D_x - agent.x \\
y_p = D_y - agent.y
\]

(4.3.3.4.7)

(4.3.3.4.8)

- Moving along the wall

After the occupant hits the wall, an offset position ahead of the occupant becomes a new drive generator. To save the computational expense, the offset position is not updated on each successive simulation time step. Instead, it is updated when the occupant reaches the current offset position. Figure 4.19 shows this behavior.
The offset position is generated by Equations 4.3.3.4.9 and 4.3.3.4.10 as follows:

\[ \Delta x = \text{moving}_\text{direction} \times \text{offset}_\text{dis} \times \cos(\text{wall}.\text{slope}) \]  

(4.3.3.4.9)

\[ \Delta y = \text{moving}_\text{direction} \times \text{offset}_\text{dis} \times \sin(\text{wall}.\text{slope}) \]  

(4.3.3.4.10)

where,
$\Delta x = x$ component of the offset distance; and

$\Delta y = y$ component of the offset distance.

$\text{moving\_direction} =$ if the moving direction is from downside to upside or left-side to right side, this value is 1, if the moving direction is from upside to downside or right-side to left-side, this value is -1.

$\text{offset\_dis} =$ the offset distance ahead of the wall-following occupant which produces the steering drive, which is set to 2 feet as default in Vacate.

- **Cornering**

If the occupant does not see any open exits or other occupants follow in a fire scenario, he may continue the wall-following behavior in heavy smoke. When occupants reach the end of the current wall that is being followed, he would turn to the next wall and keep following it. This behavior is illustrated in Figure 4.20:
In Figure 4.20, occupant A is about to turn to the next wall. The steering drive is generated by the point D. This drive is only generated when the occupant is about at the end of the wall being followed. Equations 4.3.3.4.11-4.3.3.4.12 show the details:

\[ x_p = D_x - \text{agent}.x \]  \hspace{1cm} (4.3.3.4.11) \\
\[ y_p = D_y - \text{agent}.y \] \hspace{1cm} (4.3.3.4.12)

where,

\( D_x = \text{the x-coordinate of the point D, which generates the x-component of the steering} \)
drive; and

\[ D_y = \text{the y-coordinate of the point D, which generates the y-component of the steering Drive.} \]

The location of point D is generated by first generating the coordinates of point P, and then projecting point P on to the wall that generates point C. Point C is offset to point D. The process is exactly the same as generating the coordinates of point D (in Figure 4.18) after the coordinates of point P are generated. Please refer to Equations 4.3.3.4.1-4.3.3.4.8 for details.

Instead of setting point P as a randomly spotted point (such as that illustrated in Figure 4.18), it is generated by Equations 4.3.3.4.13-4.3.3.4.14 as shown below:

\[
P_x = \text{moving direction} \times \text{offset dis} \times \cos(\text{next wall slope}) + \text{agent.x}
\]

\[
P_y = \text{moving direction} \times \text{offset dis} \times \sin(\text{next wall slope}) + \text{agent.y}
\]

(4.3.3.4.13)

(4.3.3.4.14)

where,

\[ P_x = \text{the x-coordinate of point P}; \]

\[ P_y = \text{the y-coordinate of point P}; \]

\[ \text{Next wall slope} = \text{the slope of the wall that the occupant is going to move along}; \] and

Definitions of other parameters are as same as that in Equations 4.3.3.4.9-4.3.3.4.10.
This behavior is simulated by modifying the steering drives only. No changes on the objective functions are required. This is because the global best value and personal best value [1] updated in the PSO movement calculation at each simulation time step are not needed in generating the steering drives because this behavior is assumed to happen only if the occupant can not see any other occupants in the heavy smoke. Thus, the global best value of the current region which requires the occupant see others clearly does not apply here, and the personal best value of the occupant does not apply here either, since the moving route is deterministic (i.e., moving straight ahead along the wall).

4.3.3.5 Active evacuation behavior

Unlike staying in the current region or going back to previous or other regions (which will be discussed in Section 4.3.3.6), moving to the selected final exits is defined as the active evacuation behavior.

The behavior of exit selection is governed by the objective function of the modified PSO, which is defined as the distance of the occupant to the exit in that region if there are no fire pools in the current region that the occupant is staying. The objective functions for exit selection in case of overcrowding, and in case when there are fire pools in the same region of the occupant, were derived in [1].

However, occupants can not automatically detect the fire pools outside of the current region in [1], they may head to wrong exits during the evacuation. Figure 4.21 illustrates this problem.
To solve this problem, a fire hazard detecting model has been developed which enables the occupants detect the fire pool(s) everywhere (not only the current room or region) automatically. Detailed information on this recognition is provided in Section 4.3.4.

Additional new objective functions that have been developed in this work can be classified into four categories as outlined below.
• No fire hazards inside and outside of the current region

This objective function is taken from [1] without considering the factor of occupants’ familiarity. Section 4.3.3.7 discusses the details on how to include the effects of the factor of familiarity into the objective function. For convenience, the objective function for this case is listed by equation 4.3.3.5.1.

\[
obj[] = \sqrt{(agent[],x - exit[],x)^2 + (agent[],y - exit[],y)^2} 
\]  
(4.3.3.5.1)

where,

\[
obj[] = \text{objective function values};
\]

\[
exit[],x = \text{x-coordinate of the selected exit location; and}
\]

\[
exit[],y = \text{y-coordinate of the selected exit location}.
\]

• Fire(s) in the current region, no fires outside of the current region

This objective function is also remained unchanged from [1] without considering the factor of familiarity. Section 3.6.2 in reference [1] can be consulted for more details. Here, for convenience, it is listed by equation 4.3.3.5.2.

\[
obj[] = \frac{\sqrt{(agent[],x - exit[],x)^2 + (agent[],y - exit[],y)^2}}{\sqrt{(fire[],x - exit[],x)^2 + (fire[],y - exit[],y)^2}} 
\]  
(4.3.3.5.2)

where,

\[
fire[],x = \text{x-coordinate of the fire source}
\]

\[
fire[],y = \text{y-coordinate of the fire source}
\]

• No fire(s) inside of the current region but occupants detect the fire(s) which is outside of the current region
In this case, occupants are assumed not to head to the exits which have first fire pools outside of them. So, the easiest way to develop the objective function for this case is to first to eliminate those unqualified exits (which have fire pools outside) from the candidate exits, then to calculate the distance from the occupant to each of the qualified exits in order to achieve the shortest path. Equation 4.3.3.5.3 shows the details for this as follows:

\[ \text{obj}[] = \sqrt{(\text{agent}[] . x - \text{qualified_exit}[] . x)^2 + (\text{agent}[] . y - \text{qualified_exit}[] . y)^2} \] (4.3.3.5.3)

where,

- \( \text{qualified_exit}[] . x \) = x-coordinate of the qualified exits which have no fires outside; and
- \( \text{qualified_exit}[] . y \) = y-coordinate of the qualified exits which have no fires outside.

Occupants are then head to the exit that has the minimum objective function value in Equation 4.3.3.5.3.

The means to eliminate unqualified exits is based on the results from the fire hazard detecting model that record the locations and number of the fires outside of the exits. This model is discussed in Section 4.3.4.

However, there is a case where each of the exits of the current region has fire(s) outside of them, \( i.e. \), occupants are trapped in the current region, which means that if they want to evacuate, they must head toward one or more fires. The effects of fire hazards then dominate in selecting the evacuation exit, which eliminates the possibility of deriving the objective function based on selecting the shortest path or selecting a more familiar exit. It
is assumed that if a fire pool is closer to an exit, then the exit becomes more dangerous and thus more unlikely to be selected by occupants during evacuation. A simplest way to apply this idea is to calculate the distance between the fire pool and the corresponding exit. Then, the occupant chooses the exit has the maximum distance to the fire pool. This is shown by Equations 4.3.3.5.4-4.3.3.5.5:

\[
\text{fire\_exitdis[]} = \sqrt{(\text{agent}[,].x - \text{exit}[,].x)^2 + (\text{agent}[,].y - \text{exit}[,].y)^2} \quad (4.3.3.5.4)
\]

\[
\text{selected\_exit} = \max(\text{fire\_exitdis[]}) \quad (4.3.3.5.5)
\]

where,

\(\text{Fire\_exitdis[]} = \text{the distance between the fire pool(s) and the exit(s)}\)

The objective function used in PSO is then described by Equation 4.3.3.5.6:

\[
\text{obj[]} = \sqrt{(\text{agent}[,].x - \text{selected\_exit}.x)^2 - (\text{agent}[,].y - \text{selected\_exit}.y)^2} \quad (4.3.3.5.6)
\]

- Fire(s) inside and outside of the current region

The case where there are fires both inside and outside the current region is the most complicated case. One of the methods is to use a flowchart (i.e., to go through some number of if-then-else analyses to select the best exit). However, this could produce many possibilities so the if-then-else structure gets complicated due to the fact that this case actually incorporates the former three categories. For example, some exits may not have fire pools outside, some exits may have fire pools outside but the fire pools might be very far away from those exits and actually have no hazard effects on them, and some exits may have more than enough distance from the fire pool(s) in the current region (which seems a good candidate exit but in fact is not because there is another fire pool right outside of that exit, etc). Thus, this method is not practical. Another method is to
include the process of selecting the best evacuation exit directly into the objective function, which is similar to what was done in [1]. By applying this method, the objective function does two things: 1) select the best exit for evacuation; and 2) calculate the global best function value and personal best function values for PSO to simulate the movement of the occupants. Equations 4.3.3.5.7-4.3.3.5.9 show the objective functions in the case where all the exit potentials of the current region have fire pools outside:

\[
obj[.part1] = \frac{\sqrt{(agent[x] - exit[x])^2 + (agent[y] - exit[y])^2}}{\sqrt{(fireinside[x] - exit[x])^2 - (fireinside[y] - exit[y])^2}} \tag{4.3.3.5.7}
\]

\[
obj[.part2] = \sum_{i=1}^{n} \frac{\sqrt{(fireoutside[x_i] - exit[x])^2 + (fireoutside[y_i] - exit[y])^2}}{\sqrt{(fireoutside[x_j] - exit[x])^2 + (fireoutside[y_j] - exit[y])^2}} \tag{4.3.3.5.8}
\]

\[
obj[.] = obj[.part1] + obj[.part2] \tag{4.3.3.5.9}
\]

where,

\[obj[.]=\text{overall objective function;}\]

\[obj[.].part1=\text{objective function part 1, which is equivalent to the objective function from section 3.6.2 in reference [1];}\]

\[obj[.].part2=\text{objection function part 2, which behaviors like a penalty function due to the effects from the fire pools outside of the current exit potential;}\]

\[agent[x]=x\text{-coordinate of the current occupant;}\]

\[agent[y]=y\text{-coordinate of the current occupant;}\]

\[exit[x]=x\text{-coordinate of the exit under objective function calculation;}\]

\[exit[y]=y\text{-coordinate of the exit under objective function calculation;}\]

\[fireinside[x]=x\text{-coordinate of fire pool(s) inside the current exit potential;}\]
fireinside[j].y = y-coordinate of fire pool(s) inside the current exit potential;

j = index of fire pool(s) outside of the current exit potential;

k = total number of fire pools outside of the current exit potential;

i = index of fire pools outside of the current region;

n = total number of fire pools outside of the current region;

fireoutside[j].x = x-coordinate of the j th fire pool outside of the current region;

fireoutside[j].y = y-coordinate of the j th fire pool outside of the current region;

fireoutside[i].x = x-coordinate of the i th fire pool outside of the current region; and

fireoutside[i].y = y-coordinate of the i th fire pool outside of the current region.

Note that the need for the i, j indices for the fire pools outside but not inside is due to the assumption that the fire inside of the region usually has effects on each of the exit potentials while the fire outside of the region may not have effects on some exit potentials. Figure 4.22 illustrates this in detail.
In Figure 4.22, fire pool 1 is outside of the exit potential 1 of region 15 but is not outside of the exit potential 3. Fire pool 2 is inside of region 15, therefore, the hazard effects from this fire pool should be considered in objective functions for all of the exit potentials of region 15.

The hazard effects of smoke and heat should also be incorporated into the objective function as well as the effects of fire pools. But how to combine these different effects in one objective function, as well as the lack of research on the interactions among these effects, make this problem complicated. More research is required to develop an
objective function that incorporating effects of smoke and heat, and thus is a topic for future work.

4.3.3.6 The effects of familiarity of the occupants to select the evacuation exit

Familiarity of the occupants to the environment is a critical factor for them to select an evacuation exit [95]. If an occupant is not familiar with the environment, such as a customer in a shopping mall, or a tourist in a museum, he would not response to the emergency quickly and would be more likely to investigate the current environment and then follow other occupants to the most commonly used exit. However, if the occupant is a staff number in the mall or museum, or someone else who is familiar with the environment, he may react immediately and direct other occupants to a safe place as soon as possible by evacuating them from exits that are closer to a safe place than the most commonly used exit.

Based on the above discussion, two behaviors related to familiarity are simulated in the current thesis work. First, occupants follow the crowd if they are not familiar with the current building environment. Second, if the occupant is familiar with the current building environment, they move to the nearest exit or pick an exit with less occupants heading to it because of crowding.

To simulate these two behaviors, penalty terms are added into the objective functions developed in section 4.3.3.5. The density near each of the exit potentials is recorded as in
Then, if the occupant is familiar with the environment, the penalty term is as shown in Equation 4.3.3.6.1.

\[ \text{penalty}[] = w_e \times \text{exitcounter}[] \]  

(4.3.3.6.1)

If the occupant is not familiar with the environment, the penalty term is as shown in Equation 4.3.3.6.2:

\[ \text{penalty}[] = -w_e \times \text{exitcounter}[] \]  

(4.3.3.6.2)

where,

\( w_e \) = weight for each occupant;

\( \text{exitcounter}[] \) = number of occupants waiting or moving towards the exit ahead of the current occupant [1]; and

\( \text{penalty}[] \) = penalty term.

The parameter, \( w_e \), is set to 0.5 in this algorithm, assuming that each occupant waiting at the exit corresponds to an extra distance of 0.5 feet [1].

Then in the case where there is no fire hazard is inside and outside of the current region, the objective function is modified as shown in Equation 4.3.3.6.3.

\[ \text{obj}[] = \sqrt{\text{occupant}[]_x - \text{exit}[]_x^2 + (\text{occupant}[]_y - \text{exit}[]_y)^2} + \text{penalty}[] \]  

(4.3.3.6.3)

Also, Equation 4.3.3.5.1 is modified to Equation 4.3.3.6.4 as shown.

\[ \text{obj}[] = \sqrt{\text{agent}[]_x - \text{qualified_exit}[]_x^2 + (\text{agent}[]_y - \text{qualified_exit}[]_y)^2} + \text{penalty}[] \]  

(4.3.3.6.4)
Other equations are remained unchanged from [1] under the assumption is that the fire hazard effects would dominate over the effect of familiarity (i.e., an occupant would head to the safest exit without considering whether he is familiar with the environment or not if one or more fire pools are spotted and blocking all exit potentials).

4.3.3.7 Heading to another room for refuge or going back to the previous region (i.e., passive evacuation behavior)

In Vacate, the entire floor plan is divided into different regions and rooms. Each room or region has one or more exits. The entrances for each room or region are pre-defined in the floor plan configuration. Thus, the easiest way to simulate this passive behavior is to set exits to other rooms (normally they are not connected to the outside) or previous regions (or rooms) as the objectives (for convenience, we call these exits “passive exits”), instead of setting the exits connecting to the next region which leads to the final exit to the outside as the objective.

One thing that should be emphasized here is that the global best and personal best value used in the PSO movement calculation in this passive evacuation behavior are different from those values used in active evacuation behavior (occupants are heading to the final exits that lead to the outside because PSO only updates the personal best and global best values for the “passive exits” if the occupant is using the passive evacuation behavior). By the same token, if the occupant is using the active evacuation behavior, only the personal best and global best values for the active exits are calculated in Vacate. This does not cause problems if no switches between these two behaviors (i.e., from active
evacuation behavior to passive evacuation behavior or from passive evacuation behavior to active evacuation behavior) occur. However, this is impossible due to the dynamic changes of the fire hazards environment. A simple way to solve this problem is to reinitialize the global best value and personal best values for the exit that will be set as the current objective whenever the switch of behaviors occur.

### 4.3.4 Fire hazard detecting model

This model simulates how occupants detect fire pools automatically. In previous thesis work [1], occupants are able to detect fire pools inside the current region. However, in real evacuation scenarios, it is possible that occupants detect fire pools outside of the current region from some open exits or windows. Also, in a real scenario, occupants are able to detect the dynamic change of the fire hazard environment. Currently, this model runs every 2 simulation seconds.

The basic idea behind the fire hazard detecting model is to determine if there is a wall between the occupant and the fire pool and whether the wall is blocking the eyesight of the occupant. Figure 4.23 illustrates this idea.
In Figure 4.23, occupant 1 is able to see the fire outside of the current room, and occupant 2 is not able to see it since the wall 2 is blocking his eyesight. The fire pool 2 is inside of the current room and so it is assumed that every occupant inside that room can detect the fire pool.
Based on the discussion above, the sufficient and necessary condition for an occupant to not be able to detect the fire pool is: the intersection point of the wall and the line of sight should be on the solid part of the wall and the line of sight. Figure 4.24 demonstrates this condition:
Figure 4.24: The necessary and sufficient condition for an occupant can not see detect the fire pool

In Figure 4.24, the intersection point E is on wall 2 as well as on the eyesight line between fire pool 1 and occupant 2, thus the necessary and sufficient condition is satisfied and the occupant can therefore not detect the fire pool 1. For occupant 1, there are 5 intersection points A-D (note that point B represents two overlapped points on the extension of wall 1 and wall 2) associated with fire pool 1 since there are 5 walls for the current room. None of these points satisfy the condition stated above, so occupant 1 can detect the fire pool 1. Equations 4.3.4.1-4.3.4.10 show how to identify whether an intersection point is on both the wall line and the eyesight line between the fire pool and the occupant:

\[
\text{mid wall}[][x] = \frac{\text{wall}[][x]_1 + \text{wall}[][x]_2}{2} \quad (4.3.4.1)
\]

\[
\text{mid wall}[][y] = \frac{\text{wall}[][y]_1 + \text{wall}[][y]_2}{2} \quad (4.3.4.2)
\]

\[
\text{dis inter mid}[] = \sqrt{\text{inter}[][x] - \text{mid wall}[][x]^2 + \text{inter}[][y] - \text{mid wall}[][y]^2} \quad (4.3.4.3)
\]

\[
\text{half wall length}[] = \frac{\sqrt{\text{wall}[][x]_1 - \text{wall}[][x]_2}^2 + \text{wall}[][y]_1 - \text{wall}[][y]_2^2}{2} \quad (4.3.4.4)
\]

\[
\text{min value}[] = \min(\text{half wall length}, \text{dis inter mid}) \quad (4.3.4.5)
\]

\[
\text{mid eyesightline}[][x] = \frac{\text{agent}[][x] + \text{firepool}[]}{2} \quad (4.3.4.6)
\]

\[
\text{mid eyesightline}[][y] = \frac{\text{agent}[][y] + \text{firepool}[]}{2} \quad (4.3.4.7)
\]

\[
\text{dis inter mid}[] = \sqrt{\text{inter}[][x] - \text{mid eyesightline}[][x]^2 + \text{inter}[][y] - \text{mid eyesightline}[][y]^2} \quad (4.3.4.8)
\]
\[
\text{half\_eyesightline\_length}[] = \sqrt{(\text{agent}[\cdot].x - \text{firepool}[\cdot].x)^2 + (\text{agent}[\cdot].y - \text{firepool}[\cdot].y)^2} / 2
\]

(4.3.4.9)

\[
\text{min\_value2}[] = \min(\text{half\_eyesightline\_length}[], \text{dis\_inter\_mid2}[])
\]

(4.3.4.10)

where,

\text{wall}[\cdot].x_1 = \text{the x-coordinate of the starting point of the wall};

\text{wall}[\cdot].y_1 = \text{the y-coordinate of the starting point of the wall};

\text{wall}[\cdot].x_2 = \text{the x-coordinate of the ending point of the wall};

\text{wall}[\cdot].y_2 = \text{the y-coordinate of the ending point of the wall};

\text{mid\_wall}[\cdot].x = \text{x-coordinate of the mid-point of the wall};

\text{mid\_wall}[\cdot].y = \text{y-coordinate of the mid-point of the wall};

\text{inter}[\cdot].x = \text{x-coordinate of the intersection point};

\text{inter}[\cdot].y = \text{y-coordinate of the intersection point};

\text{dis\_inter\_mid}[] = \text{the distance between the intersection point and the mid-point on the wall};

\text{hall\_wall\_length}[] = \text{the ½ length of the wall};

\text{min\_value[]} = \text{minimum value between hall\_wall\_length[]} and \text{dis\_inter\_mid[]};

\text{mid\_eyesightline}[\cdot].x = \text{x-coordinate of the mid-point on the eyesight line from the occupant to the fire pool};

\text{mid\_eyesightline}[\cdot].y = \text{y-coordinate of the mid-point on the eyesight line from the occupant to the fire pool};
dis_inter_mid2[] = the ½ distance between the intersection point and the mid-point of the eyesight line;

half_eyesightline_length[] = the ½ length of the eyesight line; and

min_value2[] = minimum value between half_eyesightline_length[] and dis_inter_mid2[].

If the value of min_value[] is half_wall_length[] and the value of min_value2[] is half_eyesightline_length[] at the same time (i.e., the intersection point is on the solid part of both of the wall and the line of sight), then the occupant is not able to detect the fire pool. If either of these is not satisfied, the occupant is able to detect the fire pool.

It is important to mention that occupants can not detect the dynamic smoke automatically in the current thesis work, and this will therefore be a topic for future work.

4.3.5 The moving speed calculation model

For a behavioral evacuation model, the ability to represent dynamic moving speed due to the dynamic environment is critical. Three inputs of the human behavior system discussed in Section 4.1, (i.e., occupants’ characteristics, building characteristics, and the fire hazard environment) affect the moving speed in the evacuation. Also, since occupants usually slow down when they are implementing wandering behavior, wall-following behavior in heavy smoke, and random walking behavior, the effects of these three behaviors are considered.
There are many other considerations for moving speed. For instance, is the moving speed the same in a mall as that in a private apartment? If it’s different, how much is it? Will they play non-trivial roles on the variation on moving speed? The answers to these questions are still not clear enough to help incorporate the effect of building characteristics into the moving speed calculation model. Therefore, the effect from the building characteristics (i.e., public place or private place) is not considered in the current thesis work and serves as a topic for future work.

As Table 4.2.1.1 shows, the moving speed of an occupant during evacuation can be affected by some critical occupant characteristics, such as the population number, density, location and distribution, physical ability, social affiliation, occupant’s health condition, gender, and age. The effects of physical ability, gender, age and occupant’s impeded moving speed due to the radiant heat on moving speed of occupants was considered in [1], and more details can be found in the reference. The effects of population number, density location and distribution are implicitly incorporated in the moving speed calculation in that work [1] by applying PSO as the movement calculation algorithm, (i.e., PSO automatically considers these effects during the simulation).

The effects of the fire hazard environment on the moving speed are actually reflected in the occupants’ health condition and, thus, impede the moving speed of occupants. The mathematical model was shown in Equations 3.5.4.1-3.5.4.4 in Section 3.5.4.
The effect of taking a group evacuation behavior on the moving speed, \textit{i.e.}, effect of social affiliation is also shown in Equations 4.3.3.2.3 and 4.3.3.2.10 in Section 4.3.3.2.

The effect of a wandering behavior or wall-following behavior on the moving speed in heavy smoke is demonstrated by Equation 4.3.5.1 as shown below.

\begin{equation}
agent[].v_{\text{max}} = agent[].v_{\text{max}} \times 0.3 
\end{equation}

(4.3.5.1)

Here, the impeded speed is achieved by simply multiplying the unimpeded speed with a constant 0.3, which means that in the heavy smoke, occupants are assumed to move at a speed that is 70\% less than the maximum unimpeded speed.

The effect of taking the random walking behavior is demonstrated by Equations 4.3.5.2 and 4.3.5.3 as shown below.

\begin{equation}
agent[].v_{\text{max}} = agent[].v_{\text{max}} \times 0.5 
\end{equation}

(4.3.5.2)

Equation 4.3.5.2 is applied when the occupant is in his pre-evacuation time (\textit{i.e.}, usually the alarm has not been activated). This equation is based on the fact that occupants will not be moving at a maximum speed while no emergency is occurring.

\begin{equation}
agent[].v_{\text{max}} = agent[].v_{\text{max}} \times 0.7 
\end{equation}

(4.3.5.3)

Equation 4.3.5.3 shows the impeded speed after the occupant’s pre-evacuation time which usually after they hear the alarm. At this point, if the occupant is still walking randomly, it is assumed they will move a little bit more quickly due to the psychological pressure from the alarm.
It should be recognized that these parameter values (0.3, 0.5, and 0.7) have been chosen based on common sense, as no research exists to provide more accurate settings.

The sequence of applying these separated effects on the moving speed of the occupants is illustrated by a flowchart, shown in Figure 4.25:
Deciding the Vmax by occupants' characteristics (age, gender, physical ability, etc)

Initializing occupants' characteristics

Adjusting the Vmax according to occupants' current behaviors (wall-following, wandering, random walking, etc)

Getting the final moving speed after applying the effects from the fire hazard environment

update to next simulation time step

Figure 4.25: the sequence of applying different effects on moving speed
4.4 Summary

In this chapter, the behavior system used in *Vacate* was introduced. Critical human behaviors have been modeled in detail. This behavior system provides a relatively sophisticated foundation upon which more research can build.

In next chapter, the *Vacate* algorithm is discussed. Extended menus, dialogs, and functions are discussed in detail.
Chapter 5

Structure and Development of Vacate

In this chapter, the combination of the fire hazard model and human behavior system in Vacate is demonstrated in the algorithm through the use of extensive flowcharts. Vacate was originally developed using Visual C++ [88] and OpenGL [89], and more functions have been developed and added into Vacate in the current thesis work to reflect the more sophisticated human behaviors and fire modeling. The functionality of the PC-based visualization tool is also discussed.

5.1 Flowchart of the final algorithm

Based on the discussion on the fire hazard model and human behavior system in previous chapters, this section provides the flowchart for the final algorithm that was used to develop the visualization tool, Vacate. The flowchart is self-explanatory, as each single piece of the algorithm has been already discussed in detail in previous chapters. Figure 5.1-5.4 shows the details of the algorithm.
Figure 5.1: Flowchart of the final algorithm (part A)
Assess the fire hazard degree for occupant i

Have occupant i decided to take single or group evacuation?

Is the pre-evacuation time for occupant i over?

Does occupant i want to stay?

Is occupant i engulfed in heavy smoke?

Another 20 seconds simulation time elapsed?

Decide the behavior (passive, active, wandering, wall-following) occupant i going to take based on previous processes

Decision: passive, active, wandering, wall-following

Has the behavior of occupant i been switched to active behavior from passive behavior or vise versa?

Re-initialize occupant i's personal best

Re-initialize the each exit's global best

Random walking behavior

Modified PSO calculation based on different selected behavior of occupant i

Figure 5.2: Flowchart of the final algorithm (part B)
Initialize all drive values to zero; i.e., \( x_p = 0; y_p = 0; x_o = 0; y_o = 0; x_f = 0; y_f = 0; x_s = 0; y_s = 0; x_w = 0; y_w = 0 \);

Assign exits for active evacuation behavior as candidate exits.

Assign exits for passive evacuation behavior as candidate exits.

Is occupant \( i \) taking active evacuation behavior?

Assume exits for active evacuation behavior as candidate exits.

Assign exits for passive evacuation behavior as candidate exits.

Is occupant \( i \) a group leader?

Calculate the focal point of occupant \( i \)

Adjust maximum speed of occupant \( i \) in case of waiting for followers.

Depend on 4 cases:

1. no fire pools are inside or outside of the current region
2. fire pools are inside of the current region but not outside
3. no fire pools are inside of the current region but fires pools are outside of the current region
4. fire pools are both inside and outside of the current region

and consider familiarity factor, apply corresponding objective functions (obj) on occupant \( i \)

\( p_{best}[i] = \text{obj} \)

\( p_{best}[i].x = \text{occupant}[i].x \)

\( p_{best}[i].y = \text{occupant}[i].y \)

\( \text{obj} < p_{best}[i] \)

Adjust maximum speed of occupant \( i \) in case of waiting for followers.

\( p_{best}[i] = \text{obj} \)

\( p_{best}[i].x = \text{occupant}[i].x \)

\( p_{best}[i].y = \text{occupant}[i].y \)

Figure 5.3: Flowchart of the final algorithm (part C)
Calculate forward drive using PSO, \( x_p, y_p \) (they are different based on different behaviors)

Calculate drive due to separation and queuing, \( x_s, y_s \)

If current region has fire pool(s)?

Calculate drive due to fire sources \( x_f, y_f \)

Calculate total drive
\[
\begin{align*}
x_t &= x_p + x_o + x_s + x_f \\
y_t &= y_p + y_o + y_s + y_f
\end{align*}
\]

Calculate the magnitude of total drive (mag)

Is \( \text{mag} > 1 \)?

Normalize total drive

Collision with wall?

Calculate the drive due to wall, \( x_w, y_w \)

\[
\begin{align*}
x_t &= x_w \\
y_t &= y_w
\end{align*}
\]

Is occupant \( i \) at desired exit?

Compute the ‘x’ and ‘y’ components of the final velocity of travel

Update position of occupant \( i \)

Is \( m_f \leq 0 \)?

occupant[\( i \)].v\(_{\text{max}}\) = 0

\( \text{No_of_dead_occup} \) ants++

Change occupant \( i \)'s region information

Re-initialize occupant \( i \)'s new personal best information

Re-initialize occupants new global best information

Figure 5.4: Flowchart of the final algorithm (part D)
5.2 Updated menu options and dialogs

*Vacate* was originally [1] developed using the objective-oriented programming language Visual C++ [88] and OpenGL [89]. Based on the final algorithm presented in the last section, numerous functions have been incorporated into *Vacate* to capture the new behaviors and fire model. The functionality built into this tool is discussed in this section as a guide for users of *Vacate*.

5.2.1 Updated Menu Options

In order to provide user interaction in *Vacate*, a set of menu options are provided as in any typical windows-based application. Three menu options are added into the previous version of *Vacate*. They are “Loading fire data”, “Type of the floor plan”, and “Alarm”. Figure 5.5 shows a screenshot of the menu options in *Vacate*.

![Figure 5.5: Menu Options](vacate-untitled.png)

In Figure 5.5, the menu option of “Loading fire data” is used to load the fire data calculated from *FDS* [67-68] into *Vacate*. The menu option of “Type of the floor plan” is used to define the type of the current floor plan under investigation, i.e., it is used to define whether the floor plan is part of a public or private building. The menu option of “Alarm” is used to define the reaction time of the alarm. Some original menu options are
also updated besides the main changes introduced above. These updated options are discussed in detail in the next sections.

5.2.2 New dialog in option of defining population

Since the characteristics of new occupants must be introduced into Vacate, a dialog box entitled ‘Setting four random traits’, defining the percentage of each occupant’s characteristics for the number of total occupants in the current floor plan, is designed to allow users to designate their desired values. The dialog is included in the menu option “Population->Setting random traits...”. Before starting the simulation, Vacate initializes (or applies) these characteristics on occupants randomly, based on the defined percentages. The dialog box is shown in Figure 5.6.

![Setting four random traits dialog box](image)

Figure 5.6: Dialog window defining percentage of total occupants for 4 occupants’ characteristics

Other detailed descriptions for defining the population can be found in [1].
5.2.3 Update in defining fire sources

Fire pools usually start as a small pool and slow to a large one. This natural feature is important in the *FDS* [67-68] calculations. To simulate this dynamic growth of fire pools, an entry of “ramping time of the fire (sec)” is included in the current dialog box of “Fire Pool Location”. Also, a fire spread rate is pre-defined as 0.03m/sec [67]. The updated dialog box is shown in Figure 5.7:

![Figure 5.7: Dialog window defining fire sources](image)

Other detailed descriptions of how the population is defined can be found in [1].

5.2.4 Loading fire data

By selecting “*Loading fire data->read *.csv files*”, six different categories of fire hazards data at (the height of 1.8 m) are loaded into *Vacate*, including:
• Concentration of CO₂ (mol/mol);
• Concentration of CO (ppm);
• O₂ (mol/mol);
• Visibility (m);
• Soot density (mg/m³); and
• Temperature (°C).

Figure 5.8 shows a screenshot of this menu option.

![Menu option of loading fire data](image)

**Figure 5.8: Menu option of loading fire data**

### 5.2.5 Option of selecting the type of the floor plan

By selecting “*Type of the floor plan->public place (office, mall, etc)*” or “*Type of the floor plan->private household*”, users can pre-defined the type of the floor plan. In current version of *Vacate*, two options are listed (public place or private household), which are critical to decide the delay time for each occupant after hearing the alarm. By default, the option of “*public place (office, mall, etc)*” is selected. The impact of the type of the floor plan change the delay time was discussed in section 4.3.1.

If the option “*Type of the floor plan->public place (office, mall, etc)*” is selected, a dialog box appears as shown in Figure 5.9:
Figure 5.9: Defining the regular delay time for public place
By default, the value in Figure 5.9 is set at 40 seconds.

If the option “Type of the floor plan->private household” is selected, a dialog box appears as shown in Figure 5.10.

Figure 5.10: Defining the regular delay time for private place
By default, the value of delay time shown in Figure 5.10 is set at 20 seconds.

As is noted in both of the dialog boxes, the final delay time varies depending on the occupants’ characteristics and the fire hazards as discussed in Section 4.3.1).
5.2.6 Option of pre-defining the alarm activation time

Depending on different simulation cases, users may want to pre-define a random activation time or a fixed activation time. Thus two options are provided in the menu options as shown in Figure 5.11.

![Figure 5.11: Defining the alarm reaction time](image)

By selecting “Alarm->Alarm with random activation time...”, a dialog box appears as shown in Figure 5.12.

![Figure 5.12: Defining the alarm with random activation time](image)

By default, a “30 seconds” maximum alarm activation time is provided. After selecting the “Start” menu option, Vacate calculates a random activation time between 0 and 30 seconds for the alarm. The alarm goes off as soon as the activation time is over.
By selecting “Alarm->Alarm with fixed activation time…”, a dialog box appears as shown in Figure 5.13. Again, in the simulation, the alarm goes off as soon as the fixed activation time is over.

Figure 5.13: Defining the alarm with fixed activation time
Chapter 6

Validation, Test cases and results

This chapter discusses the validation, test cases, and results of Vacate. First, a brief introduction of the validation of the evacuation simulation computer models is presented. Second, results of qualitative testing and quantitative validation of Vacate are discussed. Finally, concluding comments are given and critical future work is suggested for further validation of these models.

6.1 Introduction on the validation of evacuation models

Validation is an essential step in the continual development and acceptance of computer evacuation models used in fire safety engineering [91]. The most ideal form of validation would be to carry out full-scale and real-life evacuation drills and then compare those results with those predicted by computer models. However, to carry out such drills requires videotaping the entire process, filling out questionnaires, and using skilled personnel to make the drill results meaningful so that they can be analyzed and compared to the results from the evacuation models. This is usually too expensive to be considered by developers of computer evacuation models. Another way is to compare the flow characteristics of the crowd movement to the results of data from computer evacuation models. Tyagi [1] used the latter method, by comparing the initial Vacate results data
with research data obtained by Fruin [22]. The flow-density and a velocity-density relationship are achieved, suggesting the basic crowd dynamic characteristics of Vacate are valid. A third way is to compare the evacuation time from a reported experiment to the results from the evacuation model under validation. Gwynne [90] used this method to validate the buildingEXODUS evacuation model. In the current thesis work, the same approach is applied to validate the updated evacuation model, Vacate.

A systematic approach to evacuation model validation is suggested by Galea [91] which involves 4 types: 1) component testing; 2) functional validation; 3) qualitative validation; and 4) quantitative validation. Component testing is a part of the normal software development cycle checking various components performance as intended [91]. Functional validation involves checking to see whether the model possesses the range of capabilities required to perform the desired simulations [91]. The third form compares the nature of predicted human behavior with informed expectations. While this is only a qualitative form of validation, it is important, as it demonstrates that the behavioral modules built into the model are capable of producing realistic behaviors [91]. Quantitative validation compares model predictions with reliable data generated from evacuation demonstration [91]. Component testing and functional validation are certainly required for any tool that reaches a commercialization phase. In this work, validation of these two types is not discussed here. However, the validation of the third and fourth type, applied to Vacate, is discussed in detail due to their substantial impact on the behavioral evacuation models.
One of the major difficulties in the validation of evacuation models is the lack of useful quantitative data. This is because the majority of evacuation trials are not conducted for model validation purposes but to demonstrate the suitability of building design/staff procedures so as to gauge compliance to a regulation or standard. In most of these cases, insufficient data are collected to allow a detailed “validation” of evacuation models [91]. Ethic issues [97] also decrease the availability of validation data, especially referring to drills with the fire hazard environment, thereby making a convincing validation of evacuation simulation under fire emergency impossible.

Therefore, a complete validation of Vacate, including human behaviors in the fire hazard environment (such as wall-following, wandering, avoiding fire pools, etc), is not realistic. However, a simple validation of Vacate that does not require involving the fire hazard environment is possible. Section 6.2 discusses this in detail.

A test case for Qualitative Testing is performed and discussed in Section 6.3. Here, the name “Qualitative Testing” is used instead of “Qualitative Validation” due to the fact that the experimental validation data used are not sufficient to validate the predicted human behaviors in the fire hazard environment.

### 6.2 Quantitative validation of Vacate

Stapelfeldt [92] conducted an experiment in 1986 demonstrating the evacuation of one hundred police cadets from a small room within a school gym. Paulsen [93] reported on the same experiment in 1995. The evacuation was carried out specifically to generate information concerning evacuation movement. Due to the relative completeness of the
dataset, and the simplicity of the geometry, the experimental results are of particular use in quantitative validation [90].

6.2.1 Setting up the simulation in Vacate

The experimental evacuations were conducted through a single exit of variable width, using exit widths of 0.75m, 0.80m, 1.50m, and 1.60m. One hundred police cadets were grouped in a room (the dimension is not explicitly mentioned in the reference [92]). The gender distribution is unknown, although there is an indication that the population was made up of young, fit adults [137-138]. The data generated from this experiment suffers from the fact that each experiment was conducted only once. Thus, the evacuation times provided for each exit width represent the results from a single experiment rather than an average produced from a number of repeat trials [90]. In the current thesis work, however, multi-trials are simulated to get an upper and lower bound and a standard deviation of the evacuation time.

Similar settings as was applied in reference [90] are applied in Vacate for the validation of the evacuation. First the following characteristics are used: 100 males, 20-30 years old, with a maximum walking speed distribution of 1.2-1.5 m/s. No minimum walking speed was given in the experiment, so a minimum walking speed distribution of 0.6-0.8 m/s is defined based on previous research [1]. Second, due to the controlled nature of the event, i.e., there was no sociological or psychological impediment to the occupants [90]), the pre-evacuation time for each occupant is set to 0 during all simulations, assuming occupants start to move simultaneously. Third, the geometry (size of the room) is
specified as 3m in width and 8.5m in length so it maintains a population density of 4 persons/m² (required in the experiment) during the simulations.

The unit flow rates (occ/sec/m) and drive distributions [90] are pre-defined before the start of each simulation. However in Vacate, these parameters are automatically controlled by the PSO movement calculation method. Thus, they are not pre-defined in all the current validations.

As was done in the validation of buildingEXODUS [90] two different cases with two different exit widths (1.5 m and 0.75 m), are examined here. The initial position of each occupant is randomly generated and the scenarios are shown in Figures 6.1 and 6.2.

![Figure 6.1: Validation case with 1.5m exit before simulation starts](image)
6.2.2 Simulation results of the first case (involving the 1.5m exit)

The first case is given 150 simulations with the same starting position as shown in Figures 6.1 and 6.2. The simulation results for the validation case with 1.5m are compared with those from the experiment, buildingEXODUS [90] that also based on 150 simulations, data from Predtechenskii and Milinskii [23], and the results from an effective width model [94]. These results are shown in Table 6.2.2.1.

<table>
<thead>
<tr>
<th>Exit width (m)</th>
<th>Experiment results (sec)</th>
<th>Simulation results from Vacate (sec)</th>
<th>Simulation results from buildingEXODUS * (sec)</th>
<th>Predtechenskii And Milinskii* (sec)</th>
<th>Effective Width Model* (sec)</th>
</tr>
</thead>
</table>

*: these data are from reference [90]

In Table 6.2.2.1, the result from effective width model does not agree with the experiment results with an over estimation of 110%. The result from Predtechenskii and Milinskii agrees with the experimental result much more than the effective width model, but still shows a significantly longer evacuation times than that. However, the result from
*Vacate* (28.62 sec, 4.6% disagreement with the experimental result) matches the result from the experiment (30 sec) and *buildlingEXDOUS* (29.0 sec, 3.3% disagreement with the experimental result) very well which highlights the conservative nature of equations used in the Predtechenskii and Milinskii model and effective width model to calculate evacuation times.

The experiment conducted by Stapelfeldt however has a significant disadvantage that each of the cases (0.75m, 0.8m, 1.5m, and 1.60m) has only been tested once, *i.e.*, there was no replication of the experiments. Thus the evacuation times provided for each exit width represent the result from a single experiment rather than an average produced from a number of repeat trials. Had each trial been repeated several times, a range of evacuation times would have been generated with an upper and lower bounds and a standard deviation [90]. In current validation work, repeated trials (*i.e.*, 150 simulations) are applied to investigate the substantial nature of *Vacate*.

The statistical results of the 150 simulations for first case are shown in Table 6.2.2.2 as below:

*Table 6.2.2.2: Statistical results of 150 simulations for the first case*

<table>
<thead>
<tr>
<th>Number of simulations</th>
<th>Mean evacuation time $\mu$ (sec)</th>
<th>Maximum evacuation time (sec)</th>
<th>Minimum evacuation time (sec)</th>
<th>Standard deviation $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>28.62</td>
<td>31.95</td>
<td>25.60</td>
<td>1.32</td>
</tr>
</tbody>
</table>
Based on the results shown in Table 6.2.2.2, a distribution of evacuation times from 150 simulations can be calculated and the result is shown in figure 6.3.

Figure 6.3: Distribution of evacuation times from 150 simulations

As can be seen in figure 6.3, by connecting the middle point of each of blue skyline, a curve which is similar to a normal distribution curve is presented intuitively. This kind of distribution of the evacuation times agrees with the statement that E.R. Galea made in reference [91] which is “for any structure/population/environment combination, the evacuation performance of the combination is likely to follow the form of normal distribution”.

Figure 6.4 is the theoretical evacuation time distribution calculated from the mean evacuation time and standard deviation.
6.2.3 Simulation results of the second case (involving the 0.75m exit)

The only difference between the configurations in the first and second case is the exit width. Here the exit width is changed to 0.75m to investigate the influence of width to the evacuation time. Due to the small deviation of the first case and known distribution of the evacuation times (which is the normal distribution), 30 simulations are given to test this case. The statistical results of the 30 simulations for this validation case are shown in Table 6.2.3.1.

Figure 6.4: Assumed (theoretical) evacuation time distribution calculated from the mean evacuation time and standard deviation
Table 6.2.3.1: Statistical results of 30 simulations for the second case

<table>
<thead>
<tr>
<th>Number of simulations</th>
<th>Mean evacuation time (sec)</th>
<th>Maximum evacuation time</th>
<th>Minimum evacuation time</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>48.35</td>
<td>51.95</td>
<td>45.25</td>
<td>2.07</td>
</tr>
</tbody>
</table>

As shown in Table 6.2.3.1, a standard deviation is 2.07 which is a little bit larger than that from the first case. This difference can be explained by two possible reasons. 1) only 30 simulations are performed here; 2) the number of conflicts expected from the narrow exits (0.75m) in this case increases comparing to the wide exit case (1.5m) due to occupants are engaged in more interactions as they attempt to exit via the smaller opening [90].

For convenience, Table 6.2.3.2 integrating Table 6.2.2.1 is created to compare the validation results from the experiment, Vacate, buildingEXODUS, model based on Predtechenskii and Milinskii, and Effective Width Model.

<table>
<thead>
<tr>
<th>Exit width (m)</th>
<th>Experiment results (sec)</th>
<th>Simulation results from Vacate (sec)</th>
<th>Simulation results from buildingEXODUS * (sec)</th>
<th>Predtechenskii And Milinskii* (sec)</th>
<th>Effective Width Model* (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>55</td>
<td>48.35 [45.25-51.95]</td>
<td>51.5 [50.1-53.1]</td>
<td>69-74</td>
<td>168</td>
</tr>
</tbody>
</table>

In Table 6.2.3.2, the results generated using effective width model have the worst agreement of 205.5% of mean evacuation time which is then not trustable. The results
from the model of Predtechenskii and Milinskii, *Vacate* and *buildingEXODUS* have agreement of 25.5%--34.5%, 12.1%, 6.4%, respectively. However, if taking account of the effects of different drive distribution in *buildingEXODUS*, the evacuation times range from 66.2 seconds to 51.5 seconds [90] which means the biggest disagreement could be 20.4% [90]. Again the increasing disagreements for all of these evacuation models can be mainly attributed to the narrower exits (0.75m).

In general, both of the behavioral evacuation models, *Vacate* and *buildingEXODUS*, generated the simulations results match well with experimental results with a maximum disagreement of 20% of evacuation time for two cases. This feature outperforms the traditional evacuation time calculation models which are conservative.

**6.2.4 Investigating the effects of the different starting position of occupants on the evacuation time for the case involving the 1.5m exit**

Four different cases are considered here. The starting location is randomly distributed for three cases. For the last one, a special arrangement of the location is designed to test if there are significant differences between the evacuation time from this one and others. Since the model *Vacate* is trustable based on the validation results shown in section 6.2.2 and 6.2.3, only 10 simulations for each case are run. The starting location with a special arrangement is shown in figure 6.5:
Results are summarized in Table 6.2.4.1 as below:

Table 6.2.4.1: results for 4 cases with difference in starting location of occupants

<table>
<thead>
<tr>
<th>Case Index</th>
<th>Number of simulations</th>
<th>Mean evacuation time (sec)</th>
<th>Maximum evacuation time</th>
<th>Minimum evacuation time</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>28.23</td>
<td>30.95</td>
<td>26.45</td>
<td>1.23</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>28.05</td>
<td>29.40</td>
<td>25.80</td>
<td>1.16</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>28.09</td>
<td>29.50</td>
<td>24.70</td>
<td>1.40</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>27.58</td>
<td>29.40</td>
<td>25.5</td>
<td>1.21</td>
</tr>
</tbody>
</table>

In Table 6.2.4.1, all the mean evacuation times have disagreements within 8.1% (much less than 20%) compared to evacuation times from experimental results which are considered as small variations. Therefore, the difference on starting positions of occupants is considered to have no effects on evacuation times of this single room experiment.
6.3 Qualitative testing of Vacate

The tool *Vacate* can be tested against as many floor plans, fire hazard environment, and population mixes as desired. Here the floor plan used in reference [1] which is a fairly complex ground floor plan of a campus building at the University of Wales, U.K. is also used in the current thesis work. The following settings are unchanged: number of occupants (250 in total), starting locations of occupants, gender distribution of occupants, and disability distribution of occupants. The following new settings are included: location and ramping time of the fire pool, percentage (90%) of occupants that are familiar with the environment, percentage (1%) of staffs among occupants, percentage (0%) of sleeping occupants, percentage (5%) of occupants that have strong social affiliation, type of floor plan is set as public place and a fixed alarm activation time is set as 10 seconds. The configured floor plan is shown in figure 6.6.
Figure 6.6: Test Case Floor Plan (initial Setup)

In figure 6.6: the point fire source (or fire pool) is represented by a point which means it just starts burning. The fire pool grows up to a “big and yellow” in 18 seconds (ramping time) in default.
Figure 6.7: An Instant Scenario before the alarm goes off
As can be seen in figure 6.7, the blue lines connect leaders (green dots) with their followers demonstrating the group evacuation behavior. Groups have been found to affect the smooth merging of flows in corridors as they attempt to remain intact [2]. Occupants who see the fire pool are marked with black crosses. They usually start moving out right after detecting the fire pool. In figure 6.8, it can be seen clearly that most of the occupants are heading to the lower exit of the floor plan since the fire pool is blocking the upper exit. In the upright side of the floor plan, a red alarm mark is shown indicating the alarm has gone off. In figure 6.9, the smoke gets heavier and mostly fills the room with the fire pool. In figure 6.10, the floor plan is almost clear without much smoke. The total evacuation time, number of safe evacuations, and number of deaths are summarized in figure 6.11 which are 104 seconds, 250 occupants, and zero respectively.

Numerous behaviors are simulated including active evacuation, passive evacuation, group evacuation, random walking, detecting the fire pools automatically, redirecting to other exits if detecting fire pools, together with overtaking, queuing, avoiding the obstacles, variations in walking speed, and different response time (or pre-evacuation time) demonstrating the qualitative capabilities of Vacate. However, wall-following and wandering have not been observed in this testing case due to the fact no occupants have to go through the smoke area to evacuate from the current floor plan. If the reader is interested in examining these two behaviors, they can set up a special floor plan which has only one exit available during the entire evacuation simulation and apply fire hazards to predict wall-following and wandering.
Figure 6.8: An Instant Scenario after the alarm goes off
Figure 6.9: An Instant Scenario with smoke presents after the alarm goes off
Figure 6.10: An Instant Scenario shows the floor plan is almost clear

Figure 6.11: Summary of evacuation results
6.4 Summary

The predicted evacuation time from the qualitative testing case is approximately 104 seconds as summarized in figure 6.11 which could have a large variation among the experimental results due to the complexity of the floor plan, population structure, different fire scenarios and occupants’ characteristics. More validation data especially relatively complete data sets from real fire scenarios are needed. However, based on the quantitative validation performed in this chapter, it is confident to say that Vacate can predict the evacuation time with a reasonable accuracy when exact configurations of floor plan, population structure, fire scenarios, and occupants’ characteristics are given.
Chapter 7

Summary, Conclusions, and Future work

7.1 Summary and Conclusions

The purpose of this thesis work is to develop a model to predict crowd movement during evacuation in emergency situations such as fire, with particular emphasis on integration of human behaviors. The methodology is based on concepts from the heuristic optimization technique Particle Swarm Optimization (PSO), which was originated from the flocking of birds. By applying modified PSO, more complex human behaviors such as active evacuation, passive evacuation, random walking, wall-following, wandering, and group evacuation with a leader are simulated. The Human Behavior System is introduced to provide a basic frame to handle the inputs such as occupants’ characteristics, building characteristics, and fire environment and then produce the outputs such as human response to fire, evacuation modes, human behaviors, and moving speed.

The PSO method overcomes some of the drawbacks of existing computer models including implementing coordinated-based movement other than network node moment used in those models. More computer power is saved by applying PSO to give more spaces to advanced human behaviors such as looking for friends and, fire-fighting.
An updated Fire Hazard Model is included into Vacate to incorporate the effects of smoke and toxic elements on Human Tenability calculation. Instead of using Zone Fire Model to generate the fire hazard data, a Field Model Fire Dynamics Simulator is applied to simulate the effects of smoke transportation on the Information Processing and human behaviors. A simple model of combined hazard effects of smoke, heat and asphyxiants gases is introduced to give a better consideration of the overall fire hazard effects on the evacuation.

Probabilistic factors are introduced into the Information Processing Model to accommodate the uncertainty due to the complex nature of human information processing in emergency, and uncleanness due to the lack of enough research on this topic. The probabilistic based if-then-else structure used in current Information Processing Model gives a basic frame to future work. More practical and accurate prediction of Information Processing can be achieved by further modifications on pre-defined thresholds associated with probabilistic factors. More important, this probabilistic approach allows for a more profound evaluation of the evacuation process by performing a certain number of replicate runs with identical boundary conditions (or given settings) that can be analyzed statistically. Therefore, it is always recommended to give each single test case replicate runs during the development of fire safety designs to produce effective references to engineers and architects.
This methodology has been validated against the work done by Fruin for pedestrian planning and design on flow characteristics of crowd movement in reference [1]. In current work, a quantitative validation case based on the experiment conducted by Stapelfeldt has been presented to give another credit on this PSO based evacuation model.

The evacuation simulation tool *Vacate* is upgraded to a more complete behavioral evacuation simulation model. This tool is built using objective-oriented Visual C++ and OpenGL. It offers user-friendly interfaces including menus and dialogs that users can define different floor plans, place obstacles, use mixes of population, configure occupants’ characteristics, pre-define the building type, introduce point fire sources, set the activation time of alarms, load the fire data from *FDS*, and simulate the evacuation process for the given settings. The simulation results are presented by intuitive animations based on OpenGL, associated with the predicted evacuation time, number safe evacuations, and number of deaths.

### 7.2 Future work

Future work includes following five aspects. First, configurations on floor plans can be made more convenient to accommodate research on multi-floor evacuation, and large scale evacuation involving outside door and vehicle evacuation. Second, more complex human behaviors can be included in the model. Third, human tenability analysis based on the combined fire hazard effects on occupants can be performed. Fourth, thresholds used in the probabilistic-based human Information Processing Model can be further
investigated and verified. Lastly, extensive validation of the current developed model is needed.

The first future work area is to make the drawings of the layout of floor plans more convenient. Currently drawings are inputted by defining the coordinates of the starting points and ending points of walls. If more complex floor plans are required to be investigated, a more convenient drawing method is expected. A practical approach is to draw the layout of the floor plan in AutoCAD, a powerful engineering drafting software, and then load the drawing file into *Vacate*. Based on this improvement, research on the multi-floor and large scale evacuation with complex layouts will be much easier to carry on.

As to more complex human behaviors, seeking group members by the group leader during group evacuation is expected to be included in group evacuation as a topic of future work. Additional behaviors such as detecting the moving smoke, i.e., dynamic smoke, dodging the smoke barrier actively, and fire fighting may be under the future investigation.

More research on the model of combined fire hazard effects of smoke, heat and asphyxiant gases will be very helpful to improve the accuracy on human tenability analysis. This is, however, not easy to achieve because large amount of experimental data on human tenability in fire hazards are needed. Unfortunately, no sufficient data on are currently available mainly due to ethical issues.
The thresholds used in the probabilistic-based Human Information Processing Model in fire emergency also have the verification issues. There is, in general, lack of experimental data to verify the ranges of these thresholds. Physiological scientists and fire safety engineers are expected to work together to develop quantitative criteria for better defining these thresholds.

The last topic of future work deals with the need for extensive validation of *Vacate*. Currently, including *Vacate*, most of the computer evacuation models are validated through the experimental data produced from non-emergency evacuation drills which impedes the accuracy of validation to a certain degree. However, real emergency evacuation data are usually incomplete to serve for validation uses. Thus extensive validation is needed to maximally explore the nature of the evacuation models including *Vacate*, before they can be used independently for designing or training purposes. At this stage, *Vacate* is a behavioral computer evacuation simulation model for fire emergency to help engineers test the fire safety design of floor plans. The proposed topics herein for future work will bring *Vacate* into the next generation.


56. A Web-based Introduction to Fire Modeling

http://www.fpe.umd.edu/department/modeling/index.html


71. www.software.aeat.com/cfx


http://www.purdue.edu/dp/phsi/fire_model.pdf