THE DEVELOPMENT AND REPRESENTATION OF OCCUPANT PERFORMANCE IN BUILDING EVACUATION MODELING

Except where reference is made to the work of others, the work described in this dissertation is my own or was done in collaboration with my advisory committee. This dissertation does not include proprietary or classified information.

Rani A. Muhdi

Certificate of Approval:

Gerry Dozier
Associate Professor
Computer Science and Software Engineering

Gerard Davis, Chair
Assistant Professor
Industrial and Systems Engineering

Kent Oestenstad
Associate Professor
School of Public Health
University of Alabama at Birmingham

Saeed Maghsoodloo
Professor
Industrial and Systems Engineering

Joe F. Pittman
Interim Dean
Graduate School

THE DEVELOPMENT AND REPRESENTATION OF OCCUPANT PERFORMANCE IN BUILDING EVACUATION MODELING

Rani A. Muhdi

A Dissertation

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Doctor of Philosophy

Auburn, Alabama
May 10, 2008

THE DEVELOPMENT AND REPRESENTATION OF OCCUPANT PERFORMANCE IN BUILDING EVACUATION MODELING

Rani A. Muhdi

Signature of Author

May 10, 2008
Date of Graduation

VITA

Rani A. Muhdi, son of Abdullah and Neema (Deeb) Muhdi, was born in Amman, Jordan on January 29, 1977. He graduated from Saraj High School in 1994 and began his undergraduate at The University of Jordan in September of 1994. In June 1999, he earned a Bachelor of Science in Industrial Engineering. Following graduation, he worked for Al-Ganim Group. In 2000, he joined the Graduate School at East Tennessee State University in the Department of Industrial Engineering Technology. After completing a Masters of Science in 2002, he enrolled in the PhD program in Industrial and Systems Engineering at Auburn University to pursue a research interest in occupational safety and ergonomics. He married Yazmin A. Ali, daughter of Aziz Ali and Yara Landa on December 17, 2002.

DISSERTATION ABSTRACT

THE DEVELOPMENT AND REPRESENTATION OF OCCUPANT PERFORMANCE IN BUILDING EVACUATION MODELING

Rani A. Muhdi

Doctor of Philosophy, May 10, 2008
(Master of Science, East Tennessee State University, 2002)
(Bachelor of Science, The University of Jordan, 1999)

179 Typed Pages

Directed by Jerry Davis

Occupant characteristics are considered important features incorporated into most evacuation models. The relative scarcity of evacuation experiments in the literature, contributes to some extent to the continuous challenge of occupant data representation in computer evacuation models. Such a challenge is even more significant when modeling occupant behavior and performance responses to fire conditions since deteriorating conditions influence the occupants' adoption of new responses. The primary objective of this research was to bridge the gap between the development and representation of occupant data pertaining to crawling, one of the more important responses to evacuation in fire and smoke conditions. This research investigated occupant crawling speed compared to walking, and the effect of occupant characteristics; gender and body composition (BMI), on crawling in evacuation.

The study also examined the impact of route design on evacuation times for crawling movements by comparing evacuation time for a straight route to an indirect route design, and the influence of occupant characteristics on evacuation time for occupants crawling such an indirect route. After that, the current study looked into the relationship between crowd density and occupant crawling movement, by examining the impact of occupant configuration (number of occupants) and exit access width on crowd walking and crawling speeds on a flat surface. The last part of the research focused on the application of evolutionary computation techniques in building designs for walking and crawling egress, which has been evaluated by evolving the location and number of exits required to minimize evacuation time.

The results suggest a significant difference between normal walking and normal crawling speeds. Normal walking is performed at a faster rate than normal crawling. Further, gender and body composition significantly impact individual crawling speed as well as individual evacuation time when crawling an indirect route, since they are unique characteristics to the individual. Exit access width is significant to crowd crawling speed, whereas occupant configuration plays less of a factor. The study demonstrates a significant difference in crawling speeds at different exit access widths. The relationship between crowd crawling speed and density is best described by a quadratic regression model. Finally, evolutionary computation techniques can be used to find optimal building designs for walking and crawling egress. The designs are evaluated by evolving the best exit configuration(s) to minimize total evacuation time. However, the reliability of these techniques depends on the accuracy of the evacuation models utilized. The techniques have the potential to be implemented in more complex designs.

ACKNOWLEDGEMENTS

I wish to express my gratitude to my committee chair, Dr. Jerry Davis, for his guidance, wisdom, inspiration, as well as confidence in me through this learning process. I truly admire his research skills which helped make this work possible. My appreciation is also directed to Dr. Gerry Dozier, Dr. Kent Oestenstad, and Dr. Saeed Maghsoodloo for their responsiveness and support. My sincere appreciation is extended to Dr. Steven Gwynne, whose unique combination of brilliance and practical application inspired and challenged me to expand my intellectual capabilities. I would also like to thank Dr. Volker Schneider from Integrierte Sicherheits-Technik, Mr. Christian Rogsch from Bergische Universität Wuppertal, and Mr. Timo Korhonen from VTT Technical Research Centre of Finland for their assistance. In addition, thanks are due to the Deep South Center for Occupational Health and Safety, the National Institute for Occupational Safety and Health (NIOSH), and the Educational and Scientific Foundation of the Society of Fire Protection Engineers (SFPE) for their funding support. My sincere thanks go to my family and friends for their constant support and encouragement, especially my wife, who has been most supportive and patient throughout this journey. Above all, I am grateful to the Glory of God, who has blessed my life with many wonderful people and great opportunities; *“For God is full of bounty to mankind, but Most of them are ungrateful”* The Noble Qur’an, 2: 243.

Style manual or journal used:

Fire Technology, Springer Netherlands

Journal of Fire Sciences, SAGE Publications, Inc.

Fire Safety Journal, Elsevier Science Ltd.

Safety Science, Elsevier Science Ltd.

Computer software used:

Minitab 15.1.1.0, Microsoft Word 2003, Microsoft Excel 2003, Microsoft PowerPoint 2003, and AutoCAD 2006

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

The ongoing trend of advancing knowledge in building designs and structures has raised major concerns for occupant safety. Innovative methods and approaches are needed to understand and assess these complex designs to assure occupant safety and verify compliance with standards and guidelines. Traditionally, verification has been demonstrated through full-scale building evacuation drills. Although structural designs and evacuation procedures can be somewhat controlled during a full-scale evacuation experiment, and some similarities between real emergencies and experimental evacuation drills have been established [1], this option faces challenges in finding representative target populations, controlling the level of unpredictable variability, and dealing with ethical, practical, and financial difficulties [2, 3] to provide accurate evacuation data to the designs.

A promising alternative to conquer these challenges and assess occupant safety lies in computer evacuation models. Generally, a model is a representation of reality without the presence of reality itself [4]. In the context of evacuation, it refers to a close and fairly accurate approximation of real evacuation processes and features. Computer evacuation models not only assess the efficiency of evacuation processes by controlling challenges presented in evacuation drills, but also simulate the dynamic interaction between occupant, structure, and the environment.

One of the more important features incorporated into most evacuation models, relates to occupant characteristics. According to the *Life Safety Code*® [5], occupant characteristics are defined as the abilities or behaviors of people before and during a fire. Both regulations and fire safety codes, and the need for more reliable and validated computer evacuation models, suggest further attempts to understand and model occupant behavior and performance characteristics in fire [6]. The complexity of modeling occupant characteristics during evacuation, and the relative scarcity of evacuation experiments in the literature, contribute to some extent to the continuous challenge of occupant data representation in computer evacuation models.

Research Objective

It is apparent from the literature, as reported in Chapter Two of this dissertation, that there is a gap between the way occupant data is developed and the manner in which it has been represented in computer evacuation models. This gap is even broader when modeling occupant behavior and performance responses to fire conditions. The deterioration of environmental conditions and the interaction of occupants with such conditions influence the adoption of new responses such as moving through or redirecting away from smoke [7, 8]. Crawling represents another response that occupants choose, or are forced to choose, to avoid heat and smoke.

The presence and movement of smoke and fire have been incorporated into several computer evacuation models [9-17]. In order for existing and new models to have the potential to accurately simulate the impact of fire and environmental conditions on human behavior and performance responses during evacuation, it is vital to meticulously develop and represent appropriate occupant data for these responses. Simulating these responses, and others, enhances the ability of evacuation models to accurately evaluate the robustness of building designs and ultimately assess occupant safety.

The specific aim of this research is to bridge the gap between the development and representation of occupant data as it pertains to crawling, one of the important responses to evacuation in fire and smoke conditions. The astonishing lack of crawling data in literature poses fundamental challenges for evacuation modelers to integrate and validate the crawling behavior into computer evacuation models. It is, however, beyond the scope of this dissertation to investigate the likelihood of crawling, but rather focus on occupant performance once the decision to crawl has been made.

Format of the Dissertation

This dissertation is organized following the publication format. The manuscript chapters constitute the body of the dissertation. Chapters 1 and 7 are the traditional dissertation introduction and overall conclusions, respectively. Chapters 2, 3, 4, 5, and 6 are stand-alone manuscripts reporting methods, discussions, and results. Chapter 2 is a comprehensive literature review of the development and representation of occupant movement in evacuation models. Due to the special arrangement of this format, a brief literature review of the most relevant literature will be provided in each of the remaining manuscripts. Chapter 3 reports on preliminary experiments conducted to investigate crawling speed compared to walking, and the influence of occupant characteristics (gender and body composition) on speed reduction for occupants when crawling. Chapter 4 assesses the impact of exit route design on evacuation time for crawlers. Chapter 5 investigates the relationship between crawling speed and crowd density, and its representation in evacuation models. The development of occupant walking and crawling data in Chapters 3 has been employed by a software application utilizing an evolutionary computation approach to examine the effect of occupant crawling on evacuation planning (Chapter 6). The overall conclusions reached as a result of this research are presented in Chapter 7, along with a summary of the recommendations made, and the study limitations. The appendices contain information regarding the recruitment of human subjects, protocols adopted through the study, summaries of the data collected, and detailed statistical analyses supporting the results presented in the manuscript chapters.

CHAPTER 2

A REVIEW OF THE DEVELOPMENT AND REPRESENTATION OF OCCUPANT MOVEMENT DATA IN EVACUATION MODELS

Abstract. As evacuation models evolve, occupant performance data plays a key role in the development, functionality, and validation of these models. Despite the implementation of advanced computational and modeling techniques, evacuation models continue to quantify and predict occupant movement in normal and emergency conditions. This paper investigates the sources of occupant movement data on which evacuation models are based. After critically reviewing 62 different evacuation models, it is evident that there is a trend among models to utilize limited movement data sources. The sources most frequently used are nonemergency experimental studies, fire tests and incidents reports. The impact of these sources is strongly dependent upon the representation of occupant movement data in the models. The review reveals a gap between the way movement data is developed and the manner in which it has been utilized in the models. This review is an attempt to move forward the discussion of movement data experimentation and dissemination.

1. Introduction

As evacuation models are increasingly becoming a part of an innovative approach to assess occupant safety, model developers are faced with the challenge of demonstrating that their models accurately represent human physical abilities and behaviors during emergency conditions. Historically, two reasons have contributed to the challenge of representing occupant characteristics in evacuation models: (1) modeling occupant parameters for emergency evacuation based on non-emergency data [1], and (2) the relative scarcity of evacuation studies designed and conducted for modeling [2].

Evacuation models might characterize occupant parameters for emergency evacuations observed from nonemergency ones without foundation for their assumptions. The First International Symposium on Human Behavior in Fires in 1998 called for fewer, better, and universally accepted building evacuation models. Shields and Proulx [3] therefore suggested a strategic approach for the future development of models; calling for universal evacuation protocols in experimental studies, and modeling validation procedures to generate better quality data.

The lack of real evacuation data is attributed to ethical, practical, and financial difficulties [4]. The complexity of modeling occupant characteristics demands not only a vast amount of occupant data to improve the accuracy of evacuation models, but also a systematic comparison between experimental data and model predictions to provide more useful information to end users, investigate the uncertainty and variability in input and output data, and enhance the validation of models [5, 6]. Further, the advanced development of computational and modeling techniques has made the models capable of simulating conditions and situations that are yet to be supported by the experimental data available.

One of the important response characteristics of occupants identified by the *Life Safety Code*® [7] is the speed of movement (mobility), which is determined by individual physical capabilities and other crowding phenomena. The movement of occupants is a key element to the development, functionality, and validation of evacuation models. As sophisticated evacuation models continue to emerge, quantifying and predicting occupant movement remains a fundamental element in estimating the required evacuation time to reach safety (exit).

Since the work of Predtechenskii and Milinskii [8] and Fruin [9] in quantifying human movement in nonemergency conditions, the number of building evacuation models has significantly increased. Attempts to review the movement of occupants have essentially progressed into two groups: (1) some attempts have concentrated solely on reviewing the occupant movement data (values) obtained from evacuation studies, and (2) other reviews have discussed occupant movement techniques implemented in evacuation models as part of reviewing the functionality of those models.

The first group has resulted in a limited number of movement data reviews due to the relative scarcity of evacuation studies in the literature. For instance, Fahy and Proulx [10] summarized occupant data on walking speeds to feed the development and validation of evacuation models. An extended study by Lord et al. [11] reported an extensive literature review of data related to occupant walking speeds on horizontal surfaces and up and down stairs. Although the sources and values of occupant movement were reported in the studies, both reviews fell short in relating their findings to evacuation models.

Previous model reviews (the second group) have presented occupant movement in terms of the development and functionality of evacuation models. Kuligowski & Peacock [12] described the representation of occupant movement techniques in several evacuation models. The review discussed occupant movement data of 28 models but failed to categorize the data by source or type, since the primary focus of the review was primarily on modeling methods. Despite the valuable information these reviews present to model developers, fire safety engineers, and architects, none of the reviews (in both groups) has fully addressed the representation of the sources of movement data in evacuation models, or linked the implementation of data explicitly to the development of models. The purpose of this review is to categorize the models according to the movement data employed in order to identify the gap between the development of the data in evacuation studies and its representation in the evacuation models. Therefore, it is quite important to distinguish between investigating movement data available in the literature and the data actually implemented in the models [10, 11].

2. The Review Approach

The significant increase in the number of building evacuation models has resulted in a variety of evacuation model reviews [2, 4, 12-18]. The development of models at the time a review was conducted, the availability of models for commercial applications, and basically the existence of models in the literature are among some of the apparent reasons behind considering certain evacuation models for review over others.

The model selection criterion for this review is defined as any system or methodology, referred to in building evacuation research, used to calculate, simulate, or evaluate evacuation processes, is considered a candidate for review. Figure 1 depicts a suggested approach to help survey available building evacuation models to particularly address the sources of occupant movement data in the models. An intensive literature review of 62 evacuation models was conducted using the selection criterion. The surveyed models were then categorized into: (1) models that incorporate occupant data in terms of sources, measures, or functionality, along with other elements of the evacuation process (46 models), and (2) models that focus on the structure of the model and the interaction of evacuation elements without providing specific occupant data descriptions (16 models). Out of the 46 models that feature occupant data, only 34 models (Table 1) specifically address the sources of occupant movement data. The review further discusses the representation of those sources in the models. The review is solely based on evacuation literature and personal contacts with model developers and evacuation researchers.

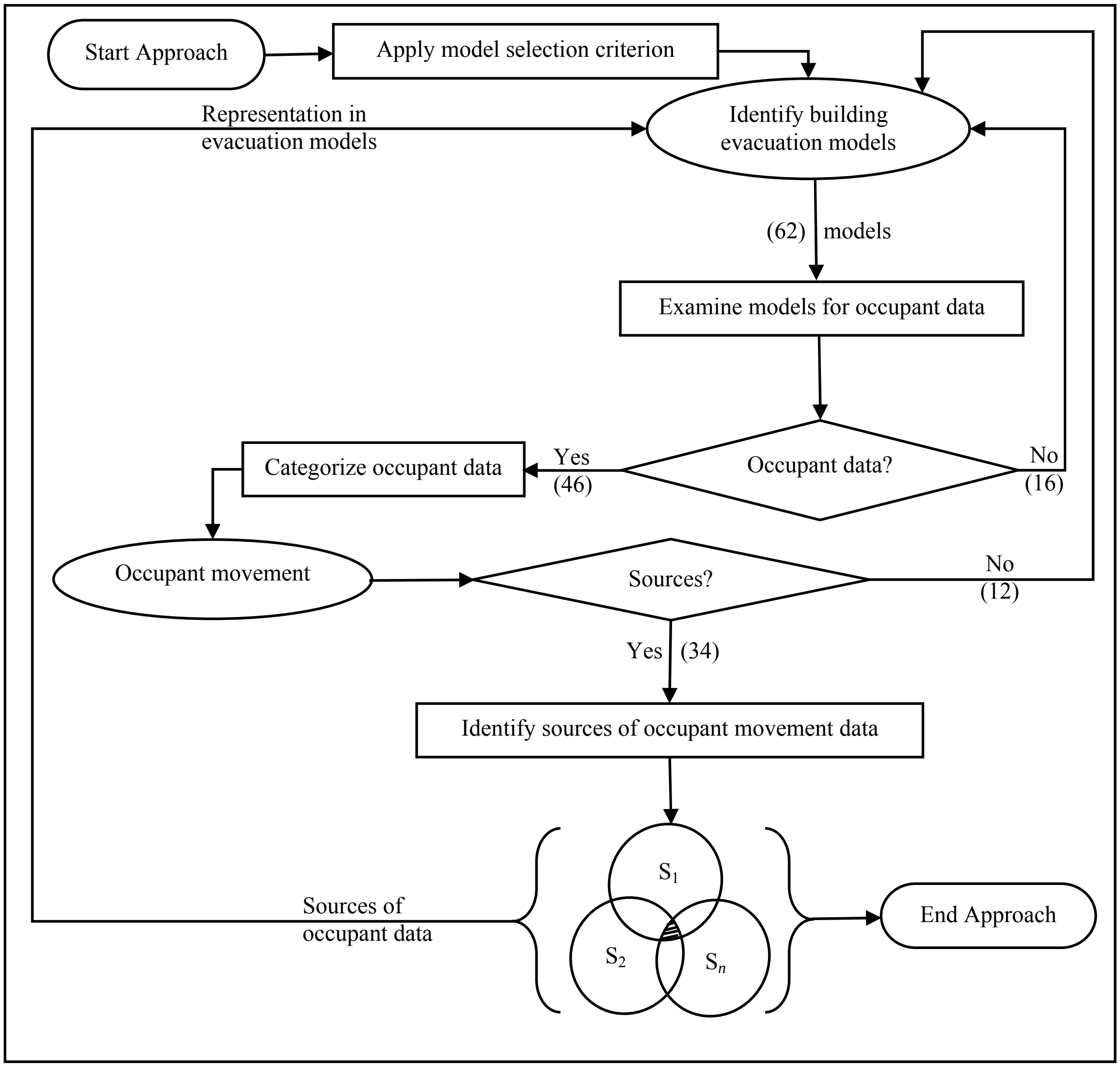


Figure 1. The approach to identify and classify occupant movement sources in evacuation models.

Table 1

Reviewed evacuation models that specify the sources of movement data

Model and Reference(s)
1. Allsafe [19]
2. ASERI [20]
3. Burstedde's Model [21]
4. CRISP III [22]
5. Daoliang's Model [23]
6. EESCAPE [24]
7. EGRESS [25, 26]
8. EgressPro [27]
9. EMBER [28]
10. Escape and Rescue model [29]
11. ESM [30]
12. EVA [31]
13. EvacSim [32]
14. Exit89 [33]
15. EXITT [34]
16. EXODUS [35, 36]
17. Firescape [37]
18. FPETool [38]
19. GridFlow [39]
20. Johnson's Model [40]
21. Kirchner's Model [41]
22. Lizhong's Model [42]
23. Magnetic Model [43]
24. MASSEgress [44]
25. PATHFINDER [45]
26. SGEM Model [46]
27. Simulex [47]
28. Social Force Model [48]
29. Song's Model [49]
30. STEPS [50]
31. Takahashi's Model [51]
32. TIMTEX [52]
33. VEgAS and Myriad [53, 54]
34. WAYOUT [55]

3. Sources of Occupant Movement Data in Evacuation Models

Human movement research in building evacuation has been underway for nearly 40 years. Some of the earliest research quantifying the movement of people is the work of Pedtechenskii and Milinskii [8], and Fruin [9]. Studies have been mainly conducted under normal conditions due to the danger inherent in emergency environments. Consequently, building evacuation models deploy nonemergency occupant movement and density data due to the lack of representative data under emergency conditions. Therefore, the movement of occupants in the models is generally unimpeded unless occupants become closer in a high density situation. This changes the speeds and flow rates assigned to individuals during evacuation based on the density of the available space. After intensive review of available models, the sources of occupant movement data can be classified into two distinct groups: experimental studies, and fire tests and incident reports.

3.1. Experimental studies

The majority of the reviewed models obtain their occupant movement data from a number of nonemerget experimental studies [8, 9, 56-67]. Tests and observations from those studies have been implemented to establish movement algorithms for several evacuation models such as EgressPro [27], EvacSim [32], GridFlow [39], PATHFINDER [45], TIMTEX [52], and WAYOUT [55]. Furthermore, the nonemergent studies have provided many of the reviewed models with default values for a range of occupant movement parameters. Examples of these parameters include unimpeded velocities, movement probabilities, average empirical velocities, adjusted travel speeds, and movement through exits, stairs, routes, and smoke conditions. The following classification of evacuation models and their movement values is based on the occupant movement parameters developed in those experimental studies.

3.1.1. Unimpeded and adjustable speeds (speed vs. density)

In the evacuation model Egress [25, 26], the default value of average speed (0.9 m/s), standard deviation (0.424 m/s), alternative haste factors of 1.5 m/s and 0.6 m/s for emergency and unconcerned crowd movement situations, respectively, and probability values are all based on the work of Predtechenskii and Milinskii [8]. The movement speed is adjusted as crowd density changes. Occupant flow is calculated as a function of density, which shows similarity to some experimental data [8, 9, 63]. The maximum density in the model is set at 5 occupants/m^2.

EgressPro [27] uses calculations from Nelson and MacLennan [61]. The program also predicts the flow of groups of persons in an emergency based on the relationship between speed of movement and the population density. Shen [30] introduced the evacuation simulation model (ESM) with adjusted travel speeds of occupants based on density. When density is less than 0.54 persons/m^2, the speed adopts the free walking speed value of 1.19 m/s. When density is greater than 3.8 persons/m^2, the occupants are moving at a much slower rate. The results are also given by Nelson and MacLennan [61].

The model EESCAPE [24] does not assign fixed values to the flow density or velocity for each individual or separate group but considers them to be a single group of a certain mean density on each section of the escape route. The model uses density on each component of the escape route to calculate the speed of the occupant through the escape route based on the work of Pauls [62] and Predtechenskii and Milinskii [8]. It also provides predictions of the time required for the total evacuation of high-rise buildings via staircases based on the work of Kendik [68]. Total evacuation times for a certain flow density on the means of escape are determined based on a mathematical method developed by Predtechenskii and Milinskii [8]. Exit89 [33] also employs Predtechenskii and Milinskii's work [8] on movement through doors and down stairs using density calculations. The model's unimpeded horizontal emergency speed and optimal density are set at 1.36 m/s and 0.92 m^2/m^2, respectively.

The evacuation model SGEM [46] and Simulex [47] implement the findings of Ando et al. [56] to represent individual unimpeded speeds. The walking speed of an individual in SGEM [46] is a function of crowd density. Unimpeded speed is considered when there is no other person in a 1.12 m^2 area around an evacuee. In the evacuation model Simulex [47], each individual is assigned a random walking speed between 0.8 and 1.7 m/s. Other specific unimpeded speeds in the model are 1.35 m/s ± 0.2 for males, 1.15 m/s ± 0.2 for females, 0.9 m/s ± 0.3 for older adults, and 0.8 m/s ± 0.3 for children.

The evacuation model MASSEgress [44] includes five population types; median, adult male, adult female, child, and elderly. The model currently shows the differences between the five population types in terms of mobility. Each population type represents a typical segment of the human population. Average walking velocity and maximum running velocity on a level surface are obtained from Eubanks and Hill [58] and Thompson et al. [66].

TIMTEX [52] applies data from tests and observations [8, 9, 62] to provide a foundation for fluid flow equations. These equations estimate evacuation time based on the relationship between population density and speed of movement. The model uses the equations specified in the SFPE Handbook [61] to move occupants through corridors and stairs. When queuing occurs, the model assumes that the upper floors dominate the flow. The model accounts for an evacuation efficiency factor of 0.68 for delay in decision to egress and the time for people to reach the corridor and move towards an exit. The flow ascending stairs (10% slower than the flow descending) and default speed of 64% of common stairs are based on Pauls [62]. Finally, the occupant movement and density of WAYOUT [55] is also based on the findings of Predtechenskii and Milinskii [8].

3.1.2. Empirical and constant speeds

Burstedde's model [21] employs an empirical average velocity of 1.3 m/s based on the work of Weidmann [67]. In the evacuation model EVA [31], walking pace on a level surface is set at approximately 1.5 m/s ignoring different agent speeds. As a result, each agent in the model moves at a constant simulated speed. The formulated natural movement was based on pedestrian steps. When considering other modes of transport such as wheelchair, bicycle, or car, the natural movement would differ.

The intended paces of movement used in Johnson's model [40]; walk, fast walk, and run are all based on Pauls [62]. The intended pace of movement used in the model is one of three options: walk at 1 m/s, fast walk at 1.5 m/s, and run at 2 m/s. In the evacuation model GridFlow [39]; the movement's algorithms employed are based on Nelson and MacLennan [61]. Each occupant is assigned an unimpeded walking speed. The default walking speeds are assigned from a theoretical normal distribution ($\mu = 1.19$ m/s, $\sigma = 0.3$ m/s). Finally, Lizhong's model [42] applies the average empirical velocity of a normal human (in a nervous state) at 1.5 m/s [8].

3.1.3. Speeds in smoke conditions

The work of Boyce et al. [57], Jin [59], and Jin and Yamada [58] provide EXITT [34] and buildingEXODUS [35, 36] with travel speeds in normal and smoke conditions. EXITT [34] applies normal travel speed for each occupant at 1.3 m/s. If the fire is serious, a faster normal speed of 1.69 m/s (30% increase) is assigned. When assisting other occupants, walking speed becomes 0.65 m/s (50% of normal). If the fire is considered serious during assisting others, the speed increases to 0.84 m/s. A value of 0.78 m/s (60% of normal) is assigned if smoke is thick and depth of the lower layer is less than 1.5 m. The value becomes 0.52 m/s when assisting others in smoky conditions. On the other hand, buildingEXODUS [35, 36] implements a default fast walk of 1.5 m/s, while walk, leap and crawl are at engineering judgments of 0.9, 0.8, and 0.2 of the fast walk, respectively. The default value of flow rate is set at 1.33 occupants/m/sec with an indefinite range.

3.1.4. Hydraulic flow speeds

The physical attributes of EvacSim [32]; maximum horizontal and stair speeds, use a bilinear travel speed model as proposed by Nelson and MacLennan [61] based on the findings of Fruin [9], Pauls [62], and Predtechenskii and Milinskii [8]. The model travel speed for disabled occupants also uses the same speed model, but incorporates a different horizontal and stair maximum velocities. Finally, the model PATHFINDER [45] also follows the hydraulic flow model of Nelson and MacLennan [61] but tracks occupant movement and position individually by room or floor to find bottlenecks and queues in designs.

3.2. Fire tests and incident reports

Fire tests and incident reports represent another major source of occupant movement data. For example, the model Allsafe [19] bases its functions on actual incidents determined through studies conducted by SINTEF on large fire incidents. Likewise, EMBER [28] imitates the dynamic movement of rescue personnel and occupants using horizontal and vertical travel speeds. The rate of occupant movement is obtained from fire tests in single-family dwellings in Los Angeles [69]. Finally, the assumptions of Firescape [37] are based on the analysis of the Beverly Hills Supper Club fire.

4. The Representation of Movement Data in Evacuation Models

Occupant movement data in the reviewed models can be determined by the model users or obtained from pre-defined values or statistical distributions. Many evacuation models are designed to allow users to modify the default movement values. Users can adjust occupant movement data in a number of models by either specifying movement speed values or defining statistical parameters of probability distributions used to generate such values. However, such flexibility given to the end user does not imply that the user can impact the movement algorithms developed in the design phase of these models, but rather the input variables of movement for specific simulation runs. The following is a description of occupant movement representation in some of the reviewed models.

In the Escape and Rescue model [29]; pre-defined speeds are assigned to 15 occupant types ranging from occupants requiring staff assistance to those moving alone.

The time scale in Kirchner's model [41] corresponds to a pre-determined empirical speed. Similarly, an occupant movement of one grid each time step results in a pre-assigned average speed for Song's model [49]. Takahashi's model [51] and STEPS [50] assume constant walking speeds that can be input by the user.

Alternatively, uniform and normal distributions have been used to generate random occupant movement values for evacuation models. Velocities in the Magnetic model [43] are decided by random values generated from a normal distribution, while positions are decided by uniform random values set to each group to increase velocity as occupants move toward an exit. The social force model [48] also assumes a normally distributed speed that is compatible with empirical data. Walking speeds in Daoliang's model [23] range according to a uniform distribution. The movement speed of each occupant in Firescape [37] is determined by a random perception of risk to provide a weight for the subjective estimate of the situation.

Finally, in the model CRISP III [22], the user defines the movement speeds for different classes of people by selecting a probability distribution and its statistical parameters (i.e., mean and standard deviation) for each class. The model then randomly assigns a speed value to each person depending on the defined probability distribution. Similarly, occupant movement in the model ASERI [20] is an individual input or generated from a statistical distribution.

5. Discussion

It is apparent that there is a general trend toward specific sources of occupant movement data in building evacuation models. The impact of these sources is strongly dependent upon the representation of occupant input data and how the models actually implement such data. For instance, an average speed of 1 m/s collected in experimental settings, and subsequently used in an evacuation model does not imply that the model will run a speed of 1 m/s during the evacuation process. The extensive employment of experimental data demonstrates the need to focus on the development and representation of such data in evacuation models.

The foregoing review exhibits a wide range of occupant movement represented in evacuation models. Table 2 summarizes some default values of occupant movement in some evacuation models. The variability in occupant data is also reflected in the sources from which it was drawn. For example, the measurements of Predtechenskii and Milinskii [8] on speed and density sometimes show a significant change in speed at the same density level. This inconsistency has also been shown by Fruin [9] when measuring average free-flow walking speeds for males and females.

Table 2

Default values of movement input data to building evacuation models

Model	Movement Condition/Type	Value (m/s)	Source
Burstedde	unimpeded	1.30	Weidmann [67]
Daoliang	walk	U~[0.5-1.50]	pre-determined by developers
EGRESS	unimpeded	N~(0.9, 0.424^2)	Predtechenskii and Milinskii [8]
	haste factor (emergency)	1.50	
	haste factor (non-emergency)	0.60	
Escape & Rescue	resident 0	1.50	pre-determined by developers
	residents 1A, 6A	1.00	
	residents 3C, 6B, 6C, 30A, 30B, 30C	0.75	
	residents 10	0.67	
	residents 1B, 20, 40	0.50	
	resident 3A	0.30	
	resident 3B	0.15	
ESM	unimpeded	1.19	Nelson and MacLennan [61]
EVA	unimpeded horizontal (emergency)	1.50	Sutherland et al. [65]
Exit89	unimpeded horizontal (emergency)	1.36	Predtechenskii and Milinskii [8]
EXITT	unimpeded	1.30	Jin [59]
	fast speed (serious fire conditions)	1.69	
	assisting others (minor fire danger)	0.65	
	assisting others (serious fire)	0.85	
	unimpeded (minor smoke conditions)	0.78	
	assisting others (serious smoke)	0.52	

EXODUS	fast walk	1.50	Jin [59]
	walk	1.35	
	leap	1.20	
	crawl	0.30	
FPETool	unimpeded on flat pathways	1.27	pre-determined by developers
	unimpeded on stairs (ascending)	0.20	
GridFlow	unimpeded	N~(1.19, 0.30^2)	Nelson and MacLennan [61]
Johnson/ Firescape	walk	1.00	Pauls [62-64]
	fast walk	1.50	
	run	2.00	
Kirchner	maximum	1.3	Burstedde et al. [21]
Lizhong	nervous state	1.50	Predtechenskii and Milinskii [8]
MASSEgress	average flat walking (median)	1.30	Thompson et al. [66] and Eubanks and Hill [58]
	average flat walking (adult male)	1.35	
	average flat walking (adult female)	1.15	
	average flat walking (child)	0.90	
	average flat walking (elderly)	0.80	
	maximum flat running (median)	4.10	
	maximum flat running (adult male)	4.10	
	maximum flat running (adult female)	4.10	
	maximum flat running (child)	3.40	
	maximum flat running (elderly)	2.75	
SGEM	walk	1.40	pre-determined by developers

Simulex	walk	U~[0.80-1.70]	Ando et al. [56]
	unimpeded (male)	U~[1.15-1.55]	
	unimpeded (female)	U~[0.95-1.35]	
	unimpeded (elderly)	U~[0.60-1.20]	
	unimpeded (child)	U~[0.50-1.10]	
Social Force	desired	N~(1.34, 0.26^2)	pre-determined by developers
	leaving a room (relaxed)	0.60	
	leaving a room (normal)	1.00	
	leaving a room (nervous conditions)	1.50	
Song	unimpeded	1.00	pre-determined by developers
STEPS	walk	1.00	pre-determined by developers

The review also reveals that the global representation of movement data is sometimes extracted from experimental studies that are limited in scope, conditions, or controls but then applied to a variety of scenarios in the models, functioning under very different assumptions. The default stair speeds used in some models are obtained from Fruin [8] who studied movement and behavior of 700 people on stairs considering gender, age, stair angle, riser height, and tread depth. However, the study involved only two specific stair dimensions; indoor (7 inch riser, 11.25 inch tread, 32^o slope), and outdoor (6 inch riser, 12.0 inch tread, 27^o slope). In another representation, the travel speeds obtained from Boyce et al. [57] and Shields et al. [70] were collected from a small number of participants, a wide range of variability in values, and simple experimental designs with low levels of control.

Another finding from this review is that occupant data is sometimes extrapolated beyond the results of the sources upon which it is based. The speed ratios of evacuating in smoke conditions implemented in some models are based on Jin [59], where 31 participants (14 males and 17 females) performed simple mathematical calculations while walking in a smoke-filled corridor. Using those results, buildingEXODUS [35, 36] applied engineering judgments to establish speed ratios for walk, leap, and crawl. The crawling ratio was established from extrapolated data [59] although crawling was never conducted in the study. Similarly, the speed ratios in EXITT [34] for serious fire conditions, assisting other occupants, and high smoke concentrations are also extracted from the same study [59].

The compatibility of movement data with their respective models was also noted as a potential issue. In the evacuation model Simulex [47], individuals are assigned random walking speeds between 0.8 and 1.7 m/s. This is intended to represent a population that contains an even distribution of males and females, with ages ranging from 12 to 55 years. The model does not demonstrate the fitness of such data to all populations although its results correlate with real life values of crowd flow. Information about the nature of the data, the subjects from which the data was generated, or data validation was not provided.

6. Conclusion

Since the initial efforts to model evacuation scenarios some 40 years ago, significant progress has been made in understanding and modeling human behavior and performance characteristics in evacuation. Regardless of the complexity of computational techniques implemented in current advanced building evacuation models, occupant data always plays, along with other evacuation elements, a fundamental role in the development, functionality, and validation of these models. In general, models have managed to incorporate occupant performance data through the presentation of occupant movement. This review was performed to investigate and compile the available sources of human performance data values employed in 34 building evacuation models[1].

It is evident from this review that there is a conspicuous trend among evacuation models to obtain occupant movement data from certain sources. The influence of these sources on the development of the models obviously varies with the variety of ways they are employed in the models. Some sources of occupant data such as experimental

---

[1] The author acknowledges that some models were not considered for this review due to the difficulty of obtaining occupant information, or the late appearance of such information in the literature at the time this review was conducted.

research on human movement in nonemergency conditions and fire incidents and reports are engaged at the early design phase of the models. On the contrary, some advanced evacuation models provide users with a level of flexibility to alter occupant input data to the models. However, the flexibility does not diminish the importance of other sources in the development of those models.

In summary, the review implies that there is a gap between the way occupant movement data is developed in the literature and the manner in which it has been represented in the models. The scarcity of occupant data has encouraged evacuation modelers to apply these limited sources of movement to situations different from those which the data was generated for. The mismatch between data and its applications in the models has also extended to model validation despite the fact that models functionality could be affected.

CHAPTER 3

THE EFFECT OF OCCUPANT CHARACTERSITICS ON CRAWLING SPEED IN EVACUATION

Abstract. The movement of occupants is a key element to the development of evacuation models which estimate the required evacuation time to reach an exit. The deterioration of environmental conditions influences occupants to adopt new responses. This study investigates crawling movement as a physical response to environmental conditions in fire. The study investigates occupant crawling speed compared to walking, and the effect of occupant characteristics; gender and body composition (BMI), on crawling in evacuation. Eighteen subjects (9 males and 9 females) within the 19-29 age stratum participated in the study (normal, overweight, and obese body composition). The findings indicate a statistical significance between normal walking and crawling speeds. Further, the study statistically demonstrates that both gender and body composition significantly impact individual crawling speed as they are unique individual characteristics. More research is needed to better understand the effect of age group, mobility capabilities, and fatigue on crawling speed. The study concludes that the development of crawling data and its representation in evacuation models will enhance the accuracy of evacuation models, and better evaluate the safety of evacuees.

1. Introduction

Evacuation models are becoming a promising alternative to the challenges of full-scale evacuation drills, used to assess the safety of occupants and building designs and structures [1]. Regardless of the complexity or techniques used, evacuation models incorporate occupant characteristics in their attempt to accurately represent the evacuation process and its features. According to the *Life Safety Code*® [2], occupant characteristics refer to the abilities or behaviors of people before and during a fire. An important occupant characteristic during fire evacuation that the *Code* identifies is speed (mobility), which is a key element in the representation of human physical abilities in evacuation models [3]. The work of Predtechenskii and Milinskii [4], Fruin [5], and many others [6-17] in quantifying human movement has significantly contributed to the representation of occupant physical characteristics in evacuation models. The findings of these studies have provided the models with a range of movement speeds (Figure 2).

The deterioration of environmental conditions during a fire, in terms of heat and smoke, and the interaction of occupants with such conditions influence the adoption of new behavioral and physical responses [18-21]. One of the physical responses to smoke and heat that occupants choose, or are forced to choose, is crawling. Despite the extensive literature on quantifying human movement, little research has been conducted on human physical abilities to crawl during evacuation. Muhdi et al. [22] compared normal and maximum crawling velocities to walking. The study suggested further research focusing on certain occupant characteristics. Another study conducted by Nagai et al. [23] compared experimental and simulated evacuation processes of walkers and crawlers through an exit. A similar study [24] investigated, experimentally and via simulation, the phenomenon of counterflow for both walkers and crawlers in a hall. Both studies [23, 24] focused on the evacuation process without emphasizing on occupant characteristics. In light of the significant absence of crawling data in the literature, it is necessary to conduct some basic experiments to further investigate occupant crawling speed compared to walking, and the effect of occupant characteristics on walking and crawling in evacuation.

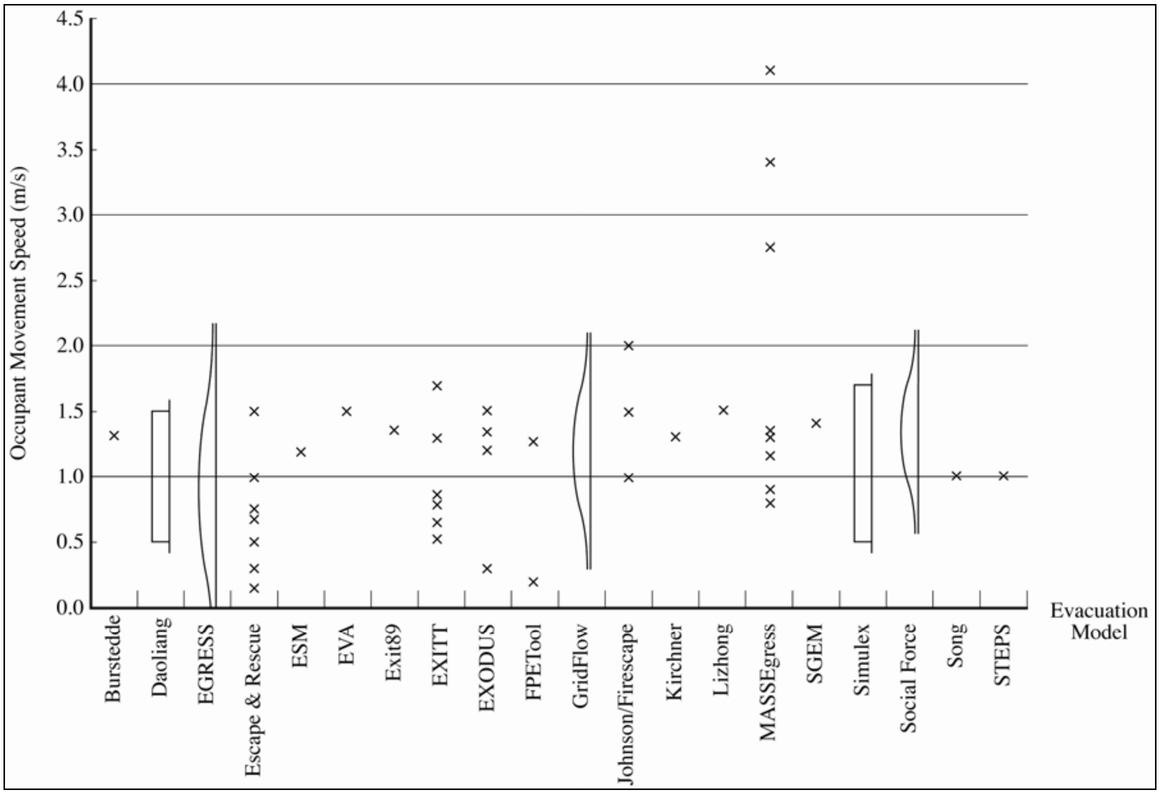


Figure 2. Default occupant movement speeds in evacuation models.

One of the characteristics that is of particular interest in this study is body composition, known as Body Mass Index (BMI). The index is a screening tool that provides a reliable indicator of body composition, and it is primarily used to classify people in one of four distinct weight categories: underweight (BMI < 18.5), normal (18.5 < BMI ≤ 25.0), overweight (25.0 < BMI ≤ 29.9), and obese (BMI ≥ 30.0). According to the 1999-2002 National Health and Nutrition Examination Survey (NHANES), an estimated 65 percent of U.S. adults are either overweight or obese [25]. This indicates a 16 percent increase compared to the age-adjusted overweight estimates obtained from the 1988-1994 NHANES III. Figure 3 compares the findings of the 1992-2002 NHANES to NHANES II and III.

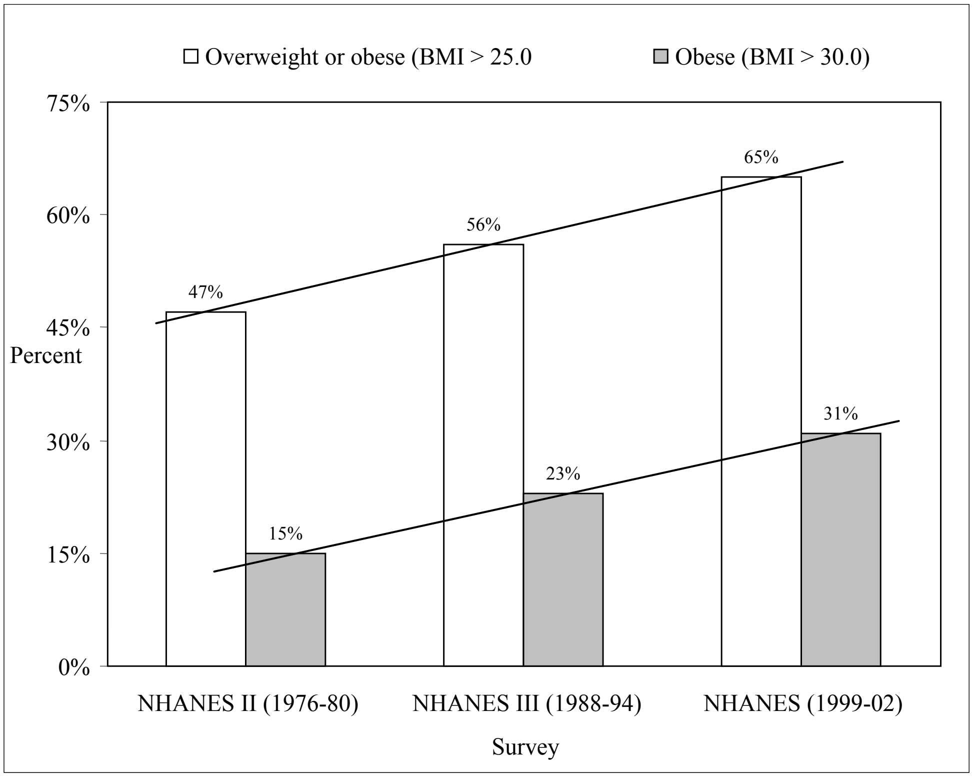


Figure 3. Age-adjusted prevalence of overweight and obesity among U.S. adults, age 20-70 years.

2. Methodology

2.1. Objective and Hypotheses

The purpose of this study is to examine the effect of occupant characteristics, in terms of gender and body composition (BMI) on walking and crawling in evacuation. The hypotheses for the study are:

Hypothesis 1: There is no significant difference between individual normal crawling speed (NC) and individual normal walking speed (NW) on a flat surface for both healthy (cognitively and physically) males and females within the 19 – 29 age stratum.

$$H_0 : \mu_{Nornal\ Crawling\ Speed} = \mu_{Normal\ Walking\ Speed}$$
$$H_1 : \mu_{Normal\ Crawling\ Speed} \neq \mu_{Normal\ Walking\ Speed}$$

Hypothesis 2: There is no significant difference between individual normal crawling speed on a flat surface for healthy (both physically and cognitively) males within the 19 – 29 age stratum and individual normal crawling speed on a flat surface for healthy (both physically and cognitively) females within the same age stratum.

$$H_0 : \mu_{Normal\ Crawling\ Speed\ \ for\ Males} = \mu_{Normal\ Crawling\ Speed\ \ for\ Females}$$
$$H_1 : \mu_{Normal\ Crawling\ Speed\ \ for\ Males} \neq \mu_{Normal\ Crawling\ Speed\ \ for\ Females}$$

Hypothesis 3: Individual normal crawling speed on a flat surface for both healthy (cognitively and physically) males and females within the 19 – 29 age stratum is unaffected by their body composition (BMI).

$$H_0 : \mu_{Normal\ Crawling\ \ for\ Normal\ Body\ Composition} = \mu_{Normal\ Crawling\ \ for\ Overweight\ Body\ Composition} = \mu_{Normal\ Crawling\ \ for\ Obese\ Body\ Composition}$$
$$H_1 : \mu_{Normal\ Crawling\ \ for\ Normal\ Body\ Composition} \neq \mu_{Normal\ Crawling\ \ for\ Overweight\ Body\ Composition} \neq \mu_{Normal\ Crawling\ \ for\ Obese\ Body\ Composition}$$

2.2. Experimental Design

In order to test these hypotheses, a mixed-factor analysis was constructed with the level of significance (α), set at 0.05. The factors in this study were activity (walking, crawling), BMI (normal, overweight, obese), and gender (male, female). The response or dependent variable was speed, measured in m/s. For each factor, three replicates ($n = 3$) were recorded.

2.3. Subjects

The analysis of variance (ANOVA) for the study indicates that a total of 18 college subjects (9 males and 9 females) within the 19-29 age stratum were recruited to participate in the study. The age stratum was selected based on the classification of the Civilian American and European Surface Anthropometry Resources (CAESAR) [26, 27]. Subjects were required to read and sign an informed consent form (Appendix 3.1) approved by the Auburn University Office of Human Subjects Research Institutional Review Board (IRB) prior to participating in the study. Each gender group included 3 subjects with a $18.5 \leq \text{BMI} < 25.0$, 3 subjects with a $25.0 \leq \text{BMI} < 30.0$, and 3 subjects with a $\text{BMI} \geq 30.0$. Subjects' BMI measures were compared to CAESAR's median BMIs for the same age stratum. Additionally, subjects completed a physical activity questionnaire (Appendix 3.2) to demonstrate their physical ability to participate in the study.

2.4. Equipment

A 100-ft test track (Figure 4) was constructed with safety cones and barrier tape. The length of the track represents the travel distance limit for a common path in a sprinklered educational occupancy or double the distance limit for dead-end paths during evacuation, as specified by the *Life Safety Code*® [2]. The track was marked every 20 ft. The start and finish lines were set 10 ft from the beginning and the end of the track, respectively, to overcome any performance acceleration or deceleration. Six photo sensors were mounted along the track and connected to a digital timer, which was linked to a computer through an Ethernet cable. Time to perform each activity (normal walking and normal crawling) was recorded to the nearest 0.01 second. Three sets of adjustable knee pads and three sizes of gloves (small, medium, and large) were provided for the subjects to perform the crawling activity. A general anthropometry kit was used to measure subjects' height and weight. Also, a Polar™ Heart Rate monitor was used for heart rate monitoring of the subjects.

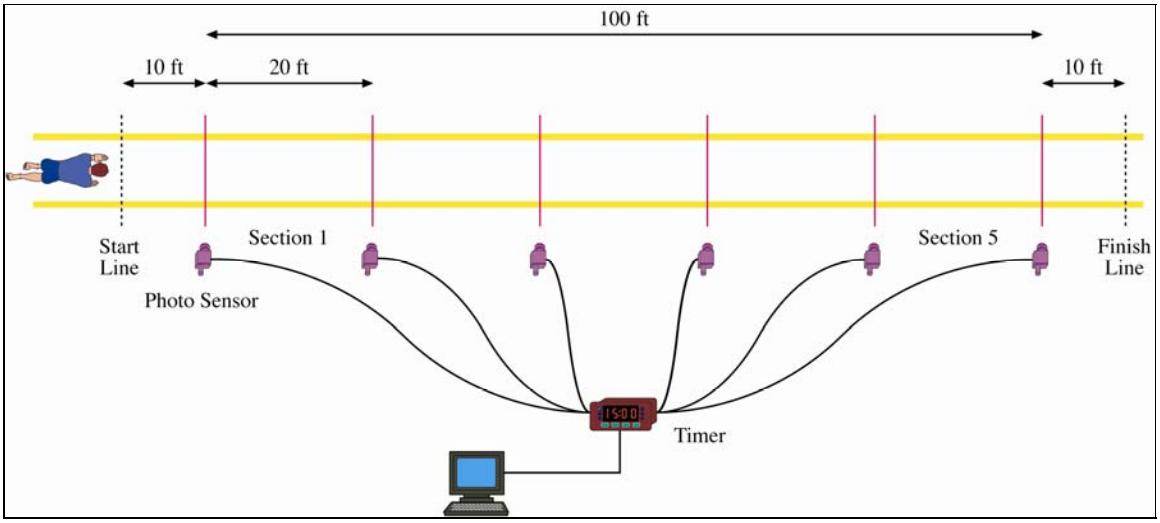


Figure 4. A 100-ft test track with a subject in the crawling position.

2.5. Protocol

Subjects performed the study individually based on a random schedule. Once at the track site, the study's procedure (Appendix 3.3) was explained in detail. After signing the informed consent form, the subject's height and weight were measured, and the heart rate monitoring equipment was put on the subject in a private waiting area. The subject was then asked to rest until his/her resting heart rate was reached. After that, the participant was guided to the start line. Next, the researcher instructed the participant to walk down the test track at a normal pace. Six time measurements ($t_0 - t_5$) were recorded and stored electronically. After crossing the finish line, the participant was escorted to the waiting area again.

In order to perform the next activity (normal crawling), the subject received a brief verbal description of the activity. After that, the subject was fitted with appropriate knee pads and gloves to eliminate any possible burns or injuries that may occur due to friction with the floor. When a standing resting heart rate level was reached again, the subject was directed to the starting line. Upon the request of the researcher, the participant crawled at a normal pace until reaching the finish line. Another six time measurements were taken and stored simultaneously.

3. Results

The purpose of the study is to examine the effect of occupant characteristics (body composition and gender) on walking and crawling. Appendix 3.4 summarizes the data for the study. The mean individual normal walking and crawling speeds on a flat surface for males and females are shown in Table 3. In order to test the hypotheses, a normality test is conducted for walking and crawling speeds (Figure 5). At $\alpha = 0.05$, the p-values for the normal distributions for walking and crawling speeds ($p_{walking} = 0.326$, $p_{crawling} = 0.753$) provide a good fit for each activity. As a result, conducting a two-sided t-test to compare between walking and crawling means is reasonable. A test of the population variances provides enough evidence to claim that the two populations have unequal variances. Thus, it is rational to assume unequal variances when using a two-sample t-test. The t statistic exceeds t_α ($17.31 > 2.069$), which implies that there is a significant difference ($p << 0.0005$) between normal walking and normal crawling speeds (hypothesis 1) as illustrated in Appendix 3.5.

Table 3

Mean normal walking and crawling speeds (m/s)

Body Composition	Walking		Crawling	
	Males	Females	Males	Females
Normal	1.73	1.62	0.90	0.81
	1.70	1.67	0.86	0.83
	1.80	1.61	0.86	0.79
Overweight	1.48	1.40	0.77	0.73
	1.51	1.42	0.79	0.77
	1.48	1.46	0.79	0.71
Obese	1.34	1.29	0.76	0.65
	1.37	1.32	0.74	0.67
	1.36	1.27	0.76	0.65

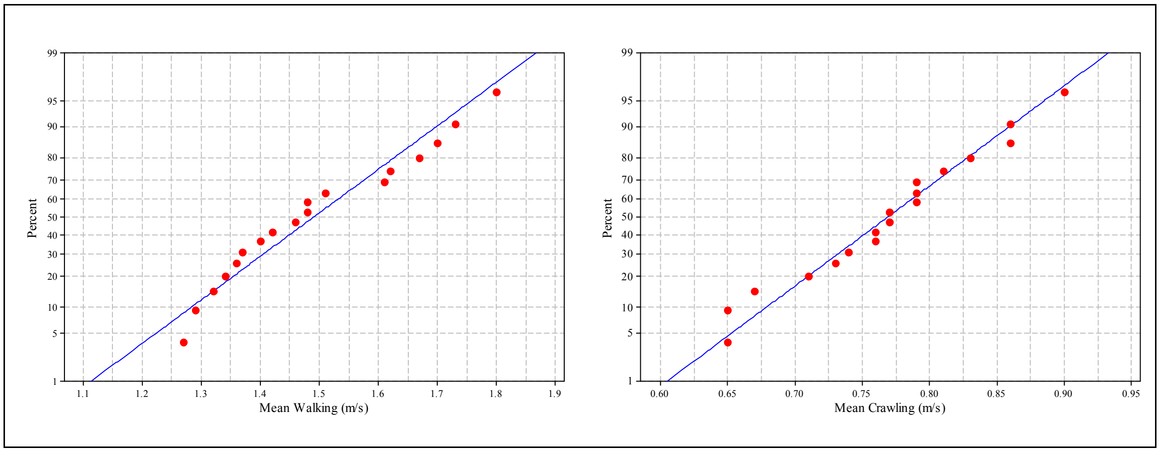


Figure 5. Probability plots of mean walking and crawling speeds.

In order to test hypotheses 2 and 3, further analysis was conducted on the crawling data. Table 4 lists crawling speeds for 18 subjects (9 males and 9 females). In reality, the levels of gender (males, females) and the levels of body composition (normal, overweight, obese) cannot be crossed since body composition is nested under gender. The subjects are also nested under both gender and body composition. In other words, each subject performed crawling for a specific gender type and body composition. Therefore, studying full-level combinations and their interactions is impracticable; rather a balanced nested design is applied because of equal number of levels of BMI within each gender type and equal number of replicates. A repeated measures ANOVA was conducted to examine the source of variability in crawling speed. The ANOVA table in Appendix 3.6 indicates that there is significant evidence for gender and body composition on crawling speed at α = 0.05. However, there is no significant evidence for subjects (blocks).

Table 4

Individual normal crawling speed data

Body Composition	Crawling					
	Males			Females		
Normal	0.89	0.93	0.86	0.82	0.77	0.85
	0.84	0.85	0.90	0.76	0.86	0.88
	0.88	0.84	0.85	0.78	0.79	0.81
Overweight	0.71	0.77	0.81	0.71	0.70	0.78
	0.84	0.74	0.78	0.75	0.77	0.78
	0.72	0.80	0.86	0.68	0.70	0.74
Obese	0.78	0.74	0.77	0.64	0.63	0.67
	0.74	0.74	0.75	0.64	0.68	0.70
	0.76	0.78	0.75	0.54	0.70	0.69

4. Discussion

This study investigated occupant crawling speed as compared to walking, and the effect of occupant characteristics on crawling in evacuation. It has been statistically shown when tested with a two-sample t-test that mean crawling speed is significantly less than mean walking speed ($p<0.0005$). *Individual* normal crawling speed presented in this study not only matches the findings of other crawling studies [22, 23], but also fits the normal distribution since the p-value is greater than the level of significance α ($0.720 > 0.05$) as illustrated in Figure 6. The mean of the crawling speed is 0.77 (95% confidence interval of 0.75 and 0.79 m/s), while the standard deviation is 0.08 (95% confidence interval of 0.065 and 0.096 m/s). This finding is vital to model developers to represent occupant crawling in evacuation models by incorporating the most reliable human performance data possible without relying on theoretical crawling data.

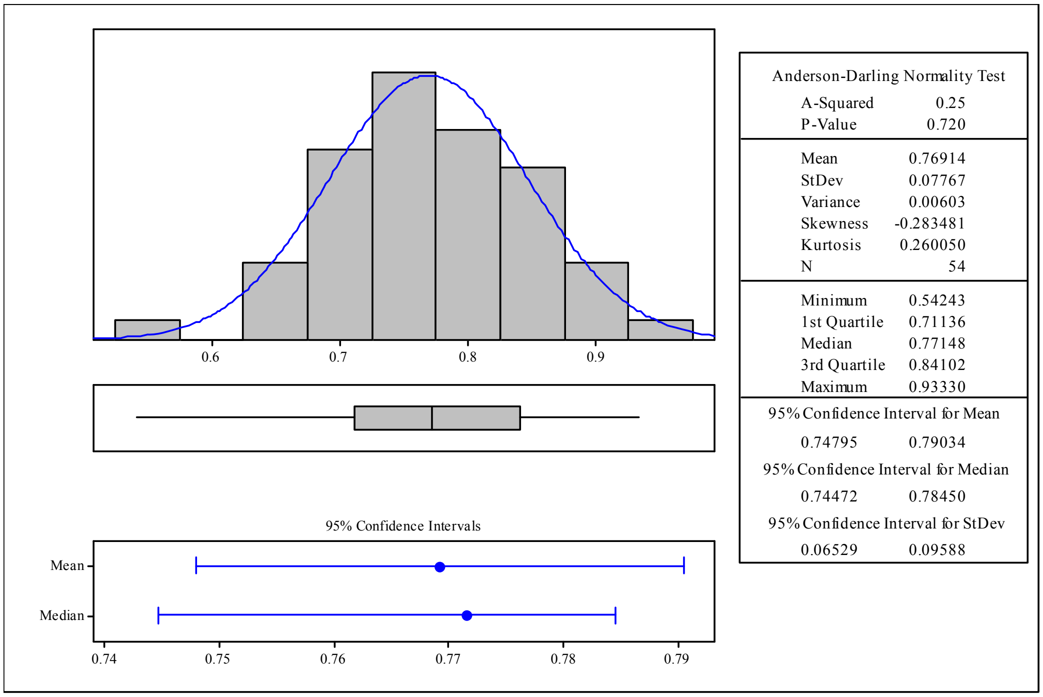


Figure 6. Graphical summary of crawling speed.

Further, the study revealed that occupant characteristics; gender and body composition, are major determinants of occupant normal crawling speed, accounting for about 80% of the variance in crawling speed ($R^2 = 79.94\%$). The ability to simulate these characteristics, and others, will improve the accuracy of evacuation models. However, it is important to state that these characteristics are unique for each occupant (within-subjects). Therefore, nested ANOVA was conducted with subjects being nested under body composition and gender. This result poses an immense challenge to model developers to represent occupant unique physical characteristics in evacuation models.

5. Conclusions

Occupant movement data plays a key role in the development of evacuation models. Despite the implementation of advanced modeling techniques, evacuation models continue to quantify and predict occupant movement in normal and emergency conditions. The present study investigates crawling movement as a physical response to environmental conditions in fire. The study compares individual crawling to individual walking speeds and the influence of occupant characteristics (gender and body composition) on the speed reduction for occupants when crawling. The findings of the study indicate a statistical difference between normal walking and crawling speeds. Furthermore, the study demonstrates statistically that both gender and body composition significantly impact individual crawling speed as they are unique characteristics to every individual.

Although the study, to the best knowledge of the author, is the first to report the effect of occupant characteristics on normal crawling in evacuation, future crawling studies should be conducted with larger samples with a focus on certain occupant characteristics such as age group and mobility capabilities. Research is also needed in crawling on different types of surfaces and under different degrees of crowd levels to quantify crowd crawling. Another need lies in studying the effect of fatigue on crawling, and its representation in the adaptive decision making process in response to evacuation. Since the current study focuses on *normal* crawling, there was no effect of fatigue on human performance. However, the effect would be more obvious in longer test areas and under actual emergency environmental conditions. Finally, the development of crawling data and its representation in evacuation models will enhance the robustness of engineering procedural designs, improve the accuracy of evacuation models, and better evaluate the safety of evacuees.

CHAPTER 4

THE IMPACT OF EXIT ROUTE DESIGN ON EVACUATION TIME FOR CRAWLERS

Abstract. According to the *Life Safety Code*®, the distance between the exit access and the exit is a function of the occupants, type and number of obstructions, and the type of hazard. This study investigates the impact of route design on evacuation times for crawling movements. The study compares evacuation time for a straight route to an indirect route design, and the influence of occupant characteristics (gender and body composition) on evacuation time for occupants crawling an indirect route. Eighteen subjects (9 males and 9 females) in the 19-29 age stratum participated in the study (normal, overweight, and obese body composition). The findings indicate a statistical difference between evacuation time for crawling in a straight route and an indirect one. Furthermore, the study reveals that both gender and body composition have a significant impact on individual evacuation time when crawling in an indirect route. The representation of different route designs in evacuation models can provide architects with a better understanding of occupant individual and global views of buildings, which further enhances the robustness of their designs.

1. Introduction

According to the *Life Safety Code*® [1], means of egress refers to “a continuous and unobstructed way of travel from any point in a building or structure to a public way consisting of three separate and distinct parts: (1) the exit access, (2) the exit, and (3) the exit discharge.” Since the exit access includes, according to the *Code*, all occupied floor spaces that lead to an exit, it comprises more floor area that either of the other distinct parts of the means of egress.

As sophisticated building evacuation models continue to emerge, quantifying and predicting occupant movement from the exit access to the exit remains a fundamental element in calculating evacuation time. In order to assess the methods of occupant movement through a building and simulate a building enclosure, it is important to examine how models represent occupant perception of means of egress. In their comprehensive review of 28 evacuation models, Kuligowski & Peacock [2] classified the occupant view of buildings into individual and global perspectives. Occupants with an individual view are usually unaware of a building’s exit access and await external knowledge to move toward the exit. On the contrary, a global view provides occupants with the best familiarity of the exit and exit access.

Regardless of the approach adopted to represent the occupant view of buildings and means of egress, occupant movement from the exit access to an exit in the models can be carried out implementing any of the following:

1. *Single route movement.* Some evacuation models [3-6] make only one exit available to occupants during evacuation. Therefore, occupant view of the building means of egress is global.

2. *Efficient route selection.* During this approach, the occupants move to an exit according to the most efficient route that would result in a minimal evacuation time, which may not be necessarily the shortest route to an exit. Occupant view to exit access in these models [7-10] is also considered global.
3. *User-defined route*. Model users can either specify each occupant's exit choice (exit familiarity) [11-16], or define a default percentage of occupants to use a certain exit [17-21]. In both cases, occupants view means of egress individually.
4. *Nearest distance route selection.* This is probably the most common method model designers implement to identify occupant movement to exit [18-26]. The shortest distance between each occupant and an exit is updated throughout the evacuation process. However, model users can alter the nearest exit route selection of occupants by indicating environmental conditions or exit congestion. It is this final approach, where occupants chose the nearest exit that will be further examined in this study.

The *Life Safety Code*® [1] dictates the maximum distance limit that occupants travel from their location in a building to the nearest exit. The travel distance is measured horizontally along the centerline of the natural trail of travel curving around obstructions. According to the *Code*, the maximum permitted travel distance is a function of several factors. Some of which are the number, age, and physical condition of occupants, type and number of obstructions, and type of hazard.

2. Methodology

2.1. Objective and Hypotheses

The purpose of this study is to evaluate the impact of turns (changing directions) to avoid obstructions on evacuation time for crawlers and compare that to the time needed to crawl in a straight exit route, free from obstructions. The impact of occupant characteristics (gender and BMI) on evacuation time for crawlers to change directions is also investigated. The hypotheses for the study are:

<u>Hypothesis 1</u>: There is no significant difference between time to evacuate in a straight path (route) and time to evacuate in an indirect route (changing directions) during evacuation for healthy (both physically and cognitively) crawlers (males and females) within the 19 – 29 age stratum.

$$H_0 : \mu_{time\ to\ evacuate,\ straight\ path} = \mu_{time\ to\ evacuate,\ indirect\ path}$$
$$H_1 : \mu_{time\ to\ evacuate,\ straight\ path} \neq \mu_{time\ to\ evacuate,\ indirect\ path}$$

<u>Hypothesis 2</u>: There is no significant difference between time to evacuate at a normal pace in an indirect route for healthy (cognitively and physically) males within the 19 – 29 age stratum and time to evacuate at normal pace for healthy (cognitively and physically) females within the same age stratum.

$$H_0 : \mu_{time\ to\ evacaute,\ indirect\ path,\ males} = \mu_{time\ to\ evacuate,\ indirect\ path,\ females}$$
$$H_1 : \mu_{time\ to\ evacute,\ indirect\ path,\ males} \neq \mu_{time\ to\ evacuate,\ indirect\ path\ females}$$

<u>Hypothesis 3</u>: Time to evacuate in an indirect path for both healthy (cognitively and physically) males and females within the 19 – 29 age stratum is unaffected by their body composition (BMI).

$$H_0 : \mu_{time\ to\ evacuate,\ indirect\ path,\ normal\ body\ composition} = \mu_{time\ to\ evacuate,\ indirect\ path,\ overweight\ body\ composition}$$
$$= \mu_{time\ to\ evacuate,\ indirect\ path,\ obese\ body\ composition}$$
$$H_1 : \mu_{time\ to\ evacuate,\ indirect\ path,\ normal\ body\ composition} \neq \mu_{time\ to\ evacuate,\ indirect\ path,\ overweight\ body\ composition}$$
$$\neq \mu_{time\ to\ evacuate,\ indirect\ path,\ obese\ body\ composition}$$

2.2. Experimental Design

In order to test these hypotheses, a mixed-factor analysis is constructed with the level of significance (α), set at 0.05. The factors in this study are route type (crawling in a straight route, crawling in an indirect route), BMI (normal, overweight, obese), and gender (male, female). The response or dependent variable is time, measured in seconds. For each factor, three replicates (n = 3) will be recorded.

2.3. Subjects

The analysis of variance (ANOVA) for the study indicates that a total of 18 college subjects (9 males and 9 females) within the 19-29 age stratum were recruited to participate in the study. The age stratum was selected based on the classification of the Civilian American and European Surface Anthropometry Resources (CAESAR) [27, 28]. Subjects were required to read and sign an informed consent form (Appendix 3.1) approved by the Auburn University Office of Human Subjects Research Institutional Review Board (IRB) prior to participating in the study. Each gender group included 3 subjects with a $18.5 \leq \text{BMI} < 25.0$, 3 subjects with a $25.0 \leq \text{BMI} < 30.0$, and 3 subjects with a $\text{BMI} \geq 30.0$. Subjects' BMI measures were compared to CAESAR's median BMIs for the same age stratum. Additionally, subjects completed a physical activity questionnaire (Appendix 3.2) to demonstrate their physical ability to participate in the study.

2.4. Equipment

A 100-ft test track (Figure 7) was constructed with safety cones and barrier tape. The length of the track represents the travel distance limit for a common path in a sprinklered educational occupancy or double the distance limit for dead-end paths during evacuation, as specified by the *Life Safety Code*® [1]. The track consisted of five-90^{o} turns (changes of direction), and was marked every 20 ft. The start and finish lines were set 10 ft from the beginning and the end of the track, respectively, to overcome any performance acceleration or deceleration effect. Six photo sensors were mounted along the track and connected to a digital timer, which was linked to a computer through an Ethernet cable. Time to perform normal crawling in both routes (straight and indirect) was recorded to the nearest 0.01 second. Three sets of adjustable knee pads and three sizes of gloves (small, medium, and large) were provided for the subjects to perform the crawling activity. A general anthropometry kit was used to measure the subjects' height and weight. Also, a Polar™ Heart Rate monitor was used for heart rate monitoring of the subjects.

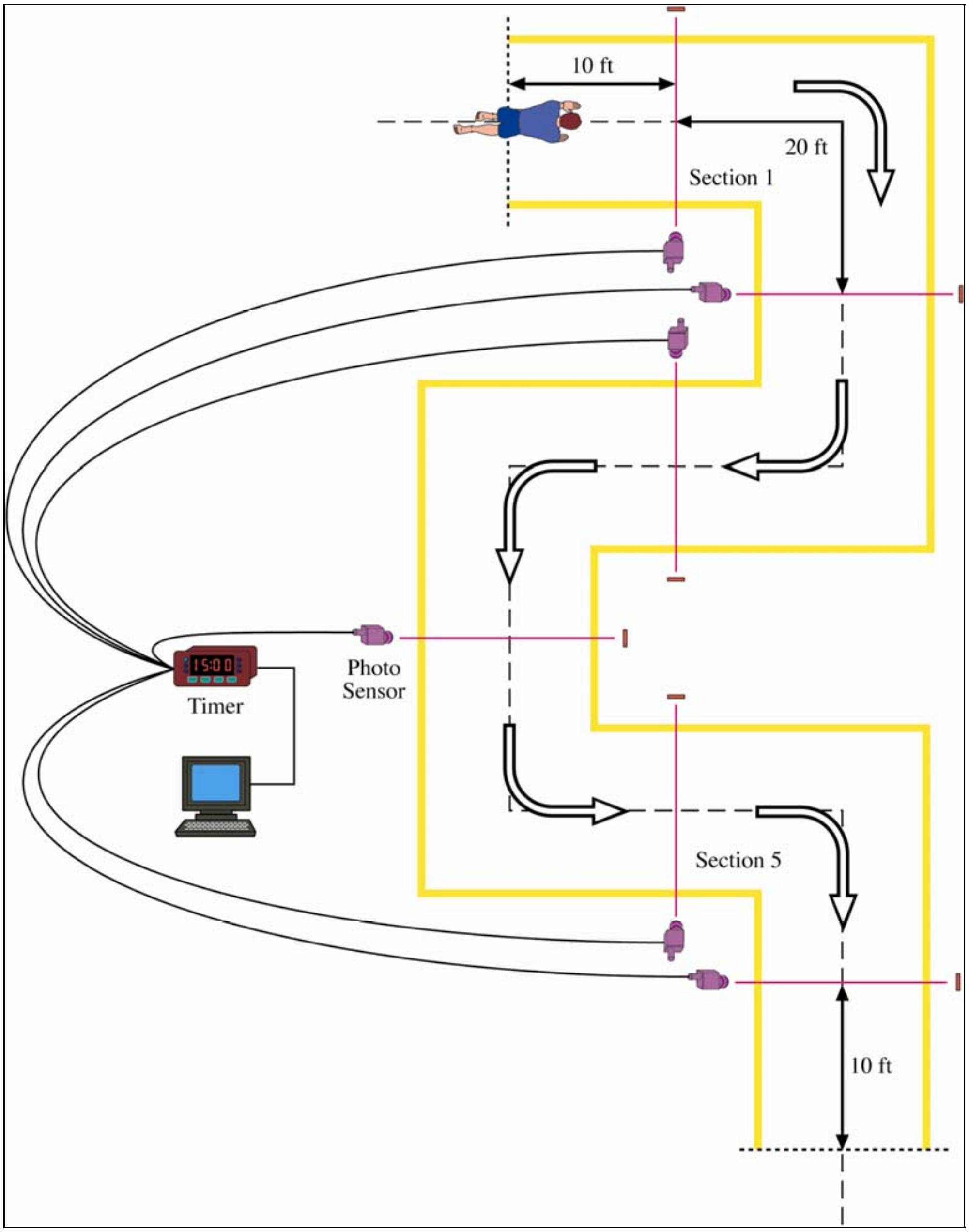


Figure 7. Indirect test track (route) with a subject in the crawling position.

2.5. Protocol

Subjects performed the study individually based on a random schedule. Once at the track site, the study procedure (Appendix 4.1) was explained in detail. After signing the informed consent form, the subject's height and weight were measured, and the heart rate monitoring equipment was put on the subject in a private waiting area. The subject was then asked to rest until his/her standing resting heart rate was reached. After that, the subject was fitted with knee pads and gloves to eliminate any possible burns or injuries that may occur due to friction with the floor. Next, the researcher instructed the participant to crawl down the indirect test track (changing directions) at a normal pace following the centerline of the natural path of travel, as defined by the *Code*. The length of both test tracks (straight and indirect) was identical, i.e., 100 ft. When a standing resting heart rate level was reached again, the subject was directed to the starting line to crawl at a normal pace until reaching the finish line. Six time measurements ($t_0 – t_5$) were recorded and stored electronically. After crossing the finish line, the participant was escorted to the waiting area.

3. Results

The main purpose of the study is to evaluate the impact of turns (changing directions to avoid obstructions) on evacuation time for crawlers and compare that to the time needed to crawl (an identical distance) in a straight exit route, free from obstructions. Additionally, the effect of crawlers' gender and BMI on evacuation time when traveling in an indirect route is examined compared to a direct one. Appendix 4.2 summarizes evacuation times of crawling (in seconds) in both route types. The mean crawling evacuation times on a flat surface for males and females are shown in Table 5. In order to test the hypotheses, a normality test is conducted for mean evacuation times in the straight and indirect routes (Figure 8). At $\alpha = 0.05$, the p-values for the normal distributions for mean crawling times in straight and indirect routes ($p_{straight} = 0.341$, $p_{indirect} = 0.315$) indicate that, at 0.05 α level, there is evidence that both sets of data follow the normal distribution. As a result, conducting a two-sided t-test to compare between the means of evacuation time for crawling in straight and indirect routes is statistically reasonable. Since the same activity is performed in both routes (normal crawling), it is rational to assume equal variances when using a two-sample t-test. However, a test of the population variances confirms such rationale of equality between variances. The t statistic exceeds t_α ($|-2.56| > 2.069$), which implies a significant difference ($p = 0.015$) between the *mean* times to evacuate crawling in straight and indirect routes (hypothesis 1) as illustrated in Appendix 4.3.

Table 5

Mean crawling evacuation times for straight and indirect routes

Body Composition	Straight Route		Indirect Route	
	Males	Females	Males	Females
Normal	34.08	37.53	37.69	39.45
	35.33	36.90	38.98	40.58
	35.51	38.52	36.13	40.75
Overweight	39.93	41.77	42.06	44.47
	38.76	39.71	44.41	43.92
	38.59	43.23	43.09	44.89
Obese	39.97	47.17	45.48	47.43
	41.00	45.24	46.73	47.28
	39.85	47.85	47.69	47.24

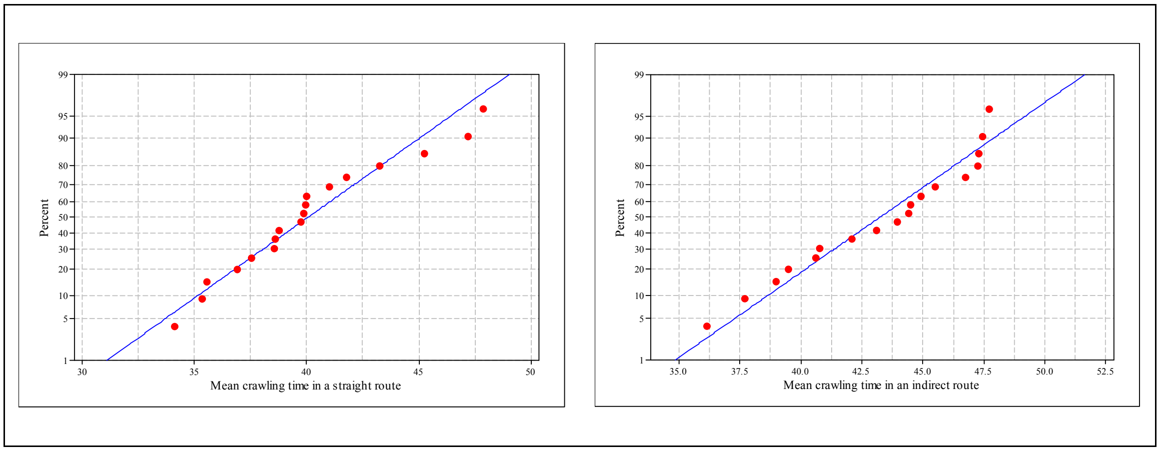


Figure 8. Probability plots of mean evacuation times on straight and indirect routes.

In order to test hypotheses 2 and 3, further analysis was conducted on the evacuation times crawling an indirect route. Table 6 lists evacuation times for 18 subjects (9 males and 9 females) crawling an indirect route. In reality, the levels of gender (males, females) and the levels of body composition (normal, overweight, obese) cannot be crossed since body composition is nested under gender. The subjects are also nested under both gender and body composition. In other words, each subject performed crawling for a specific gender and body composition type. Therefore, studying full-level combinations and their interactions is impracticable; rather a balanced nested design is applied because of equal number of levels of BMI within each gender and also equal number of replicates. A repeated measures ANOVA was conducted to examine the source of variability in evacuation time. The ANOVA table in Appendix 4.4 indicates that there is significant evidence for gender and body composition on time to evacuate crawling through an indirect path at $\alpha = 0.05$. However, there is no significant evidence for subjects (blocks).

Table 6

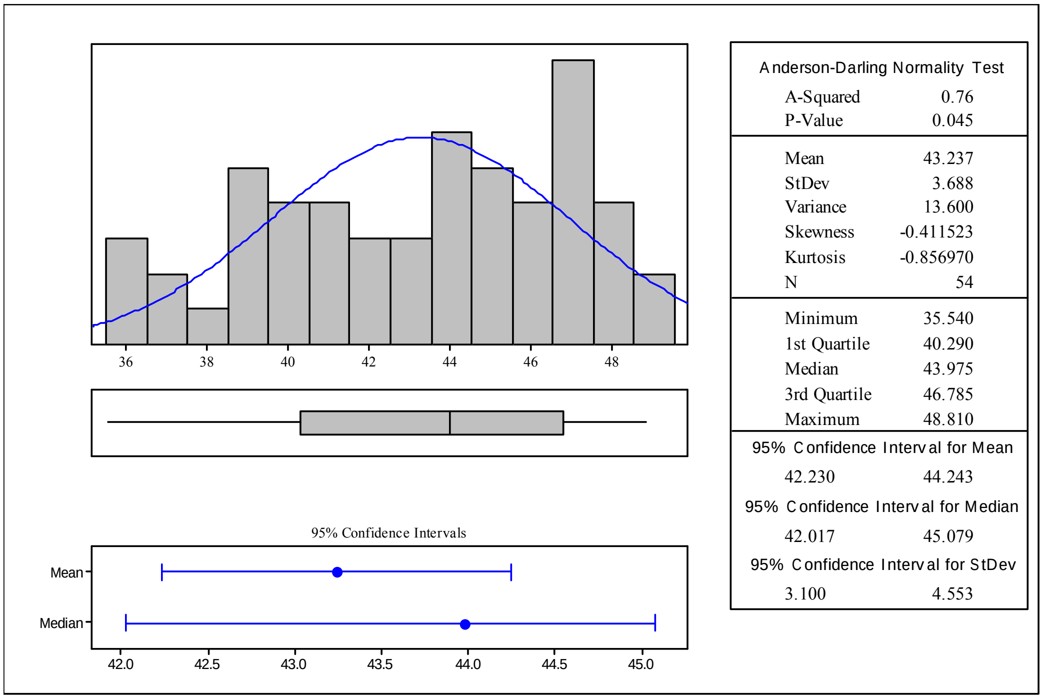
Individual evacuation time data for crawling in an indirect route

Body Composition	Indirect Route					
	Males			Females		
Normal	37.23	36.18	39.66	38.38	41.26	38.70
	39.20	39.06	38.67	41.86	39.45	40.43
	37.21	35.54	35.65	40.14	41.49	40.61
Overweight	43.35	40.34	42.48	44.33	45.10	43.98
	44.17	43.34	45.72	42.30	45.20	44.27
	43.20	41.32	44.75	45.04	45.65	43.97
Obese	47.02	45.52	43.89	47.13	46.94	48.21
	44.59	46.83	48.77	46.23	47.85	47.76
	47.37	46.90	48.81	47.05	47.91	46.77

4. Discussion

This study investigated the impact of turns (changing direction) on evacuation time for crawlers compared to the time required to crawl (an identical distance) in a straight path, and the effect of occupant characteristics on time to evacuate crawling an indirect route. It has been statistically demonstrated when tested with a two-sample t-test that mean time to crawl in an indirect route is significantly *greater* than mean time to crawl in a straight route ($p = 0.015 < \alpha = 0.05$). *Individual* time to evacuate crawling an indirect route presented in this study does not fit the normal distribution since the p-value is slightly less than the level of significance α ($0.045 < 0.05$) as illustrated in Figure 9. The mean time to evacuate was 43.24 sec (95% confidence interval of 42.23 and 44.24 sec), while the standard deviation was 3.69 sec (95% confidence interval of 3.10 and 4.55

sec). This indicates that occupants react to changes in route design differently, especially when adopting new physical responses (such as crawling) to deteriorating environmental conditions.



Anderson-Darling Normality Test

A-Squared	0.76
P-Value	0.045
Mean	43.237
StDev	3.688
Variance	13.600
Skewness	-0.411523
Kurtosis	-0.856970
N	54
Minimum	35.540
1st Quartile	40.290
Median	43.975
3rd Quartile	46.785
Maximum	48.810

95% Confidence Interval for Mean

42.230	44.243

95% Confidence Interval for Median

42.017	45.079

95% Confidence Interval for StDev

3.100	4.553

Figure 9. Graphical summary of individual evacuation time for crawlers in an indirect route.

Further, the study revealed that occupant characteristics; gender and body composition, are major determinants of evacuation time of crawlers in an indirect route, accounting for about 90% of the variance in evacuation time (R^2 = 92.21%). The ability to simulate these characteristics, and others, will improve the accuracy of evacuation models. However, it is important to state that these characteristics are unique for each occupant (within-subjects). Therefore, nested ANOVA was conducted with subjects being nested under body composition and gender.

5. Conclusions

Occupant movement from the exit access to the exit remains a fundamental element in calculating evacuation time. Evacuation models rely on a variety of movement algorithms to represent occupant view of building design, enclosure, and means of egress. The present study investigated the impact of route design on evacuation time for crawling as a physical response to environmental conditions in fire. The study compared crawlers' evacuation times for a straight route to an indirect route design, and the influence of occupant characteristics (gender and body composition) on evacuation time for occupants crawling an indirect route. The findings of the study indicated a statistical difference between evacuation time for a straight route and an indirect one. Furthermore, the study showed statistically that both gender and body composition significantly impact individual evacuation time when crawling an indirect route as they are unique characteristics to every individual.

Although the study, to the best knowledge of the author, is the first to report the effect of occupant characteristics on indirect route design for normal crawling in evacuation, future crawling studies should be conducted with larger samples with a focus on certain occupant characteristics such as age group and physical conditions. Research is also needed in crawling on different types of surfaces and under different degrees of crowd levels to quantify crowd view of means of egress. Another need lies in studying the effect of fatigue on crawling as occupants try to avoid obstacles during evacuation, and its representation in the adaptive decision making process in response to evacuation. Since the current study focuses on *normal* crawling, there was no effect of fatigue on human performance even in different route designs. However, the effect would be more obvious in longer test areas and under actual emergency environmental conditions.

Further, the finding of the study is vital to validate the algorithms employed in the models to quantify and predict occupant movement throughout building enclosure by comparing the most reliable human performance data available to model output for a given route design without relying on hypothetical data. Finally, the development of crawling data and its representation in different route designs will provide architects with a more realistic understanding of occupant individual and global views of building enclosure to further enhance the robustness of their designs.

CHAPTER 5

THE DEVELOPMENT OF MOVEMENT-DENSITY RELATIONSHIP FOR CRAWLING

Abstract. Occupant movement in evacuation models has been simulated and predicted based on a number of variables, including crowd density. This study investigates the relationship between crowd density and occupant crawling movement, as a physical response to environmental conditions in fire. This is conducted by examining the impact of occupant configuration (number of occupants) and exit access width on crowd walking and crawling speeds on a flat surface. The findings of the study suggest that exit access width is significant to crowd crawling speed, whereas occupant configuration plays less of a factor. The results further demonstrate that there is a significant difference in the crawling speed at the different levels of the exit access width due to the effect of crowd density. The relationship between crowd crawling speed and density is best described in the study by a quadratic regression model. The study concludes with the need to continuously develop new predictive movement methods, or enhance existing ones in order to cope with the level of detail required to ensure occupant safety. In light of the significant absence of crawling data in the literature, this study contributes to the improvement of the accuracy and functionality of occupant movement in existing and future evacuation models.

1. Introduction

A lack of real evacuation data poses a challenge to the development and representation of occupant movement in evacuation models. As a result, researchers have been driven to configure and apply predictive approaches to overcome such obstacles [1]. One of the approaches that has been commonly applied to simulate occupant movement in evacuation models is based on occupant density. The relationship between crowd density and horizontal walking speed has been previously developed from observations and experiments in different crowd places, namely public buildings [2], walkways [3-7], railway stations [8], stairs [2, 3, 9, 10], and queues [3]. Table 7 summarizes density and speed values reported in some of these studies. The findings from crowd movement research have significantly contributed to the development of movement algorithms in a number of evacuation models. Some evacuation models in which the relationship between density and crowd speed has been implemented are; buildingEXODUS [11, 12], CRISP II [13], EESCAPE [14], Egress [15], ESM [16], EvacSim [17], Exit89 [18], PATHFINDER [19], and Simulex [20].

The successful implementation of such relationship (walking speed vs. density) in evacuation models is currently limited to walking. The deterioration of environmental conditions in evacuation influences occupants to adopt new behaviors [21-24]. The representation of these behaviors in evacuation models in terms of density and speed introduces more realistic movement algorithms to evaluate the consequences of these behaviors on model outcomes, and hopefully to enhance the robustness of evacuation procedures and building designs. One of the responses that occupants choose, or are forced to choose, is to avoid heat and smoke by crawling. The purpose of this study is to examine the relationship between crowd crawling speed and crowd density.

Table 7

Density and speed values reported in crowd movement studies

Study	Density (persons/m^2)	Crowd movement	Speed (m/s)
Ando et al. [8]	0.8	Free	1.4-1.6
	1.8	Non-contact	0.5-1.0
	4	Restricted (stagnation)	< 0.5
Fruin [3]	0.4	Adjustable	1.3-1.4
Nelson and MacLennan [9]	0.54	Comfortable	1.2
	3.8	Slow	≈ 0
Older [6]	4	Restricted	0.3
Pauls [10]	0.54	Independent	1.25
	4-5	Restricted (standstill)	≈ 0
Polus et al. [7]	0.1	Free	1.3
	2.2	Jammed	0.7

2. Crawling Data in the Literature

An exhaustive review of the literature on occupant crawling revealed a significant shortage of the development of crawling data in human performance studies and its representation in evacuation models. Muhdi et al. [25] conducted one of the few performance studies in evacuation that measured normal and maximum crawling and walking speeds. Their results suggest that maximum walking is performed at a significantly higher rate than normal walking, whereas normal crawling is performed at a significantly lower rate than normal walking. Maximum crawling, on the other hand, showed no significant difference compared to normal walking. The average normal walking speed in the study was measured at 1.32 m/s (4.33 ft/s), while maximum walk, normal and maximum crawl were 163%, 54%, and 111% of normal walking, respectively, or 2.15, 0.71, and 1.47 m/s (7.05, 2.33, and 4.82 ft/s).

Another study by Nagai et al. [26] compared experimental and simulated evacuation processes of walkers and crawlers through an exit. Individual crawling speed was measured at 0.73 m/s (2.4 ft/s), which is comparable with that of Muhdi et al. [25]. The study further demonstrated the effect of initial density (number of occupants/maximum capacity) on mean flow rate (persons/sec) for both walkers and crawlers through different exit widths. A similar study [27] investigated, experimentally and via simulation, the phenomenon of counterflow for both walkers and crawlers in a hall. The researchers obtained the mean crawling speed by averaging all individuals' crawling speeds. Each individual speed was calculated based on crawling distance, which was measured from an individual's initial position to the other end of the hall. Therefore, in the Nagai et al. study [27], the relationship between crawling speed and density reflects individual crawling speed and not crowd crawling speed as influenced by density.

With respect to crawling movement being incorporated into evacuation models, to the best knowledge of the author, only buildingEXODUS [11, 12] simulates crawling behavior during evacuation. The model assumes standing and crawling heights of 1.7 and 1 m, respectively, and applies a default empirical crawling speed of 0.3 m/s (0.98 ft/s), which is 20% of its default fast walking speed of 1.5 m/s (4.92 ft/s). A crawling speed of 0.3 m/s (0.98 ft/s) is significantly less than the findings of Muhdi et al. [25] and Nagai et al. [26], i.e., 0.71 (2.33 ft/s) and 0.73 m/s (2.4 ft/s), respectively. Therefore, in an attempt to incorporate crawling data into evacuation models, Muhdi et al. [28] employed the crawling data found in Muhdi et al. [25] and Nagai et al. [26] into buildingEXODUS [11, 12] to test the accurate representation of crawling speeds in the model. The researchers emphasized the importance of incorporating reliable occupant data into evacuation models to verify the model outcomes, and suggested the development of a density-speed relationship for crawlers to improve upon the model's representation of crawling movement.

3. Methodology

3.1. Objective and Hypotheses

The purpose of this study was to investigate the relationship between crowd crawling speed and crowd density. This is accomplished by examining the impact of the number of occupants (occupant configuration) and width of the exit access on crowd normal walking and crawling speeds. The hypotheses for the study are:

Hypothesis 1: Crowd normal **walking** speed of healthy (cognitively and physically) occupants (males and females) within the 19 – 29 age stratum is unaffected by the width of the exit access (W).

$$H_0 : \mu_{Crowd\ Nornal\ Walking\ Speed\ at\ W_1} = \mu_{Crowd\ Normal\ Walking\ Speed\ at\ W_2} = \ldots = \mu_{Crowd\ Normal\ Walking\ Speed\ at\ W_n}$$

$$H_1 : \mu_{Crowd\ Nornal\ Walking\ Speed\ at\ W_1} \neq \mu_{Crowd\ Normal\ Walking\ Speed\ at\ W_2} \neq \ldots \neq \mu_{Crowd\ Normal\ Walking\ Speed\ at\ W_n}$$

Hypothesis 2: Crowd normal **walking** speed of healthy (cognitively and physically) occupants (males and females) within the 19 – 29 age stratum is unaffected by occupant configuration (number of occupants).

$$H_0 : \mu_{Crowd\ Walking\ Speed\ \ for\ 2\ occupants} = \mu_{Crowd\ Walking\ Speed\ \ for\ 3} = \ldots = \mu_{Crowd\ Walking\ Speed\ \ for\ n\ occupants}$$

$$H_1 : \mu_{Crowd\ Walking\ Speed\ \ for\ 2\ occupants} \neq \mu_{Crowd\ Walking\ Speed\ \ for\ 3} \neq \ldots \neq \mu_{Normal\ Walking\ Speed\ \ for\ n\ occupants}$$

Hypothesis 3: Crowd normal **crawling** speed of healthy (cognitively and physically) occupants (males and females) within the 19 – 29 age stratum is unaffected by the width of the exit access (W).

$$H_0 : \mu_{Crowd\ Nornal\ Crawling\ Speed\ at\ W_1} = \mu_{Crowd\ Normal\ Crawling\ Speed\ at\ W_2} = \ldots = \mu_{Crowd\ Normal\ Crawling\ Speed\ at\ W_n}$$
$$H_1 : \mu_{Crowd\ Nornal\ Crawling\ Speed\ at\ W_1} \neq \mu_{Crowd\ Normal\ Crawling\ Speed\ at\ W_2} \neq \ldots \neq \mu_{Crowd\ Normal\ Crawling\ Speed\ at\ W_n}$$

Hypothesis 4: Crowd normal **crawling** speed of healthy (cognitively and physically) occupants (males and females) within the 19 – 29 age stratum is unaffected by occupant configuration (number of occupants).

$$H_0 : \mu_{CrowdCrawling\ Speed\ for\ 2\ occupants} = \mu_{Crowd\ Crawling\ Speed\ for\ 3} = \ldots = \mu_{Normal\ Crawling\ Speed\ for\ n\ occupants}$$
$$H_1 : \mu_{Crowd\ Crawling\ Speed\ for\ 2\ occupants} \neq \mu_{Crowd\ Crawling\ Speed\ for\ 3} \neq \ldots \neq \mu_{Normal\ Crawling\ Speed\ for\ n\ occupants}$$

3.2. Experimental Design

In order to test these hypotheses, a mixed-factor analysis was constructed with the level of significance (α), set at 0.05. The study design considered two activities (walking, crawling), three exit access widths ($W_1 = 3$, $W_2 = 4$, $W_3 = 5$ ft) and five configurations ($C_1 = 2$, $C_2 = 4$, $C_3 = 5$, $C_4 = 7$, $C_5 = 9$ occupants). Each configuration is designed with consideration of gender and BMI. The response or dependent variable is speed, measured in m/s. For each factor, two replicates ($n = 2$) were recorded.

3.3. Subjects

The analysis of variance (ANOVA) for the study required a total of 20 college subjects within the 19-29 age stratum recruited to participate in the study. The age stratum was selected based on the classification of the Civilian American and European Surface Anthropometry Resources (CAESAR) [29, 30]. Subjects were required to read and sign an informed consent form (Appendix 5.1) approved by the Auburn University

Office of Human Subjects Research Institutional Review Board (IRB) prior to participating in the study. Five of the males are classified as having a normal weight ($18.5 \leq \text{BMI} < 25.0$), four overweight ($25.0 \leq \text{BMI} < 30.0$), and one obese ($\text{BMI} \geq 30.0$), whereas, for the female group, seven are normal ($18.5 \leq \text{BMI} < 25.0$), two are overweight ($25.0 \leq \text{BMI} < 30.0$), and one is obese ($\text{BMI} \geq 30.0$). The proportion of males and females, as well as, BMI within each gender, is rational to the national data for the 19 – 29 age stratum obtained by CAESAR [29, 30], which is provided in Appendix 5.2. The combination of gender and BMI categories was randomly selected from the sample without replacement within each configuration, but with replacement between configurations. Additionally, subjects completed a physical activity questionnaire (Appendix 3.2) to demonstrate their physical ability to participate in the study.

3.4. Equipment

A 50-ft test track (Figure 10) was constructed with adjustable widths. The length of the track represents the distance limit for dead-end paths during evacuation, as specified by the *Life Safety Code*® [31]. The start and finish lines were set 10 ft from the beginning and the end of the track, respectively, to overcome any performance acceleration or deceleration effect. Six photo sensors were mounted along the track and connected to a digital timer, which was linked to a computer through an Ethernet cable. Time to perform each activity (normal walking and normal crawling) was recorded to the nearest 0.01 second. Three camcorders were mounted along the track to capture a length of 10 ft each. Adjustable knee pads and gloves were provided for the subjects to perform the crawling activity. A general anthropometry kit was used to measure the subjects' height and weight. Also, a Polar™ Heart Rate monitor was used for heart rate monitoring of the subjects.

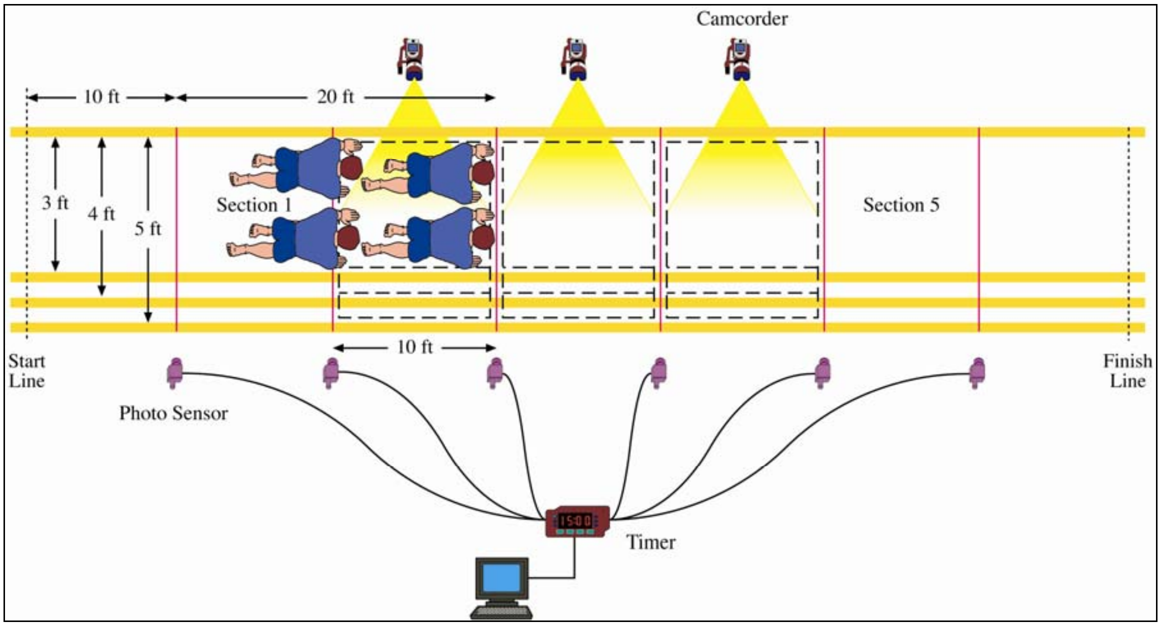


Figure 10. Test track with adjustable widths.

3.5. *Protocol*

Subjects were randomly assigned to configurations, track width, and activities. Once at the track site, the study's procedure was explained in detail (Appendix 5.3). After signing the informed consent form, the subject's height and weight were measured, and the heart rate monitoring equipment was put on the subject in a private waiting area. The subjects were then asked to rest until his/her standing resting heart rate was reached. After that, the subjects were fitted with knee pads and gloves to eliminate any possible burns or injuries that may occur due to friction with the floor during the crawling activity. Next, the researcher instructed the participants to walk down the test track at a normal pace. Six time measurements ($t_0 – t_5$) were recorded and stored electronically. After crossing the finish line, the participants were escorted to the waiting area. The normal walking activity was then repeated at three different track widths.

In order to perform the next activity (normal crawling), the subjects were received a brief verbal description of the activity. Once resting heart rate level was reached again, the subjects were directed to the start line. Upon the request of the researcher, the participants crawled at a normal pace until reaching the finish line. Another six time measurements were taken and stored. The normal crawling activity was also repeated at three different widths.

4. Results

The purpose of the study was to investigate the relationship between crowd crawling speed and crowd density. Further, the study examined the impact of occupant configuration (number of occupants) and the width of the exit access on crowd normal walking and crawling speeds. Table 8 summarizes crowd walking and crawling speeds on the flat surface at different configurations and exit access widths. In order to test hypotheses 1 and 2, a general linear model of crowd walking versus configurations and exit access widths was performed in Minitab (Appendix 5.4). The analysis of variance (ANOVA) for crowd walking speed, using adjusted sum of squares, indicated that the width of the exit access was statistically significant ($p \ll 0.0005$) to crowd walking speed, whereas occupant configuration was statistically insignificant ($p = 0.420 > \alpha$). The effect of occupant configuration on crowd walking speed was further analyzed. All 10 pairwise comparisons among levels of occupant configuration; $C_1 = 2$, $C_2 = 4$, $C_3 = 5$, $C_4 = 7$, $C_5 = 9$ occupants, were evaluated. The results in Appendix 5.4 reveal that none of the levels of occupant configuration was statistically significant with respect to crowd walking speed.

Table 8

Crowd normal walking and crawling speeds (m/s) at different configuration and exit access width levels

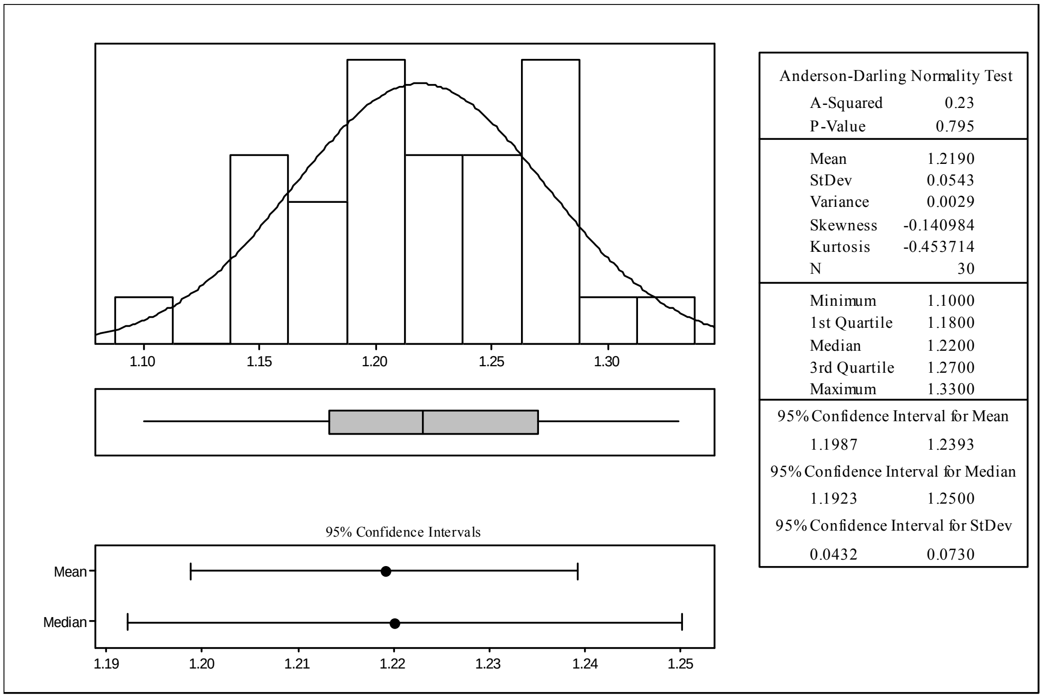
Activity	Configuration (occupants)	Exit access width (ft)		
		$W_1 = 3$	$W_2 = 4$	$W_3 = 5$
Walking	$C_1 = 2$	1.23 1.19	1.22 1.22	1.25 1.27
	$C_2 = 4$	1.18 1.24	1.27 1.30	1.19 1.14
	$C_3 = 5$	1.23 1.20	1.27 1.25	1.17 1.18
	$C_4 = 7$	1.26 1.21	1.20 1.27	1.10 1.15
	$C_5 = 9$	1.28 1.20	1.28 1.33	1.14 1.15
Crawling	$C_1 = 2$	0.71 0.72	0.74 0.74	0.66 0.63
	$C_2 = 4$	0.65 0.71	0.70 0.81	0.69 0.68
	$C_3 = 5$	0.66 0.68	0.76 0.77	0.68 0.66
	$C_4 = 7$	0.69 0.66	0.75 0.81	0.62 0.64
	$C_5 = 9$	0.68 0.63	0.76 0.73	0.64 0.66

The interaction between occupant configuration and exit access width was significant ($p = 0.014 < \alpha$). This implies that occupant configuration has no effect on crowd walking speed. However, when the effect of occupant configuration is examined at different levels of exit access width, it is concluded that this is not the case. In other words, occupant configuration has an effect on crowd walking speed, but it depends on the level of exit access width. Therefore, the knowledge of the interaction between the occupant configuration and the exit access width is more useful than the knowledge of the main effect of each factor independently.

Next, the impact of exit access width and occupant configuration on crowd crawling speed was examined (hypotheses 3 and 4). The analysis of variance (ANOVA) for crowd crawling speed, illustrated in Appendix 5.5, indicated that the width of the exit access was statistically significant ($p << 0.0005$) to crowd crawling speed, whereas occupant configuration was statistically insignificant ($p = 0.712 > \alpha$). As a result, the effect of occupant configuration on crowd crawling speed was further analyzed. The pairwise comparisons among levels of occupant configuration with respect to crowd crawling speed; $C_1 = 2$, $C_2 = 4$, $C_3 = 5$, $C_4 = 7$, $C_5 = 9$ occupants, revealed similar results to crowd walking speed; none of the levels of occupant configuration was statistically significant. Furthermore, the interaction between occupant configuration and exit access width was insignificant ($p = 0.406 > \alpha$). This implies that occupant configuration has no effect on crowd crawling speed even when examined at different levels of exit width access.

5. **Discussion**

This study examined the impact of the occupant configuration (number of occupants) and the width of the exit access on crowd normal walking and crawling speeds. It has been demonestrated that the exit access width is significant to both crowd walking and crawling speeds ($p<0.0005$). However, the occupant configuration is insignificant to both speeds ($p_{\text{crowd walking}} = 0.420$ and $p_{\text{crowd crawling}} = 0.712$). Crowd walking speed presented in the study fits the normal distribution. At $\alpha = 0.05$, the p-value for the normal distribution for crowd mean walking speed ($p_{walking} = 0.795 > \alpha = 0.05$) providing a good fit of normality for crowd walking (Figure 11). The mean of the walking speed is 1.22 (95% confidence interval of 1.20 and 1.24 m/s), with a standard deviation of 0.05 (95% confidence interval of 0.04 and 0.0 m/s).



Anderson-Darling Normality Test	
A-Squared	0.23
P-Value	0.795
Mean	1.2190
StDev	0.0543
Variance	0.0029
Skewness	-0.140984
Kurtosis	-0.453714
N	30
Minimum	1.1000
1st Quartile	1.1800
Median	1.2200
3rd Quartile	1.2700
Maximum	1.3300
95% Confidence Interval for Mean	
1.1987	1.2393
95% Confidence Interval for Median	
1.1923	1.2500
95% Confidence Interval for StDev	
0.0432	0.0730

Figure 11. Normality test of crowd walking speed.

The study further revealed that none of the occupant configuration levels had an impact on crowd crawling speed (p-values >> α). Thus, the focus has been on the exit access width. Pairwise comparisons among levels of the exit access width were conducted. The results in Appendix 5.5 demonstrate that there is a significant difference of crowd crawling speed at the exit access width of 3 ft when compared to that at 4 ft ($p = 0.001 << 0.05$), while it is statistically insignificant at 5 ft exit access width. In other words, at any occupant configuration level, crowd crawling speed increases at the 4-ft exit access width, but then decreases at a larger exit access width (5 ft). Figure 12 illustrates the effect of the levels of the exit access width on the *mean* crowd crawling speed.

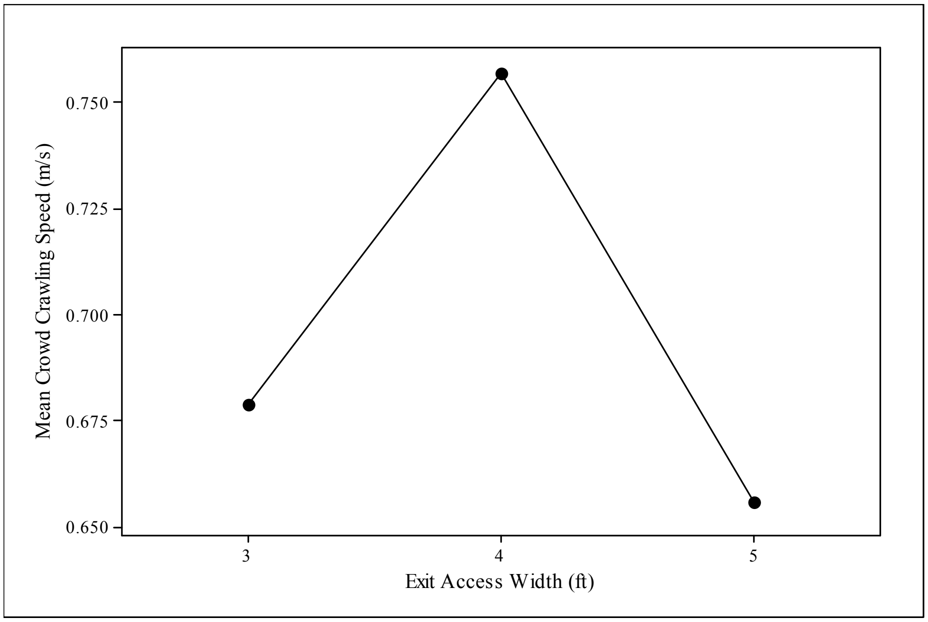
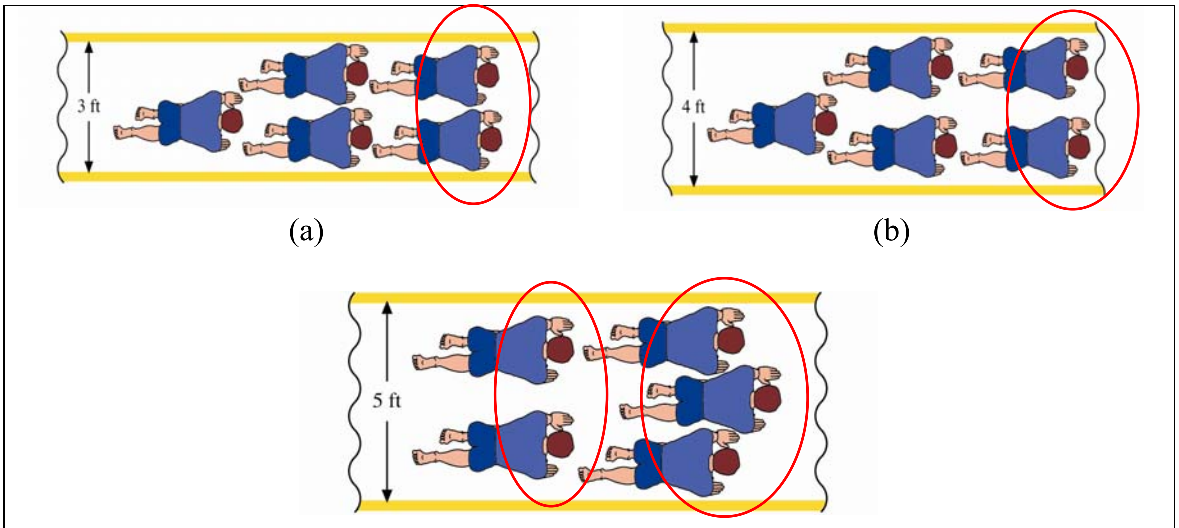


Figure 12. Main effect plot of exit access width on crowd crawling speed.

Observations from the study indicate that two crawlers can barely fit in the 3-ft wide exit access (Figure 13a), which results in a mean crowd crawling speed of 0.68 m/s. When the width increases to 4 ft (Figure 13b), the two crawlers can now comfortably move along the track at a faster speed (0.76 m/s). When the exit access width is extended to 5 ft (Figure 13c), it is expected that crawling speed would either increase or remain similar to that in 4-ft width. On the contrary, crowd crawling speed has decreased significantly (0.66 m/s) due to the fact that more crawlers could line up in parallel.



(a) (b)

(c)

Figure 13. Study observation at (a) 3-ft, (b) 4-ft, and (c) 5-ft wide exit access width.

The primary conclusion of those observations is that the location of crawlers with respect to the exit access width affects the density of crawlers, which is also critical to crowd crawling speed calculations. In order to calculate the crowd density, the number of crawlers in a unit area has been captured through the camcorder as crawlers pass through the designated area along the test track. Appendices 5.6 and 5.7 show the calculations of crowd density and the regression analysis, respectively. The relationship between crowd crawling speed and crowd density is shown in Figure 14. The quadratic model (p-value = 0.004) appears to provide a good fit to the data. The R^2 indicates that crowd density accounts for 42.7% of the variability in crowd crawling speed.

$$S = 0.7973 + 0.2909\, d - 0.1503\, d^2$$

where (1)

$S = Crawling\ Speed\ (m/s)$, *and*

$d = Crowd\ Density\ (persons/m^2)$

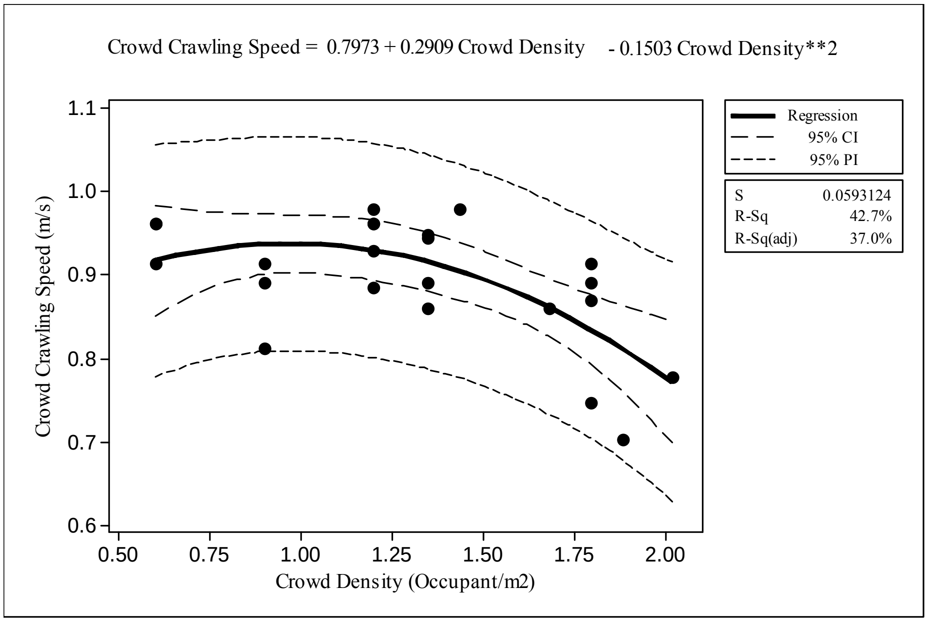


Figure 14. The relation between crawling speed and density on a flat surface.

6. Conclusions

Occupant movement in evacuation models is commonly based on the density of the space, which is currently limited to walking speed on flat surfaces and stairs. The present study investigates the relationship between crowd density and occupant walking and crawling movement. The latter is a physical response to environmental conditions in fire. This is accomplished by examining the impact of occupant configuration (number of occupants) and exit access width on crowd walking and crawling speeds on a flat surface. The findings of the study statistically show that the exit access width is significant to both crowd walking and crawling speeds, whereas occupant configuration is insignificant to both speeds. The results further demonstrate that there is a significant difference in crawling speed at different levels of the exit access width. This implies that the density of the crawlers affects crawling speed. The relationship between crowd crawling speed and density is best described in a quadratic regression model.

Finally, there is a need to continuously develop new predictive movement methods, or enhance existing ones in order to cope with the level of detail required to ensure occupant safety. In light of the significant absence of crawling data in the literature, this study contributes to the field of fire safety by providing experimental data for use in evacuation models, improving the accuracy and functionality of existing and future models, and introducing a realistic movement algorithm to evaluate the consequences of crawling on model outcomes. The ability to directly assess the impact of fire and smoke conditions upon evacuee performance requires the use of more sophisticated computational tools and reliable evacuation and fire data.

CHAPTER 6

THE APPLICATION OF EVOLUTIONARY COMPUTATION IN LAYOUT DESIGN FOR WALKING AND CRAWLING EGRESS

Abstract. According to the *Life Safety Code*®, building design and structure must provide protection to the occupants of a building in order to reach safety. As evacuation models are implemented to understand and assess building designs to assure occupant safety, the effectiveness of such evaluation relies heavily on the models' ability to reflect the detailed interaction between the occupant, building design, and environment. The purpose of this study is to demonstrate the application of evolutionary computation techniques, namely the Estimation of Distribution Algorithm (EDA), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO), in building design for walking and crawling egress. This has been undertaken by evolving the optimal placement and number of exits required to minimize evacuation time. The algorithms are applied to a layout known to be in compliance with the *Life Safety Code*®. The best exit configurations are presented for each algorithm. The performance of the algorithms varies by activity. A comparison between the algorithms' performance is also drawn. The study suggests that the algorithms have the potential to be implemented in more complex design problems. The study further suggests the need to validate the configurations found by the algorithms by conducting actual evacuation drills.

1. Introduction

Evacuation procedures and planning present a challenge to building occupants and emergency responders during evacuation and rescue operations. The challenge is partially caused by the creative designs and complex structures that exist in modern buildings. The ongoing trend of advancing knowledge in building designs and structures has raised major concerns for occupant safety. Innovative methods and approaches are needed to understand and assess these designs to assure occupant safety and verify building compliance with standards and guidelines. Traditionally, prescriptive codes have been applied to building designs to establish occupant safety without the need to demonstrate the level of safety achieved, or the effectiveness of evacuation procedures [1]. A more recent approach to evaluate occupant safety in building designs lies in the application of performance-based assessment techniques such as expert analysis, engineering (hydraulic) calculations, and evacuation drills [2]. The application of these techniques introduces major obstacles to safety engineers. For instance, expert analysis is a qualitative technique rather than a quantitative one, and is based on individuals' sole experience and judgment, engineering calculations consider a number of simplifying assumptions, which ignore the representation of evacuation behavioral complexity, and evacuation drills present ethical, practical, and financial difficulties to safety engineers.

A potential alternative to these challenges and obstacles lies in computer-based evacuation models. The development of evacuation models in the last three decades has mainly contributed to the assessment of occupant safety and evacuation procedures in a variety of building designs, under a range of environmental conditions. The effectiveness of such evaluation relies mainly on the models' ability to reflect the detailed interactions between the occupant, building design, and environment. The deterioration of environmental conditions during a fire, in terms of heat and smoke, and the interaction of occupants with such conditions influence the adoption of new behavioral and physical responses [3-6]. A number of studies [1, 2, 7-9] have suggested crawling as a physical response to a descending hot layer of smoke. As a result, it is important to understand the robustness of evacuation procedures and the consequences of encountering such response when assessing building designs based on the standards and guidelines of the *Life Safety Code*® [10].

According to the *Code*, the components of a building design and structure must provide protection to the occupants of a building in order to reach safety. The *Code* uses the term *means of egress* to reflect the compliance of those components with standard and guidelines. The *Code* defines means of egress as “a continuous and unobstructed way of travel from any point in a building or structure to a public way consisting of three separate and distinct parts: (1) the exit access, (2) the exit, and (3) the exit discharge.” In addition, the geometry of a building, the location of exits, and the number of exits influence the means of egress for all those occupying a building. The purpose of this study was to evaluate the application of evolutionary computation techniques, namely the Estimation of Distribution Algorithm (EDA), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO), in building designs to assess the means of egress for walking and crawling occupants by evolving the location and number of exits required to minimize total evacuation time.

2. The Approach

In order to examine the effect of occupant crawling on building design in terms of the optimal placement and number of exits, an evacuation model needs to be developed. The layout selected for this study, a ballroom, is representative in terms of the area, number of occupants, exit width, and occupant load factor to be in compliance with the *Life Safety Code*® [10]. Occupant walking and crawling speeds for the model were employed from experimental studies (Chapter 3 of this dissertation). Occupant sizes and anthropometric measurements were obtained from the Civilian American and European Surface Anthropometry Resources (CAESAR) [11, 12]. For validation purposes, the performance of the evacuation simulation model was then compared to another well-known evacuation model, namely ASERI. Finally, several evolutionary computation techniques were implemented to investigate the optimal location and number of exits that minimized the overall evacuation time. Figure 15 illustrates the approach followed in this study.

3. The Development of the Evacuation Model

Since the keystone work of quantifying people movement in nonemergency conditions [13, 14], a growing body of research has been recognized in modeling building evacuation in both normal and emergency conditions. Kuligowski [15] reported that the development of the first generation of computer evacuation models started in the mid 1960s. Since then, the number of evacuation models has significantly increased mainly due to advancing computational techniques and the availability of evacuation data [16].

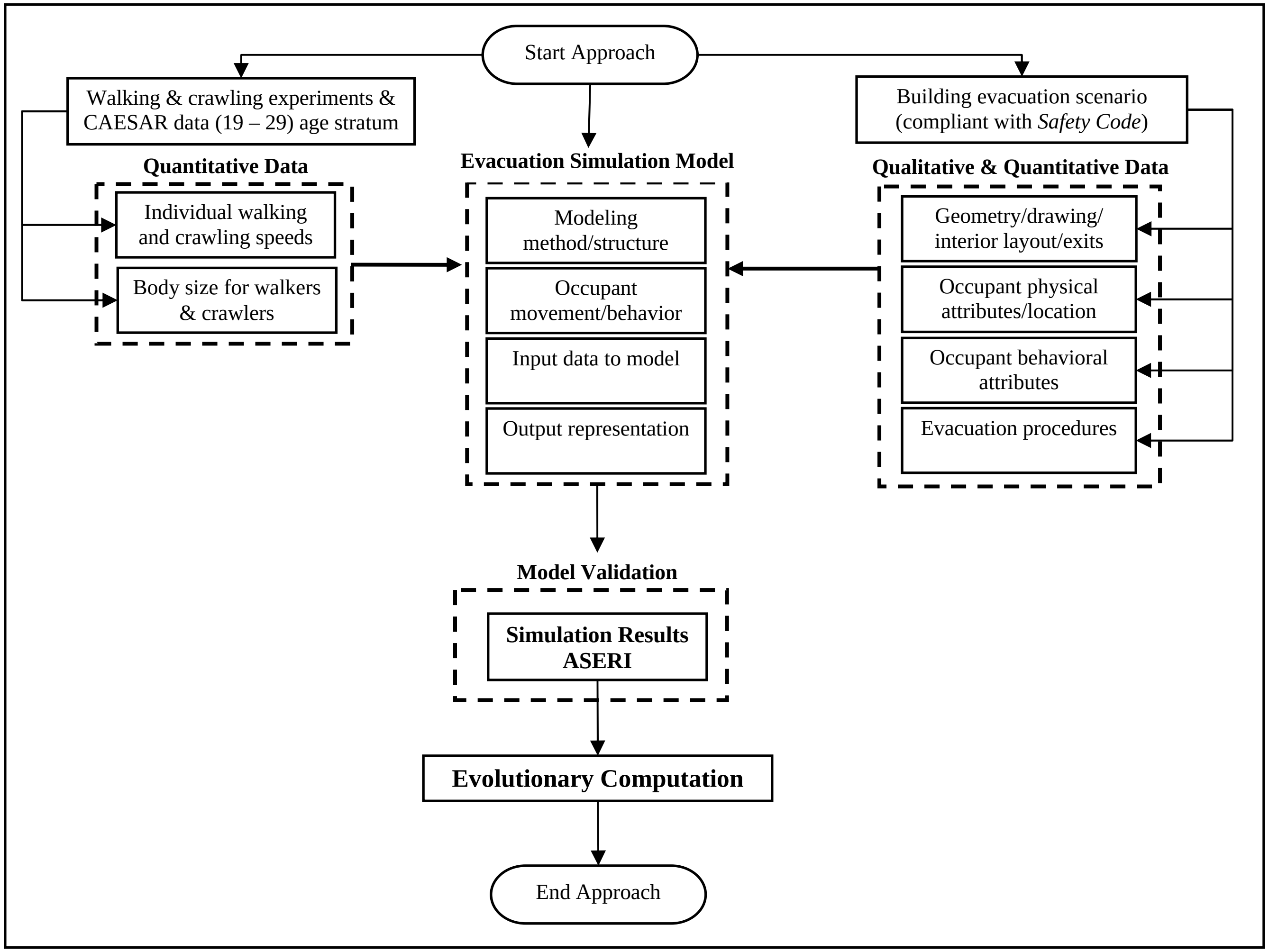


Figure 15. The approach to implementing evolutionary computation into an evacuation simulation model.

Evacuation models vary in structure, computation method, and complexity. The simplest model structure utilizes straightforward calculational methods to estimate evacuation times. The next level of complexity is network flow (flow-based) evacuation models, which represent paths and exits by arcs and nodes, respectively [17]. Although network models are useful to minimize distance to exit(s) and/or evacuation time, they lack the ability to represent the stochastic nature of the evacuation process caused by the human and hazard elements. The most complex models are the ones that incorporate occupant performance and behavioral variables into the evacuation process. In these models, a set of attributes are assigned to each occupant (agent) to assess the optimal escape route. The simulation is usually performed in a series of time steps to track occupant movement and decision-making (behavior).

3.1. The Model Structure

In order to evaluate the application of evolutionary computation techniques in building designs for walking and crawling occupants, an evacuation model is needed to simulate occupant movement and behavior. Helbing and Molnár [18] suggested that occupant motion can be realistically described using a mathematical model named the *social forces model*. The main effects that determine the motion of an occupant are reaching a certain destination at certain period of time, which requires desired direction and velocity, and a repulsive effect which is the influence of an occupant on others or that provided by a boundary.

The evacuation model in the study was based on a simplified framework of the *social forces model*, namely the *artificial potential field* approach [19]. In the model, an exit location creates an attractive force for an occupant, while obstacles/barriers and other occupants act as repulsive forces. The resultant force acting on an occupant forms a potential field, whose gradient drives the occupants at every time-step of the simulation. In order to calculate the movement of an occupant, each force is inversely proportional to the square of the distance between the occupant and the source of the force. If A, O, and E denote the set of all attraction, obstacle, and occupant vectors, respectively, and $d(\vec{p},\vec{q})$ represents the Euclidean distance between vectors $\vec{p}$ and $\vec{q}$, then, for a given occupant position, the resultant force acting on that occupant $F(\vec{p})$ is calculated as shown in Equation 1. The gradient of F is calculated according to Equations 2, 3 and 4. To compute the direction of movement, the current ∇F is averaged with the previous one, as shown in Equation 5. In order to determine occupant change in location during a time step, the gradient vector is normalized and multiplied by the occupant speed.

$$F(\vec{p}) = \sum_{\vec{a}\in A} \frac{1}{d(\vec{p},\vec{a})^2} - \sum_{\vec{o}\in O} \frac{1}{d(\vec{p},\vec{o})^2} - \sum_{\substack{\vec{e}\in E \\ \vec{e}\neq\vec{p}}} \frac{1}{d(\vec{p},\vec{e})^2} \tag{1}$$

$$\frac{\partial F}{\partial x} = \sum_{\vec{a}\in A} \frac{-2(p_x - a_x)}{d(\vec{p},\vec{a})^4} - \sum_{\vec{o}\in O} \frac{-2(p_x - o_x)}{d(\vec{p},\vec{o})^4} - \sum_{\substack{\vec{e}\in E \\ \vec{e}\neq\vec{p}}} \frac{-2(p_x - e_x)}{d(\vec{p},\vec{e})^4} \tag{2}$$

$$\frac{\partial F}{\partial y} = \sum_{\vec{a}\in A} \frac{-2(p_y - a_y)}{d(\vec{p},\vec{a})^4} - \sum_{\vec{o}\in O} \frac{-2(p_y - o_y)}{d(\vec{p},\vec{o})^4} - \sum_{\substack{\vec{e}\in E \\ \vec{e}\neq\vec{p}}} \frac{-2(p_y - e_y)}{d(\vec{p},\vec{e})^4} \tag{3}$$

$$\nabla F = \left\langle \frac{\partial F}{\partial x}, \frac{\partial F}{\partial y} \right\rangle \tag{4}$$

$$\nabla F_{avg} = \frac{\left(\nabla F_{t-1} + \nabla F_t\right)}{2} \tag{5}$$

The repulsive forces acting on an occupant from obstacles/barriers and other occupants diminish when the distance to the occupant exceeds a pre-determined minimum value. The obstacle $\vec{o}$ and occupant $\vec{e}$ vectors are checked at every time step of the simulation. When the distance is within 0.03 m (0.1 ft), the contribution of those particular repulsive vectors are included in the summation of the resultant force. The minimum distance applied here is more conservative when compared to that applied in other studies [20-21], where a distance of 0.08 m (0.26 ft) is considered to activate the repulsive forces on an occupant. The model also accounts for trampled and/or crushed occupants during the evacuation process. At each simulation time-step, the model checks each occupant for overlapping by other occupants or obstacles by a distance of the occupant radius. Therefore, dead occupants do not obstruct the movement of the other ones since they no longer act as repulsive forces.

4. The Layout Design

The layout design for this study consists of a small banquet hall (39’ x 22’); with 7 fixed obstacles, and 24 occupants, as illustrated in Figure 16. The area of the room, number of occupants, and occupant load factor are all in compliance with the *Life Safety Code*® [10]. The effect of the layout symmetry on the level of difficulty in searching for an optimal solution is yet to be explored. This is because of the unexpected number of local minima in the artificial potential field in the evacuation simulation.

The possible exit locations are determined by calculating how many 3-ft wide doors would fit along each wall without separation. If a wall does not allow an integral number of doors, the set of doors are centered along the wall with the excess space placed in each corner. The doors are then numbered starting with the far left door along the north wall and continuing clockwise. In this way, the presence or absence of the exits is represented by a one-dimensional Boolean array. Although this approach is limited to a set of fixed door locations, it uses a fixed-length encoding scheme to represent a variable number of doors. In all, the room had the potential for 35 specific exit door locations.

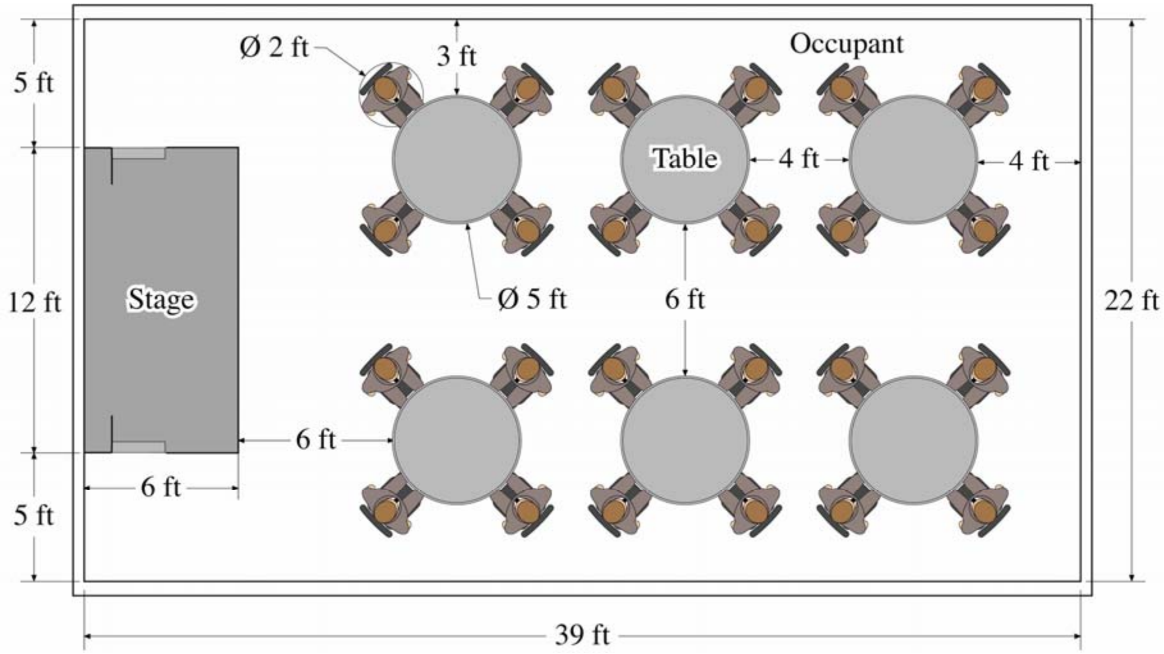


Figure 16. The layout design for the banquet hall.

5. Occupant Size and Shape Representation

The size and shape of individuals in an evacuation model influence occupant movement, density, and response to surroundings. Many evacuation models rely on movement techniques to model the dynamic of spatial systems during the evacuation process, where a discrete environment is updated in steps according to global rules. As a result, occupant shape is a critical element of that spatial system representation and dynamic environment. Meanwhile, the size of individuals assesses the method of movement throughout a building and simulates the presence of occupants and building enclosure such as walls, rooms, exits, corridors, stairs, and obstacles. The majority of the models obtain their occupant shape and size from anthropometric studies [22, 23], or people movement research [13, 14, 24-26].

The scarcity of civilian anthropometric data led researchers to seek alternative anthropometric measurements to represent occupant shape and size in evacuation models. Predtechenskii and Milinskii [13] and Ando et al. [27] observed a projected area of people based on the *average* dimensions (measurements) of a person’s width and breadth obtained at the shoulder and chest levels, respectively, while Fruin [14] applied shoulder breadth and body depth measurements obtained from U.S. Army human factors design recommendations. Figure 17 exemplifies a range of anthropometric measurements and body sizes adopted in some crowd movement studies.

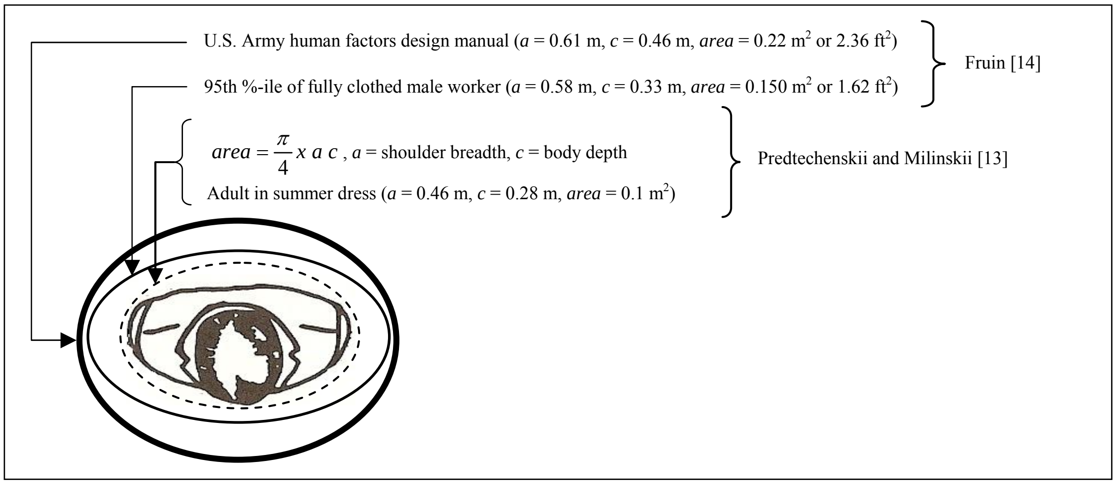


Figure 17. A range of anthropometric measurements and body sizes adopted in people movement studies.

On the contrary, crawling modeling studies (1, 2, 7-9] and evacuation models [28, 29] have never taken anthropometric measurements into consideration when simulating crawlers size and shape. Thus, as reliable observations of civilian anthropometric measurements are becoming more available due to advanced modern technologies, it is essential to incorporate recent and reliable anthropometric measurements into evacuation models. The most comprehensive and reliable source for civilian anthropometric data available to date is that of the Civilian American and European Surface Anthropometry Resources or CAESAR [11, 12]. The CAESAR project is an international anthropometric survey that collected 3-D whole body scans for two postures; standing and seated, using a cyberware WB4 scanner. The project measured more than 13,000 3-D scans taken from 4,431 subjects sampled from the U.S., Canada, Netherlands, and Italy, and classified into three age strata; 18 – 29, 30 – 44, and 45 – 65. The anthropometric body measurements of CAESAR were used in this study to model walkers and crawlers physical attributes.

According to the *Human Engineering Guide to Equipment Design* [30], the crawling position is achieved when a subject rests on their knees and flattened palms with arms and thighs perpendicular to the floor and feet comfortably extended and spaced. Crawling length is measured from the most rearward point on the foot (the tip of the longest toe-first or second digit) to the most forward point on the head (vertex). Since CAESAR did not collect data on crawling length, an approximation (Equation 6) has been developed from CAESAR body dimensions (Figure 18). The range of movement for ankle extension is based on data from Barter et al. [31]. For simplicity, crawler width is represented in the study from the CAESAR shoulder breadth (bideltoid) dimension (Figure 19).

$$Crawling\ length \approx sitting\ height + right\ lateral\ femoral\ Epicondyle\ to\ right\ latteral\ malleolus + \{foot\ length\ x\ \cos(ankle\ extension)\} \quad (6)$$

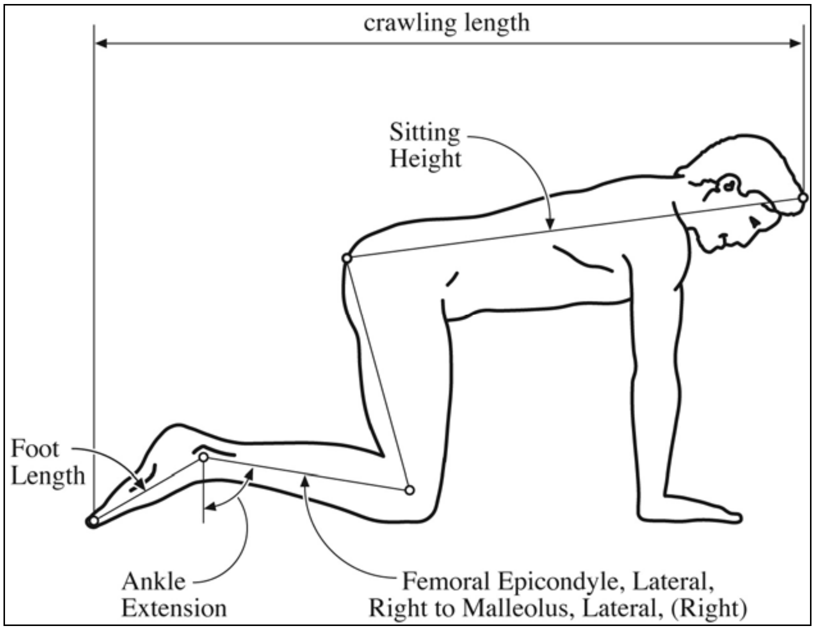


Figure 18. An approximation of crawling length (sagittal plane).

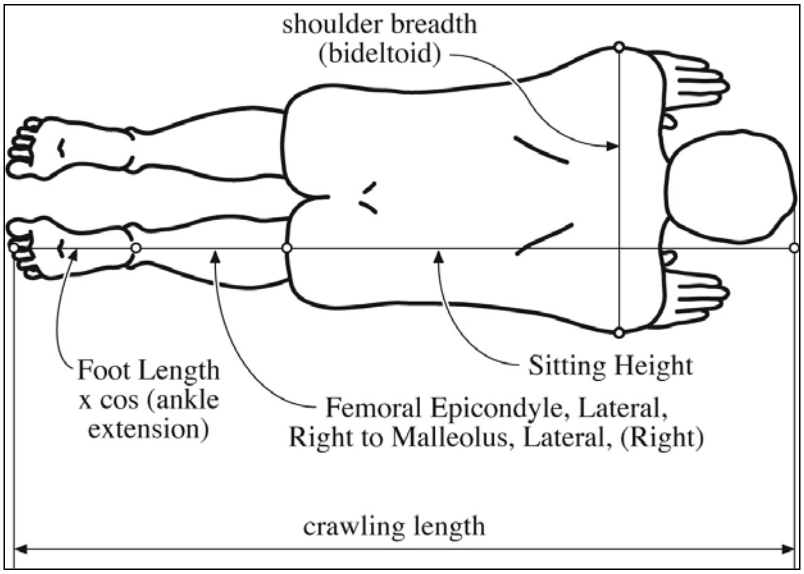


Figure 19. Crawling dimensions based on CAESAR measurements (transverse plane).

The only representation of crawler shape in evacuation literature was found in Nagai et al. [7, 8], where crawlers were represented by a 0.4 m x 0.8 m-rectangular grid. For the purpose of this study, crawler shape is approximately represented by three circles attached in a linear configuration; a leading circle for the head and shoulder, and two "following circles" for the lower back and extremities, respectively as illustrated in Figure 20. In order to simulate crawling movement in the potential field model, "the following circles" contribute to repulsive forces to other leading circles but not to other attached circles. The anthropometric estimates of crawling body dimensions for U.S. male adults aged 19 – 29 years, based on CAESAR data, are presented in Table 9.

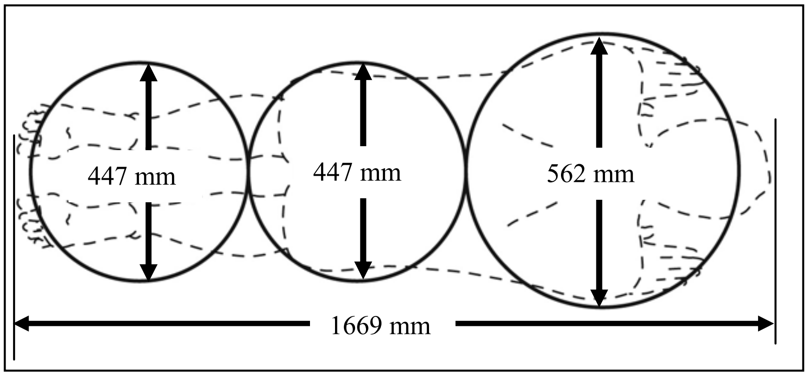


Figure 20. Mathematical representation of occupant crawling shape and size.

Table 9
Crawling body dimensions for U.S. male adults aged 19 – 29 years (mm)

Dimension	μ	σ	95th %ile
Crawling Length	1531	69	1669
Crawling Width (Shoulder Breadth-bideltoid)	494	34	562
Hip Breadth (sitting)	375	36	447

6. Model Verification and Validation

One of the most challenging tasks facing evacuation model developers is the verification and validation of their models. According to Banks et al. [32], verification relates to the correct structure of a model by comparing the computer representation to the conceptual model, whereas validation attempts to confirm that the model is a true representation of a real system. With respect to evacuation models, verification can be conducted by testing the performance and functionality of various modules of the computer model. This includes checking the code to examine the performance of model components, and testing a series of model capabilities to ensure the accurate representation of the model functionality [33]. In this study, the evacuation simulation model has been verified by inspecting its code routinely and assessing its ability to perform scenarios with expected outcomes.

The majority of evacuation modeling literature has concentrated on model validation, assuming verification is an integral part of the development phase of the model. Evacuation models have been validated against building code requirements [34], fire drills and movement experiments [35-41], literature on past evacuation trials [42-44], or other evacuation models [45, 46]. For the purpose of this study, the evacuation simulation model has been validated against another evacuation model, ASERI [35]. The selection of ASERI is due to its continuous space structure, occupant behavior and movement representation, ability to import CAD drawings, and visualization capability. The layout utilized for the study, with two random locations of 3-ft exit door (scenarios are illustrated in Appendix 6.1), has been run by both models. Since ASERI is not designed to model crawling, the validation has been conducted for walking.

The input data to the models are occupant speed and body size. Occupant speed is normally distributed with a mean of 1.5 m/s and a standard deviation of 0.16 m/s, based on the results from Chapter 3 of this dissertation. However, since ASERI uses normal distributions that are limited at the boundaries given by the standard deviation, the standard deviation of occupant movement in ASERI is set at 0.48 m/s to contain over 99% of the speed distribution. Occupant size is represented by a circle with a diameter equivalent to 95 percentile U.S. male adults aged 19 – 29 years representing shoulder breadth (bideltoid), based on U.S. CAESAR data (Table 9).

Once the input data were identified for each model, total evacuation times resulted from 100 simulation runs, for each scenario, have been compared (Appendix 6.2). The results shown in Table 10 reflect reasonable outcomes. In scenario 1, where the exit door is located in the middle bottom of the banquet hall, the potential field model under-predicted the average total evacuation time by 1.4 sec in comparison with ASERI. In scenario 2, where the exit door is placed in the bottom right of the banquet hall, the potential field model over-predicted ASERI's average total evacuation time by 0.9 sec.

Table 10

Comparison between total evacuation times of 100 simulation runs produced by ASERI and the potential field model

	Scenario 1		Scenario 2	
	ASERI	Potential Field Model	ASERI	Potential Field Model
Min	9.2	7.4	11.6	11.3
Max	12.8	14.8	14.4	16.6
Average	11.0	9.6	12.9	13.8

7. Evolutionary Computation (EC)

Evolutionary computation is the discipline devoted to the design, development, and analysis of problem solvers based on natural selection [47]. Evolutionary computation techniques have been applied to a range of design, scheduling, and optimization problems [48]. Figure 21 illustrates the basic structure of an EC. A set (population) of candidate solutions (individuals) for the optimization problem is randomly initialized and evaluated with respect to an objective function. The evaluation function assigns candidate solutions fitness values corresponding to how well the solutions optimize the problem. After the initial population is evaluated, a subset of the population is chosen to become parents for the next generation, allowing the selected parents to create offspring through procreation operators such as crossover and mutation. The procreation operators modify and combine the genetic composition of the parents to create offspring. A subset of the offspring is evaluated and selected for inclusion in the next generation of the population. This process is repeated until some stopping criterion is reached; the discovery of an optimal solution or exceeding a maximum number of iterations.

```
Procedure EC {
   t = 0;
   Initialize P(t);
   Evaluate P(t);
   While (Not Done) {
      Parents(t) = SelectParents(P(t));
      Offspring(t) = Procreate(Parents(t));
      Evaluate(Offspring(t));
      P(t+1)= SelectSurvivors(P(t),Offspring(t));
      t = t + 1;
   }
}
```

Figure 21. Pseudocode structure of an EC.

7.1. Estimation of Distribution Algorithms

Estimation of Distribution algorithms (EDAs) attempt to leverage the statistical properties of the fitness landscape in order to create children. In EDAs, there are neither crossover nor mutation operators. During each generation, the new population is created by sampling the probability distribution of the current population. For binary-coded chromosomes, the EDA makes use of the probability distribution function of selected individuals. For real-coded chromosomes, the probability density function is used instead [49]. In both cases, a set of parents is selected from the population. The probability distribution/density function is calculated for the set, and used to create a new population of offspring. EDAs operate along one dimension at a time when creating children (offspring). Essentially, for binary-coded chromosomes along a particular dimension, a random parent is selected, and its gene value is used to create the child gene. For the real-coded chromosomes along a particular dimension, the mean and standard deviation of the set of the parent genes are calculated. Each child gene (along that dimension) is created according to Equation 7, where *i* denotes the offspring (child) number, *dim* represents the dimension, and *N(0,1)* is the standard normal random variable, which differs for each offspring by sampling the probability density function for the set of parents.

$$offspring_{i,\dim} = \mu_{\dim} + \sigma_{\dim} . N(0,1) \tag{7}$$

7.2. Genetic Algorithms

Genetic Algorithms (GAs) were developed by John Holland through his work in simulating natural evolution using binary strings (chromosomes), which represent candidate solutions for the problem of interest [50]. The GA starts with a population of randomly generated chromosomes. The population goes through a series of generations. During each generation, a set of chromosomes from the population is selected, through some selection strategy, to become the parents in the next generation. Once the parents are chosen, they are exposed to one or both of the genetic operators; crossover and mutation. During crossover, the chromosomes of two parents are mixed to form one or more offspring. On the other hand, mutation modifies the chromosome of a single parent to produce an offspring. The modification typically entails some type of random change applied to one or more of the alleles (i.e. components) of the chromosome. Once the genetic operators are applied to the parents, a set of offspring is produced. Finally, the GA determines which of the offspring and parents survive to the next generation.

7.3. Particle Swarm Optimization Algorithm

Particle Swarm Optimization (PSO), developed by Kennedy and Eberhart, is inspired by the movement and behavior of bird flocks and insect swarms to solve optimization problems [51]. In the PSO model, each particle is composed of three vectors $\vec{x}$, $\vec{p}$, and $\vec{v}$ which represent the particle's current location, best location found, and velocity, respectively. The vectors are of the same dimensionality as the search space, and each particle maintains a value corresponding to the fitness of the $\vec{x}$ vector and a value corresponding to the fitness of the $\vec{p}$ vector. As the particles in the swarm move through the search space, their velocities are updated according to Equation 8.

$$v_{id} = v_{id} + \phi_1 R_1(0,1)\left(p_{id} - x_{id}\right) + \phi_2 R_2(0,1)\left(g_{id} - x_{id}\right) \tag{8}$$

In the equation, v_{id} is the velocity of the *i*th particle along the *d*th dimension. The *g* vector represents the best location found by the particles in the current vector's neighborhood, and $R_1(0, 1)$ and $R_2(0, 1)$ are random numbers in the interval [0, 1]. Finally, ϕ_1 and ϕ_2 are two constants that control the influence of the individual and global best locations, respectively, on the particle's velocity. These values are often referred to as cognitive and social learning rates [52]. After the velocity vector and the particles' location are updated, the fitness of the new location is evaluated and compared to the fitness of the particle's personal best location. If the new location is better, then it becomes the new personal best location for the particle.

8. Methodology

8.1 Evaluation Function

The assessment of the fitness of a candidate solution with respect to evaluating a set of exit locations required several criteria. The most important one is total evacuation time, which is defined as the time needed for all occupants to leave the banquet hall. Another element to take into account is the number of occupants who are crushed to death in their attempt to evacuate. The penalty for a crushed occupant, in the fitness function, is significantly higher than that for an occupant who is unable to escape by the end of the allotted simulation time. This is because a crushed occupant has no chance of escaping regardless of time. Since the algorithm would likely generate solutions where each occupant has a door nearby, which is noncompliant with the *Life Safety Code*® guidelines, the third and final element of the fitness function is the number of exit locations.

In order to calculate the fitness value of a given configuration of exit locations, the simulation evacuation model was set at a maximum simulation time (T_{max}). The limit values for walking and crawling maximum evacuation times resulted from 100 simulation runs (Appendix 6.3) of a single-exit configuration, located in the middle of the lower wall of the banquet hall (Scenario 1 in Appendix 6.1). Such a configuration was reported to be a common best solution among similar studies; Garret et al. [53] and Muhdi et al. [54]. The T_{max} limits for walking and crawling were set at 10,000 and 35,100 milliseconds (ms), respectively. Each limit value represents three standard deviations from the mean of its 100 simulation runs of each activity ($\mu + 3\sigma$).

Two different fitness functions were applied, depending on the number of occupants able to evacuate. At any simulation run, when all occupants safely evacuate the banquet hall in a time less than the allotted maximum evacuation time ($t < T_{max}$), the fitness value for a configuration of exits is calculated according to Equation 9, where n represents the number of exit doors in a configuration. The fitness function favors configurations with $n \leq 2$ due to the high penalty score against configurations with three or more exits. If some occupants are unable to evacuate due to trampling to death or running out of time, the fitness score is computed via Equation 10, where a represents the number of evacuees who are still alive but could not escape in the time allowed, and d represents the number of evacuees who are trampled to death. Thus, the fitness function penalizes for long evacuation times, the number of occupants who are crushed, and configurations with three or more exits.

$$t + 10{,}000\ (\max(n,2) - 2) \tag{9}$$

$$T_{\max} \times a + 1.5T_{\max} \times d + 10{,}000\ (\max(n,2) - 2) \qquad (10)$$

For each walking or crawling evacuation simulation run, occupant walking and crawling speeds were drawn randomly from normal distributions, obtained from Chapter 3 of this dissertation, with $\mu_{\text{walking}} = 1.5$, $\sigma_{\text{walking}} = 0.16$, $\mu_{\text{crawling}} = 0.77$, and $\sigma_{\text{crawling}} = 0.08$ m/s. The evaluation function (evacuation simulation) was run 10 times for a given layout configuration to establish a 95% upper bound for the 10 fitness values based on the mean and standard deviation of the fitness evaluations ($\text{fitness}_{\text{upper}} = \bar{x}_{fitness} + k.s_{fitness}$). The k value is 3.981, obtained from Jay L. Devore, *Probability and Statistics for Engineering and Sciences*, 7th edition.

8.2 Encoding Scheme

Each chromosome in the population was encoded as an array of N binary values, where N denotes the maximum number of exits that may be located along the perimeter of the banquet hall. The binary values represent whether a door should be placed at that location of the room or not (0 for no door, 1 for door).

8.3 EC Setup

An elitist EDA was used to search for the best layout configuration. This indicates that the best individual for each generation was allowed to survive. The EDA was constructed with a population size of 100. For the GA, the initial population of 78 individuals was generated in a binary format, similar to that in Garret et al. [51]. A binary tournament was used to select parents. This implies that two individuals were randomly chosen from the population, their fitness values were compared, and the individual with the lower fitness value became a parent. Each pair of parents then underwent a uniform crossover, at the rate of 100%, to generate offspring. No modifications have been made on the offspring (mutation rate was set at 0%). The PSO was applied with 100 particles, a global neighborhood, and constriction coefficient. Updates were done asynchronously. The cognition and social rates were 2.8 and 1.3, respectively.

8.4 Experimental Setup

For a given layout configuration, each EC was executed for 30 independent runs with a maximum of 25000 function evaluations per run. The EC used the upper bound of the fitness evaluation to evolve solutions. Hence, 2500 different individuals were evaluated by the EC, and each individual was assessed 10 times, giving a total of 2500 x 10 = 25000 function evaluations.

9. Results

The purpose of this study was to evaluate the application of Estimation of Distribution Algorithm (EDA), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO), in building designs to dictate the means of egress for walking and crawling occupants. This has been conducted by evolving the location and number of exits required to minimize total evacuation time. Each algorithm produced 30 runs of best exit configurations, which were often unique solutions to the evacuation planning problem. Therefore, each run of the EC returned the best suggested exit location. Appendix 6.4 lists all 30 solutions for each algorithm, along with their function evaluations, fitness values, and exit locations, for walking and crawling, respectively. For both activities, two of the algorithms (EDA and GGA) produced 2-exit best solutions, while PSO yielded a 3-exit solution. The exit locations varied by algorithm and activity. For walking, the best exit locations for the EDA and GGA were 13 and 19, whereas for the PSO solution, the best exit locations were 10, 17, and 21. On the other hand, the best exit locations for crawling were 3 and 13 for the EDA, 19 and 29 for the GGA, and 12, 17, and 21 for the PSO. Table 11 lists the percentage of the 30 solutions that have number of exits equivalent to that found in the best exit configuration. Figures 22 through 26 illustrate the best exit locations of EDA, GGA, and PSO solutions for both activities. The similarity between best solutions found by each algorithm was captured based on the probability calculations of each of the 40 exit locations being selected by all of the 30 runs of a single algorithm. Figures 27 and 28 present the probabilities of best exit locations for all 30 runs of each algorithm for walking and crawling, respectively. Figure 27 clearly shows that there is at least 20% chance that all three algorithms would choose exit location 17 in their best solution for the walking activity. However, such a chance decreases to 10 % for crawling when exit 19 or 29 is chosen, as shown in Figure 28. The maximum probability values of best exit locations range from 0.27 to 0.37 for walking, and 0.27 and 0.47 for crawling. Appendix 6.5 provides the probability values for all exit locations classified by activity and algorithm type.

Table 11

The percentage of the solutions with a certain number of exits

	Walking			Crawling		
Number of Exits	EDA	GGA	PSO	EDA	GGA	PSO
2	96.7	83.3	0	100	100	0
3	3.3	16.7	20	0	0	16.7
4	-	-	23.3	-	-	16.7
5	-	-	40	-	-	20
6 or more	-	-	16.7	-	-	46.6

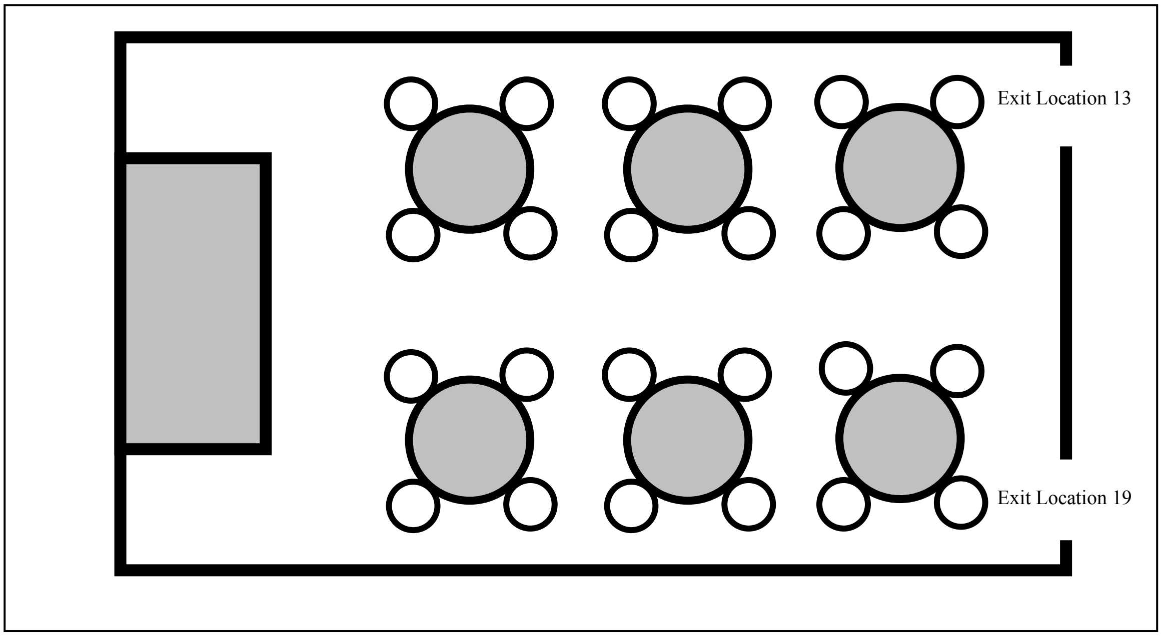


Figure 22. Best exit locations of the EDA and GGA solutions for walking.

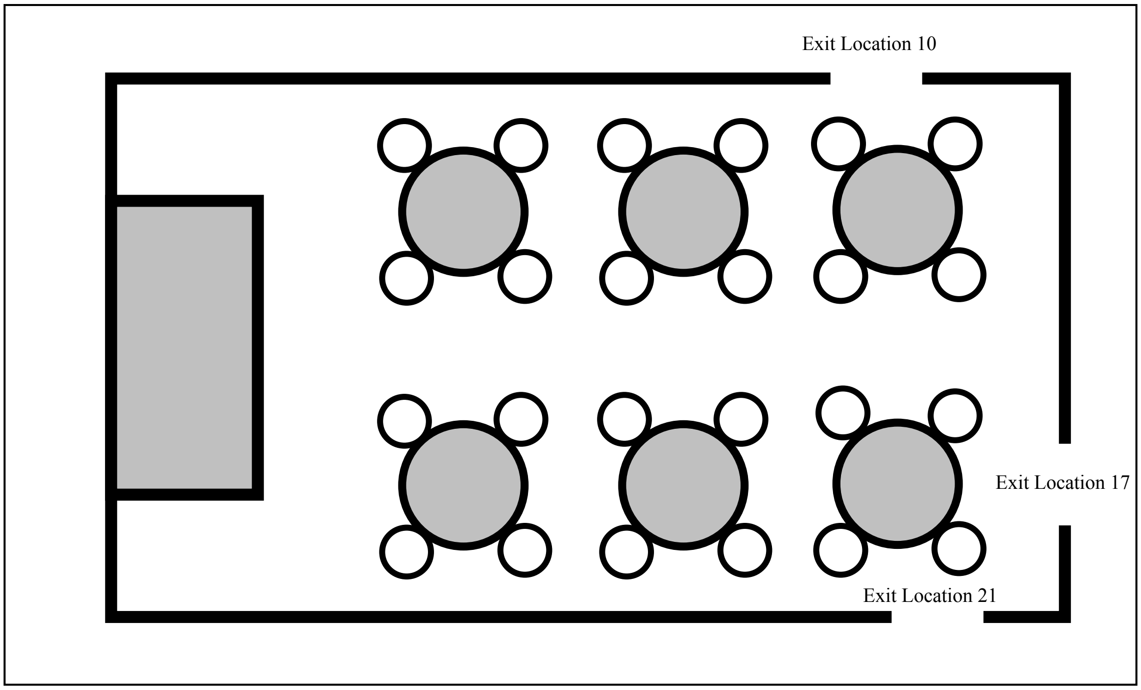


Figure 23. Best exit locations of the PSO solution for walking.

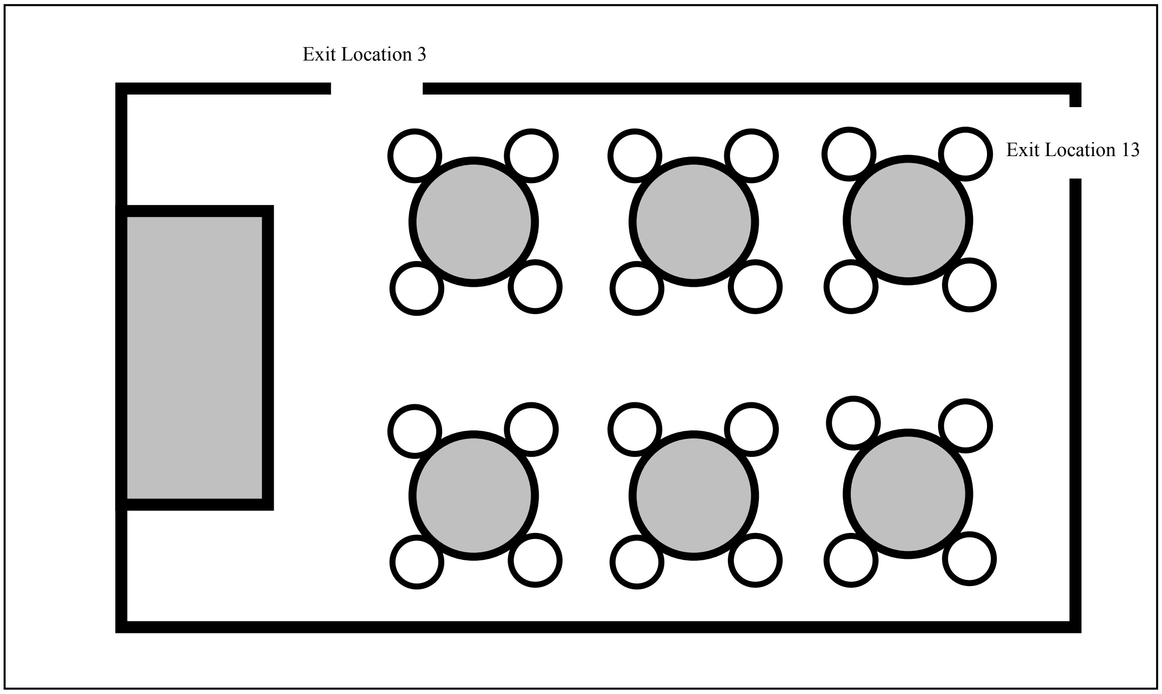


Figure 24. Best exit locations of the EDA solution for crawling.

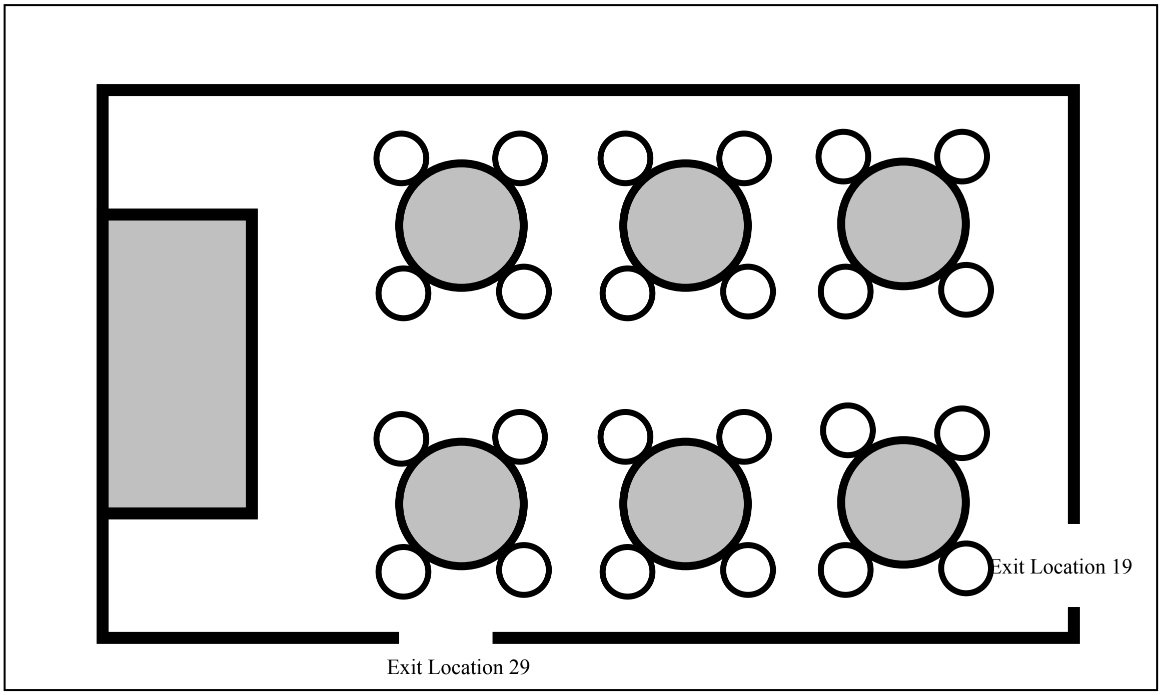


Figure 25. Best exit locations of the GGA solution for crawling.

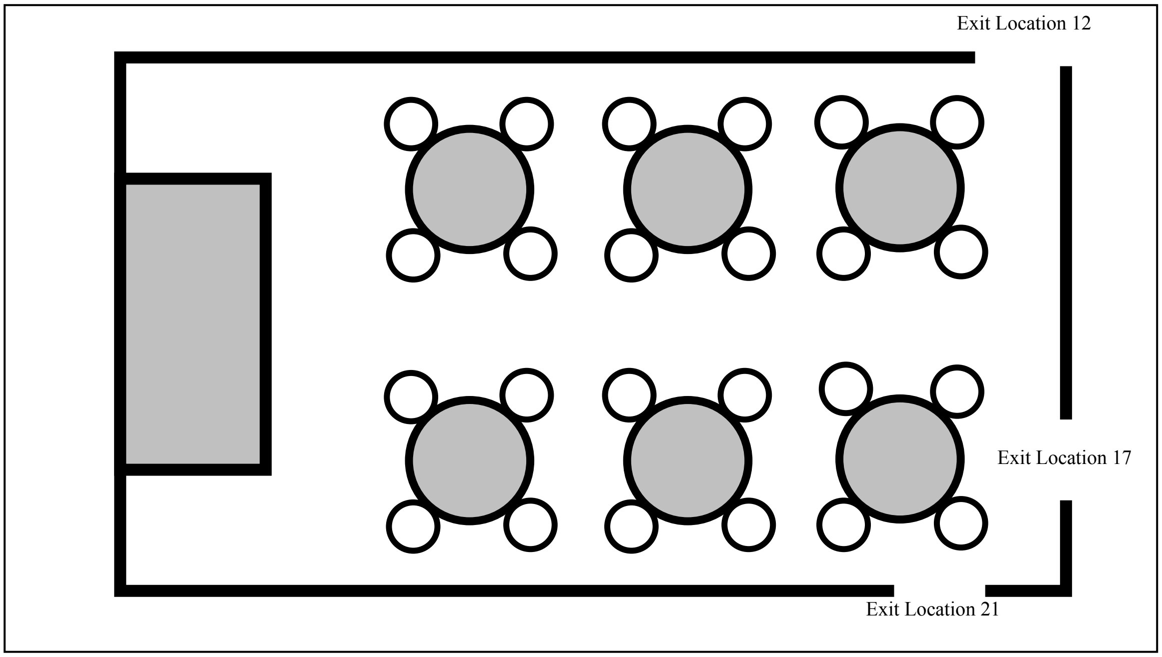


Figure 26. Best exit locations of the PSO solution for crawling.

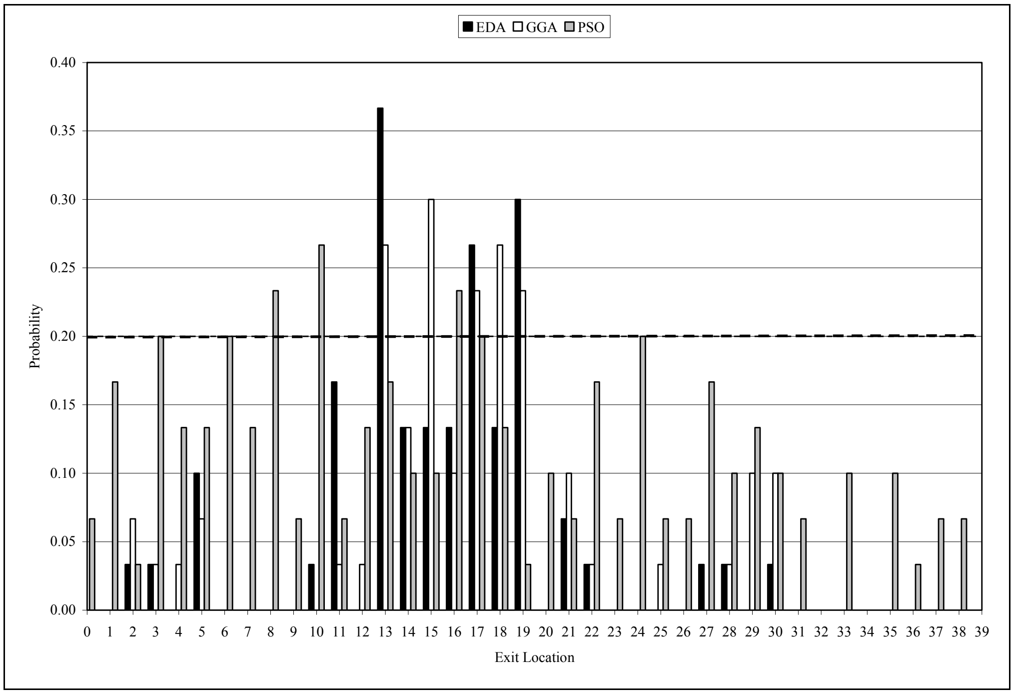


Figure 27. Probabilities of best exit locations for walking.

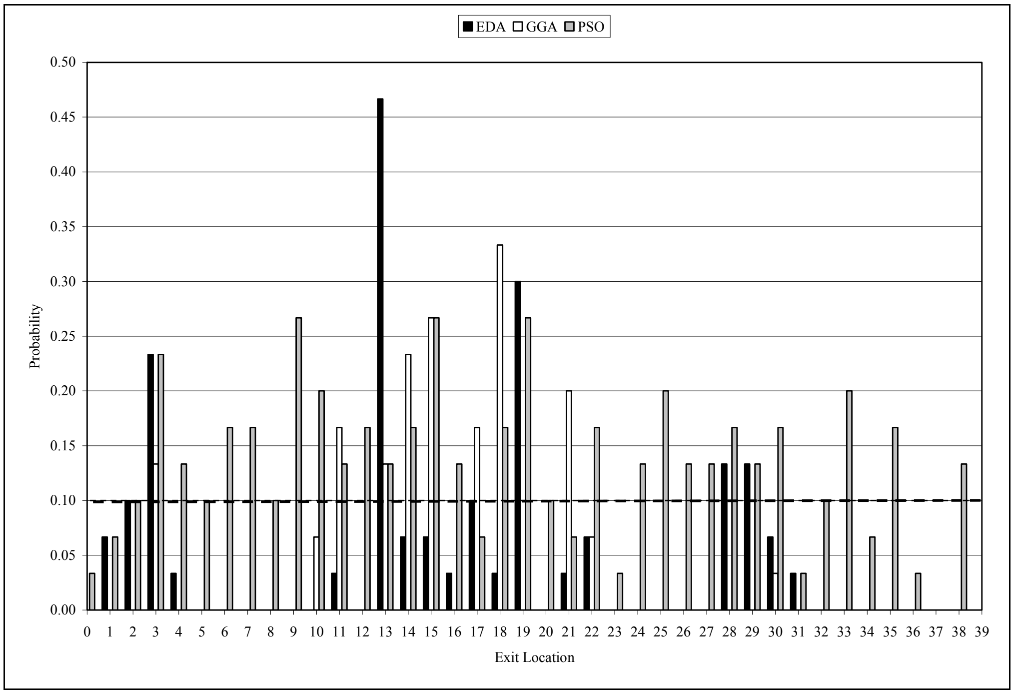


Figure 28. Probabilities of best exit locations for crawling.

10. Discussion

This study examined the application of evolutionary computation algorithms in evacuation planning to determine the location and number of exits required to optimize evacuation time. Although the algorithms undertook the same planning problem (banquet hall), their performance in finding best configurations differed for both walking and crawling occupants. For walking, both the EDA and the GGA required significantly fewer mean function evaluations and achieved lower mean fitness values than the PSO when tested with a two-sample t-test at α of 0.05 ($p << 0.0005$). However, there was no significant difference in mean function evaluations or fitness values between the EDA and the GGA. In regard to crawling, the PSO needed significantly less mean function evaluations than the EDA and the GGA ($p = 0.001 < \alpha = 0.05$). However, a comparison between mean fitness values for crawling revealed that the EDA and GGA significantly achieved lower mean fitness values than the PSO (P << 0.0005). Appendices 6.6 and 6.7 provide the t-test comparisons of mean function evaluations and fitness values for walking and crawling, respectively.

Once the best exit configurations were found, the evacuation process was then simulated 1000 runs to compare the average total evacuation time and number of casualties for each activity. Such comparisons further confirm the quality of the best configuration found by each algorithm. Tables 12 and 13 summarize the results of the simulation runs for walking and crawling, respectively. For the walking activity, the EDA and GGA best exit configurations resulted in a total evacuation time that is significantly longer than that found by the PSO due to the extra exit location (2 exits for the EDA and GGA vs. 3 for the PSO). However, the evacuation simulation runs revealed that the number of casualties resulted is significantly less for the EDA and GGA than that for the PSO (P << 0.0005). Such observation clearly indicates that the location of exits in walking is more important to the evacuation planning problem than the number of exits when the number of exits in a solution is relatively low. For the crawling activity, the best exit configurations found by the EDA and the GGA (Figures 24 and 25) were almost similar because of the symmetrical geometry of the design problem. Therefore, there is no significant difference in total evacuation times for crawling between the two solutions (P = 0.221 > 0.05). However, since the best exit solution found by the PSO is located on the right side of the hall, it takes occupants more time to reach the exits. As a result, total evacuation time is significantly longer for the PSO in comparison with the EDA and GGA. The longer it takes to reach the exits, the less congestion levels are at the exits, which results in fewer casualties, as shown in Table 13. Appendices 6.8 and 6.9 illustrate the t-test comparisons of mean total evacuation time and number of casualties for walking and crawling, respectively.

Table 12
Summary of the evacuation simulation runs for walking

	Exit Configuration			
	(13,19)		(10,17,21)	
	Evac. Time (ms)	Number of Casualties	Evac. Time (ms)	Number of Casualties
Min	6400	0	5300	0
Max	9600	2	8500	3
Mean	7759.7	0.22	6683.5	0.47
St. Dev	613.5	0.46	505.0	0.62

Table 13
Summary of the evacuation simulation runs for crawling

	Exit Configuration					
	(3,13)		(19,29)		(12,17,21)	
	Evac. Time (ms)	Number of Casualties	Evac. Time (ms)	Number of Casualties	Evac. Time (ms)	Number of Casualties
Min	14900	0	14300	0	14400	0
Max	22700	3	23800	3	29100	2
Mean	17690.8	0.31	17759.5	0.34	18877.5	0.11
St. Dev	1219.4	0.54	1288.4	0.58	1778.9	0.31

11. Conclusions

The study has demonstrated the application of evolutionary computation techniques, namely Estimation of Distribution Algorithm (EDA), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO), in building designs to dictate the means of egress for walking and crawling occupants. For both activities, the EDA and GGA generated 2-exit best solutions, while the PSO found 3-exit best solutions. The performance of the algorithms to find such solutions has varied by activity. For walking, it has been shown that there was no significant difference between the three algorithms in terms of function evaluations. However, the EDA and GGA outperformed the PSO in fitness values. For crawling, the PSO required significantly less function evaluations than the other two algorithms but resulted in greater fitness values. The study suggests that the EDA is particularly well-suited to solve such evacuation planning problem.

Finally, although the algorithms are applied to a relatively simple design problem, they have the potential to be implemented in more complex designs. However, since such implementation is solely dependent on the outcome of the evacuation model used, a continuous development of evacuation models with accurate representation of occupant performance and behavior characteristics is highly needed, especially in deteriorating environmental conditions. There is also a need to constantly develop new predictive crawling movement methods to cope with the level of detail required in evacuation crawling. In light of the significant absence of occupant size and shape for crawling occupants in the literature, further research is needed to investigate the impact of crawling on the interaction between occupants during evacuation. Another future work is the validation of the design suggestions found by the algorithms in real evacuation scenarios.

CHAPTER 7

CONCLUSIONS

1. Introduction

Computer evacuation models are a promising alternative to evaluate occupant safety and verify a building's compliance with standards. The effectiveness of such evaluation relies exclusively on the models' ability to accurately demonstrate the dynamic interaction between occupant characteristics, building design, and environmental conditions. One of the important features incorporated into most evacuation models, relates to occupant characteristics. Regulations and fire safety codes, and the need for more reliable and validated computer evacuation models, suggest further attempts to understand and model occupant behavior and performance characteristics in fire.

The complexity of modeling occupant characteristics during evacuation, and the relative scarcity of evacuation experiments in the literature, contribute to some extent to the continuous challenge of occupant data representation in computer evacuation models. It is apparent from the literature that there is a gap between the development and representation of occupant data in the models. The gap is even broader when modeling occupant behavior and performance responses to fire conditions since deteriorating conditions influence the occupants' adoption of new responses.

2. Summary of Findings

An attempt has been made in this research to bridge the gap between the development and representation of occupant characteristics pertaining to crawling, one of the more important responses to evacuation in fire and smoke conditions. A review of the literature revealed an astonishing lack of crawling data in evacuation research, which poses fundamental challenges for evacuation modelers to integrate and validate the crawling performance and behavior into evacuation models.

In order to bridge the gap between the development and representation of occupant crawling data, this research investigated occupant crawling speed compared to walking, and the effect of occupant characteristics; gender and body composition (BMI), on crawling in evacuation. The study then examined the impact of route design on evacuation times for crawling movements by comparing evacuation time for a straight route to an indirect route design, and the influence of gender and body composition on evacuation time for occupants crawling such as an indirect route. After that, the current study looked into the relationship between crowd density and occupant crawling movement, by examining the impact of occupant configuration (number of occupants) and exit access width on crowd walking and crawling speeds on a flat surface. The last part of the research focused on the application of evolutionary computation techniques in building designs for walking and crawling egress, which has been evaluated by evolving the location and number of exits required to minimize evacuation time. The results of the research can be summarized as follows.

1. Occupant movement data plays a key role in the usefulness of evacuation models. The development of crawling data and its representation in evacuation models

enhance the accuracy of evacuation models, and better evaluate the safety of evacuees.

2. There is a significant difference between normal walking and normal crawling speeds. Further, gender and body composition significantly impact individual crawling speed as they are unique characteristics to the individual.
3. The findings reveal a difference between evacuation times when crawling in different routes. Both gender and body composition have a significant impact on individual evacuation time when crawling an indirect route. The representation of different route designs in evacuation models can provide architects with a better understanding of occupant individual and global views of buildings, which might further enhances the robustness of their designs.
4. Exit access width is significant to crowd crawling speed, whereas occupant configuration plays less of a factor. The study demonstrates that there is a significant difference in crawling speeds at different exit access widths due to crowd density.
5. The relationship between crowd crawling speed and density is best described by a quadratic regression model. In light of the significant absence of crawling data in the literature, such a relationship contributes to the improvement of the accuracy and functionality of occupant movement in existing and future models.
6. Evolutionary computation techniques can be used to find optimal building designs for walking and crawling egress. The designs are evaluated by evolving the best exit configuration(s) to minimize total evacuation time. However, the reliability of

these techniques depends on the accuracy of the evacuation models utilized. The techniques have the potential to be implemented in more complex designs.

3. Limitations of Study

It is as important to discuss the limitation of a research study, as it is to discuss the findings. The limitations of the study can be categorized as follows.

1. Participant representation: The experimental part of the study was based on a limited sample. The recruited subjects were in the 19-29 age stratum and healthy (both physically and cognitively). No consideration was given to other age groups or mobility capabilities.
2. Experimental settings: The experiments were conducted in a controlled environment. As in real evacuation scenarios, confounding variables may have an impact on the results. For instance, the crawling activity was performed on a smooth, dry, and flat surface. Testing crawling on a variety of surface textures (different coefficients of friction) and the presence of heat and smoke could result in more realistic performances. Another limitation of this study, related to experimental settings, was the examination of only two characteristics (gender and BMI). The impact of additional physiological characteristics such as heart rate, energy expenditure, and fatigue would provide evacuation models with more accurate representation of crawling.
3. The evacuation model constructed for the application of evolutionary computation incorporated a limited number of occupant performance and behavior attributes. Further, the evolutionary computation approach described in this study is not

applicable to all existing evacuation models. The integration of such approach has to be incorporated in the early design stages of evacuation models.

4. Recommendations for future research

Future research should be conducted with larger samples with a focus on certain occupant characteristics such as age and mobility capabilities. Research is also needed in crawling on different types of surfaces and under different degrees of crowd levels to quantify crowd crawling. Another need lies in studying the effect of fatigue on crawling, and its representation in the adaptive decision making process in response to evacuation. Since the current study focuses on *normal* crawling, there was no effect of fatigue on human performance. However, the effect would be more apparent in longer test areas and under actual emergency environmental conditions. There is also a need to continuously develop new predictive movement methods, or enhance existing ones in order to cope with the level of detail required to ensure occupant safety. Finally, in light of the significant absence of occupant size and shape for crawling occupants in the literature, further research is needed to investigate the impact of crawling on the interaction between occupants during evacuation.

REFERENCES

CHAPTER ONE

[1] J. Pauls, "Building Evacuation: Research Methods and Case Studies," in *Fires and Human Behavior*, D. Canter (ed.), John Wiley & Sons, Ltd, UK, 1980, pp. 251-275.

[2] S. Gwynne, E.R. Galea, M. Owen, P.J. Lawrence, and L. Filippidis, "A Review of the Methodologies Used in the Computer Simulation of Evacuation from the Built Environment," in *Building and Environment*, vol. 34, 1999, pp. 741-749.

[3] E. Galea and S. Gwynne, "Principles and Practice of Evacuation Modeling," Center for Numerical Modeling and Process Analysis, The University of Greenwich, London, Paper 04/IM/112, 2004.

[4] J.W. Schmidt, " Introduction to Simulation Modeling," in *Proceedings of the 1977 Winter Simulation Conference*, H.J. Highland (ed.), National Bureau of Standards, Gaithersburg, MD, 1977, pp. 4-6.

[5] R. Coté and G.E. Harrington, *Life Safety Code Handbook*®, National Fire Protection Association, Quincy, MA, 2006.

[6] T.J. Shields and G. Proulx, "The Science of Human Behaviour: Past Research Endeavours, Current Developments and Fashioning a Research Agenda," in *Proceedings of the Sixth International Symposium on Fire Safety Science*, M. Curtat (ed.), Poitiers, France, 2000, pp. 95-114.

[7] J.L. Bryan, "Smoke as a Determinant of Human Behavior in Fire Situation," University of Maryland, College Park, 1977.

[8] P.G. Wood, "Survey of Behavior in Fires," in *Fires and Human Behavior*, D. Canter (ed.), John Wiley & Sons, Ltd, UK, 1980, pp. 83-95.

[9] A.W. Heskestad and Ø.J. Meland, "Determination of Evacuation Times as a Function of Occupant and Building Characteristics and Performance of Evacuation Measures," in *Proceedings of the 1st International Symposium on Human Behaviour in Fire*, T.J. Shields (ed.), Belfast, 1998, pp. 673-680.

[10] V. Schneider, "Application of the Individual-based Evacuation Model ASERI in Designing Safety Concepts," in *Proceedings of the Second International*

Symposium on Human Behavior in Fire, T.J. Shields (ed.), Boston, MA, 2001, pp. 41-51.

[11] J.N. Fraser-Mitchell, "An Object Oriented Simulation (CRISP II) for Fire Risk Assessment," in *Proceedings of the 4th International Symposium of Fire Safety Science*, T. Kashiwaga (ed.), Ontario, Canada, 1994, pp. 793-804.

[12] G.N. Berlin, "A Simulation Model for Assessing Building Fire Safety," in *Fire Technology*, vol. 18, no. 1, 1982, pp. 66-76.

[13] L.S. Poon, "EvacSim: A Simulation Model of Occupants with Behavioural Attributes in Emergency Evacuation of High-rise Building Fires," in *Proceedings of the 4th International Symposium of Fire Safety Science*, T. Kashiwaga (ed.), Ontario, Canada, 1994, pp. 681-692.

[14] R. Fahy, "Exit 89-An Evacuation Model for High-rise Buildings: Model Description and Example Applications," in *Proceedings of the 4th International Symposium on Fire Safety Science*, T. Kashiwagi (ed.), Ontario, Canada, 1994, pp. 657-668.

[15] B.M. Levin, "EXITT: A Simulation Model of Occupant Decisions and Actions in Residential Fires," *Proceedings of the Second International Symposium on Fire Safety Science*, T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. Seeger, C. Grant, and P. Pagni (eds.), Tokyo, Japan, 1989, pp. 561-570.

[16] E. Galea and J.M.P. Galparsoro, "A Computer-based Simulation Model for the Prediction of Evacuation from Mass-transport Vehicle," in *Fire Safety Journal*, vol. 22, 1994, pp. 341-366.

[17] M. Owen, E.R. Galea, and P.J. Lawrence, "The EXODUS Evacuation Model Applied to Building Evacuation Scenarios," in *Journal of Fire Protection Engineering*, vol. 8, no. 2, 1996, pp. 65-86.

CHAPTER TWO

[1] J.L. Bryan, “Human Behavior in Fire: The Development and Maturity of a Scholarly Study Area,” in *Proceedings of the First International Symposium on Human Behavior in Fire*, T.J. Shields (ed.), Belfast, 1998, pp. 249-253.

[2] E. Galea and S. Gwynne, “Principles and Practice of Evacuation Modeling,” Center for Numerical Modeling and Process Analysis, The University of Greenwich, London, Paper 04/IM/112, 2004.

[3] T.J. Shields and G. Proulx, “The Science of Human Behaviour: Past Research Endeavours, Current Developments and Fashioning a Research Agenda,” in *Proceedings of the Sixth International Symposium on Fire Safety Science*, M. Curtat (ed.), Poitiers, France, 2000, pp. 95-114.

[4] S. Gwynne, E.R. Galea, M. Owen, P.J. Lawrence, and L. Filippidis, “A Review of the Methodologies Used in the Computer Simulation of Evacuation from the Built Environment,” in *Building and Environment*, vol. 34, 1999, pp. 741-749.

[5] R. Fahy, “Available Data and Inputs into Models,” in *Workshop on Building Occupant Movement during Fire Emergencies*, E.D. Kuligowski and R.D. Peacock (eds.), National Institute of Standards and Technology, NIST SP 1032, Gaithersburg, MD, 2005, pp. 62-67.

[6] B. Meacham, J. Lord, A. Moore, R. Fahy, G. Proulx, and K. Notarianni, “Investigation of Uncertainty in Egress Models and Data,” in *Proceedings of the 3rd International Symposium on Human Behaviour in Fire*, Belfast, Northern Ireland, 2004, pp. 419-428.

[7] R. Coté and G.E. Harrington, *Life Safety Code Handbook®*, National Fire Protection Association, Quincy, MA, 2006.

[8] V.M. Predtechenskii and A.I. Milinskii, *Planning for Foot Traffic in Buildings*, Amerind Publishing Co. Pvt. Ltd, New Delhi, 1978.

[9] J. Fruin, *Pedestrian Planning and Design*, Rev. Ed., Elevator World, Inc., Mobile, AL, 1987.

[10] R. Fahy and G. Proulx, “Toward Creating a Database on Delay Times to Start Evacuation and Walking Speeds for Use in Evacuation Modeling,” in *Proceedings of the 2nd International Symposium on Human Behaviour in Fire*, T.J. Shields (ed.), Boston, MA, 2001, pp. 241-252.

[11] J. Lord, B. Meacham, A. Moore, R. Fahy, and G. Proulx, “Guide for Evaluating the Predictive Capabilities of Computer Egress Models,” National Institute of Standards and Technology, NIST GCR 06-886, Gaithersburg, MD, 2005.

[12] E. Kuligowski and R.D. Peacock, “A Review of Building Evacuation Models,” National Institute of Standards and Technology, NIST Technical Note 1471, Gaithersburg, MD, 2005.

[13] R. Friedman, “An International Survey of Computer Models for Fire and Smoke,” in *Journal of Fire Protection Engineering*, vol. 4, no. 3, 1992, pp. 81-92.

[14] E.D. Kuligowski, “The Evaluation of a Performance-based Design Process for a Hotel Building: The Comparison of Two Egress Models,” Masters Thesis, Abstracts International, 42(04), p. 1322, AAT 1417603, University of Maryland, 2003.

[15] S.M. Olenick and D.J. Carpenter, “An Updated International Survey of Computer Models for Fire and Smoke,” in *Journal of Fire Protection Engineering*, vol. 13, no. 2, 2003, pp. 87-110.

[16] G. Santos and B.E. Aguirre, “Critical Review of Emergency Simulation Models,” in *Workshop on Building Occupant Movement during Fire Emergencies*, E.D. Kuligowski and R.D. Peacock (eds.), National Institute of Standards and Technology, NIST Technical Note 1471, Gaithersburg, MD, 2005.

[17] P.A. Thompson and E.W. Marchant, “Computer and Fluid Modeling of Evacuation,” in *Safety Science*, vol. 18, 1995, pp. 277-289.

[18] J.M. Watts, “Computer Models for Evacuation Analysis,” in *Fire Safety Journal*, vol. 12, 1987, pp. 237-245.

[19] A.W. Heskestad and Ø.J. Meland, “Determination of Evacuation Times as a Function of Occupant and Building Characteristics and Performance of Evacuation Measures,” in *Proceedings of the 1st International Symposium on Human Behaviour in Fire*, T.J. Shields (ed.), Belfast, 1998, pp. 673-680.

[20] V. Schneider, “Application of the Individual-based Evacuation Model ASERI in Designing Safety Concepts,” in *Proceedings of the Second International Symposium on Human Behavior in Fire*, T.J. Shields (ed.), Boston, MA, 2001, pp. 41-51.

[21] C. Burstedde, K. Klauck, A. Schadschneider, and J. Zittartz, “Simulation of Pedestrian Dynamics Using a Two-dimensional Cellular Automaton,” in *Physica A*, vol. 295, no. 3-4, 2001, pp. 507-525.

[22] J.N. Fraser-Mitchell, “An Object Oriented Simulation (CRISP II) for Fire Risk Assessment,” in *Proceedings of the 4th International Symposium of Fire Safety Science*, T. Kashiwaga (ed.), Ontario, Canada, 1994, pp. 793-804.

[23] Z. Daoliang, Y. Lizhong, and L. Jian, “Exit Dynamics of Occupant Evacuation in an Emergency,” in *Physica A*, vol. 363, 2006, pp. 501-511.

[24] E. Kendik, “Methods of Design for Means of Egress: Towards a Quantitative Comparison of National Code Requirements,” in *Proceedings of the First International Symposium on Fire Safety Science*, C. Grant and P. Pagni (eds.), National Institute of Standard and Technology, Gaithersburg, MD, 1985, pp. 497-511.

[25] N. Ketchell, S. Cole, D.M. Webber, C.A. Marriott, P.J. Stephens, I.R. Brearley, J. Fraser, J. Dohney, and J. Smart, “The EGRESS Code of Human Movement and Behaviour in Emergency Evacuation,” in *Proceedings of the International Conference on Engineering for Crowd Safety*, in R.A. Smith and J.F. Dickie (eds.), UK, 1993, pp. 361-370.

[26] AEA Technology Safety and Risk Management, A technical summary of the AEA EGRESS code, AEAT/NOIL/27812001/0029 (R) Issue 1, UK, 2001.

[27] Combustion Science and Engineering, Egress models: EgressPro 2002, Retrieved: 27/7/06, available online http://www.firemodelsurvey.com/

[28] G.N. Berlin, “A Simulation Model for Assessing Building Fire Safety,” in *Fire Technology*, vol. 18, no. 1, 1982, pp. 66-76.

[29] D.M. Alvord, “The Escape and Rescue Model: A Simulation Model for the Emergency Evacuation of Board and Care Homes,” National Bureau of Standard, NBS-GCR-83-453, Washington, DC, 1983.

[30] T. Shen, “ESM: A Building Evacuation Simulation Model,” in *Building and Environment*, vol. 40, 2005, pp. 671-680.

[31] A. Turner and A. Penn, “Encoding Natural Movement as an Agent-based System: An Investigation into Human Pedestrian Behavior in the Built Environment,” in *Environment and Planning B: Planning and Design*, vol. 29, 2002, pp. 473-790.

[32] L.S. Poon, “EvacSim: A Simulation Model of Occupants with Behavioural Attributes in Emergency Evacuation of High-rise Building Fires,” in *Proceedings of the 4th International Symposium of Fire Safety Science*, T. Kashiwaga (ed.), Ontario, Canada, 1994, pp. 681-692.

[33] R. Fahy, “Exit 89-An Evacuation Model for High-rise Buildings: Model Description and Example Applications,” in *Proceedings of the 4th International Symposium on Fire Safety Science*, T. Kashiwagi (ed.), Ontario, Canada, 1994, pp. 657-668.

[34] B.M. Levin, “EXITT: A Simulation Model of Occupant Decisions and Actions in Residential Fires,” *Proceedings of the Second International Symposium on Fire Safety Science*, T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. Seeger, C. Grant, and P. Pagni (eds.), Tokyo, Japan, 1989, pp. 561-570.

[35] E. Galea and J.M.P. Galparsoro, “A Computer-based Simulation Model for the Prediction of Evacuation from Mass-transport Vehicle,” in *Fire Safety Journal*, vol. 22, 1994, pp. 341-366.

[36] M. Owen, E.R. Galea, and P.J. Lawrence, “The EXODUS Evacuation Model Applied to Building Evacuation Scenarios,” in *Journal of Fire Protection Engineering*, vol. 8, no. 2, 1996, pp. 65-86.

[37] W.E. Feinberg and N.R. Johnson, “Firescape: A Computer Simulation Model of Reaction to a Fire Alarm,” in *Journal of Mathematical Sociology*, vol. 20, no. 2-3, 1995, pp. 247-269.

[38] S. Deal, “Technical Reference Guide for FPETool Version 3.2,” National Institute of Standards and Technology, NISTIR 5486-1, Gaithersburg, MD, 1995.

[39] M. Bensilum and D. Purser, “GridFlow: An Object-oriented Building Evacuation Model Combining Pre-movement and Movement Behaviours for Performance-based Design,” in *7th International Symposium on Fire Safety Science*, D. Evans (ed.), Worcester Polytechnic Institute, MA , 2002, pp. 941-952.

[40] N.R. Johnson and W.E. Feinberg, “The Impact of Exit Instructions and Number of Exits in Fire Emergencies: A Computer Simulation Investigation,” in *Journal of Environmental Psychology*, vol. 17, 1997, pp. 123-133.

[41] A. Kirchner, H. Klüpfel, K. Nishinari, A. Schadschneider, and M. Schreckenberg, “Simulation of Competitive Egress Behavior: Comparison with Aircraft Evacuation Data,” in *Physica A*, vol. 324, 2003, pp. 689-697.

[42] Y. Lizhong, F. Weifeng, and F. Weicheng, “Modeling Occupant Evacuation Using Cellular Automota: Effect of Human Behavior and Building Characteristics on Evacuation,” in *Journal of Fire Sciences*, vol. 21, no. 3, 2003, pp. 227-239.

[43] S. Okazaki and S. Matsushita, “A Study of Simulation Model for Pedestrian Movement with Evacuation and Queuing,” in *Proceedings of the International*

Conference on Engineering for Crowd Safety, R.A. Smith and J.F. Dickie (eds.), UK, 1993, pp. 271-280.

[44] X. Pan, C. Han, K.H. Law, and J. Latombe, “A Computational Framework to Simulate Human and Social Behaviors for Egress Analysis,” in *Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering*, Montréal, Canada, 2006, pp. 1206-1215.

[45] J. Cappuccio, “Pathfinder: A Computer-based, Timed Egress Simulation,” in *Fire Protection Engineering*, vol. 8, 2000, pp. 11-12.

[46] S.M. Lo, Z. Fang, P. Lin, and G.S. Zhi, “An Evacuation Model: the SGEM Package,” in *Fire Safety Journal*, vol. 39, 2004, pp. 169-190.

[47] P.A. Thompson and E.W. Marchant, “A Computer Model for the Evacuation of Large Building Populations,” in *Fire Safety Journal*, vol. 24, 1995, pp. 131-148.

[48] D. Helbing, I. Farkas, and T. Vicsek, ”Simulating Dynamical Features of Escape Panic,” in *Nature*, vol. 407, 2000, pp. 487-490.

[49] W. Song, X. Xu, B. Wang, and S. Ni, “Simulation of Evacuation Processes Using a Multi-grid Model for Pedestrian Dynamics,” in *Physica A*, vol. 363, 2006, pp. 492-500.

[50] Matt McDonald Group, Ltd., STEPS Software, Retrieved: 28/7/06, Available online http://www.mottmac.com/skillsandservices/software/stepssoftware

[51] K. Takahashi, T. Tanaka, and S. Kose, “An Evacuation Model for Use in Fire Safety Design of Buildings,” in *Proceedings of the 2nd International Symposium on Fire Safety Science*, T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. Seeger, C. Grant, and P. Pagni (eds.), Tokyo, Japan, 1989, pp. 551-560.

[52] S.S. Harrington, “TIMTEX: A Hydraulic Flow Model for Emergency Egress,” Unpublished master’s thesis, University of Maryland at College Park, 1996.

[53] G.K. Still, “Crowd Dynamics,” PhD Dissertation, University of Warwick, Last updated: 7/2/07, Available online http://www.crowddynamics.com, Accessed January 2005.

[54] Crowd Dynamics, Myriad, Last updated: 24/8/06, available online http:/crowddynamics.com, Accessed July 2007.

[55] V.O. Shestopal and S.J. Grubits, “Evacuation Model for Merging Traffic Flows in Multi-room and Multi-storey Buildings,” in *Proceedings of the Fourth*

International Symposium on Fire Safety Science, T. Kashiwagi (ed.), Ontario, Canada, 1994, pp. 625-632.

[56] K. Ando, H. Ota, and T. Oki, “Forecasting the Flow of People,” in *Railway Research Review*, vol. 45, 1988, pp. 8-14.

[57] K.E. Boyce, T.J. Shields, and G.W.H. Silcock, “Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and on an Incline,” in *Fire Technology*, vol. 35, no. 1, 1999, pp. 51-67.

[58] J. Eubanks and P. Hill, *Pedestrian Accident Reconstruction and Litigation*, 2nd Ed., Lawyers & Judges Publishing Co., Tucson, 1998.

[59] T. Jin, “Visibility through Fire Smoke,” in *Journal of Fire and Flammability*, vol. 9, 1978, pp. 135-155.

[60] T. Jin and T. Yamada, “Experimental Study of Human Behavior in Smoke Filled Corridors,” in *Proceedings of the Second International Symposium on Fire Safety Science*, T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. Seeger, P. Pagni, and C. Grant (eds.), Tokyo, Japan, 1989, pp. 511-520.

[61] H.E. Nelson and H.A. MacLennan, “Emergency Movement. Section 3 / Chapter 14,” in *The SFPE Handbook of Fire Protection Engineering*, 2nd Ed., J. Dilenno, C. Beyer, R. Custer, W. Walton, J. Watts, D. Drysdale, and J. Hall (eds.), NFPA, Quincy, MA, 1995.

[62] J. Pauls, “Building Evacuation: Research Methods and Case Studies,” in *Fires and Human Behavior*, D. Canter (ed.), John Wiley & Sons, Ltd, UK, 1980, pp. 251-275.

[63] J. Pauls, “Calculating Evacuation Time for Tall Buildings,’ in *Fire Safety Journal*, vol. 12, 1987, pp. 213-236.

[64] J. Pauls, “Movement of People. Section 3 / Chapter 13,” in *The SPFE, Handbok of Fire Protection Engineering*, 2nd Ed., J. Dilenno, C. Beyer, R. Custer, W. Walton, J. Watts, D. Drysdale, and J. Hall (eds.), NFPA, Quincy, MA, 1995.

[65] D.H. Sutherland, K.R. Kaufman, and J.R. Moitoza, “Kinematics of Normal Human Walking,” in *Human Walking*, J. Rose and J.G. Gamble (eds.), Williams and Wilkinsore, Baltimore, MD, 1994, pp. 23-44.

[66] P. Thompson, H. Lindstrom, P. Ohlsson, and S. Thompson, “Simulex: Analysis and Changes for IMO Compliance,” in *Proceedings of 2nd International*

Conference: Pedestrian and Evacuation Dynamics, E. Galea (ed.), The University of Greenwich, London, 2003, pp. 173-184.

[67] U. Weidmann, “Transporttechnik der FussgNanger,” in *Schriftenreihe des IVT*, vol. 80, 1992, ETH, ZNurich.

[68] E. Kendik, “Determination of the Evacuation Time Pertinent to the Projected Area Factor in the Event of Total Evacuation of High-rise Office Buildings via Staicases,” in *Fire Safety Journal*, vol. 5, 1983, pp. 223-232.

[69] U.S. Fire Administration. *F*ire Tests in Single-family Dwellings in Los Angeles, CA, 1980.

[70] T.J. Shields, K.E. Dunlop, G.W.H. Silcock, *Escape of disabled people from fire: A measurement and classification of capability for assessing escape risk*, PRE Press, UK, 1996.

CHAPTER THREE

[1] J. Pauls, "Building Evacuation: Research Methods and Case Studies," in *Fires and Human Behavior*, D. Canter (ed.), John Wiley & Sons, Ltd, UK, 1980, pp. 251-275.

[2] R. Coté and G.E. Harrington, *Life Safety Code Handbook*®, National Fire Protection Association, Quincy, MA, 2006.

[3] R. Fahy, "Available Data and Inputs into Models," in *Workshop on Building Occupant Movement during Fire Emergencies*, E.D. Kuligowski and R.D. Peacock (eds.), National Institute of Standards and Technology, NIST SP 1032, Gaithersburg, MD, 2005, pp. 62-67.

[4] V.M. Predtechenskii and A.I. Milinskii, *Planning for Foot Traffic in Buildings*, Amerind Publishing Co. Pvt. Ltd, New Delhi, 1978.

[5] J. Fruin, *Pedestrian Planning and Design*, Rev. Ed., Elevator World, Inc., Mobile, AL, 1987.

[6] K. Ando, H. Ota, and T. Oki, "Forecasting the Flow of People," in *Railway Research Review*, vol. 45, 1988, pp. 8-14.

[7] K.E. Boyce, T.J. Shields, and G.W.H. Silcock, "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and on an Incline," in *Fire Technology*, vol. 35, no. 1, 1999, pp. 51-67.

[8] J. Eubanks and P. Hill, *Pedestrian Accident Reconstruction and Litigation*, 2nd Ed., Lawyers & Judges Publishing Co., Tucson, 1998.

[9] T. Jin, "Visibility through Fire Smoke," in *Journal of Fire and Flammability*, vol. 9, 1978, pp. 135-155.

[10] T. Jin and T. Yamada, "Experimental Study of Human Behavior in Smoke Filled Corridors," in *Proceedings of the Second International Symposium on Fire Safety Science*, T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. Seeger, P. Pagni, and C. Grant (eds.), Tokyo, Japan, 1989, pp. 511-520.

[11] H.E. Nelson and H.A. MacLennan, "Emergency Movement. Section 3 / Chapter 14," in *The SFPE Handbook of Fire Protection Engineering*, 2nd Ed., J. Dilenno, C. Beyer, R. Custer, W. Walton, J. Watts, D. Drysdale, and J. Hall (eds.), NFPA, Quincy, MA, 1995.

[12] J. Pauls, “Building Evacuation: Research Methods and Case Studies,” in *Fires and Human Behavior*, D. Canter (ed.), John Wiley & Sons, Ltd, UK, 1980, pp. 251-275.

[13] J. Pauls, “Calculating Evacuation Time for Tall Buildings,’ in *Fire Safety Journal*, vol. 12, 1987, pp. 213-236.

[14] J. Pauls, “Movement of People. Section 3 / Chapter 13,” in *The SPFE, Handbok of Fire Protection Engineering*, 2nd Ed., J. Dilenno, C. Beyer, R. Custer, W. Walton, J. Watts, D. Drysdale, and J. Hall (eds.), NFPA, Quincy, MA, 1995.

[15] D.H. Sutherland, K.R. Kaufman, and J.R. Moitoza, “Kinematics of Normal Human Walking,” in *Human Walking*, J. Rose and J.G. Gamble (eds.), Williams and Wilkinsore, Baltimore, MD, 1994, pp. 23-44.

[16] P. Thompson, H. Lindstrom, P. Ohlsson, and S. Thompson, “Simulex: Analysis and Changes for IMO Compliance,” in *Proceedings of 2nd International Conference: Pedestrian and Evacuation Dynamics*, E. Galea (ed.), The University of Greenwich, London, 2003, pp. 173-184.

[17] U. Weidmann, “Transporttechnik der FussgNanger,” in *Schriftenreihe des IVT*, vol. 80, 1992, ETH, ZNurich.

[18] J.L. Bryan, “Smoke as a Determinant of Human Behavior in Fire Situation,” University of Maryland, College Park, 1977.

[19] P.G. Wood, “Survey of Behavior in Fires,” in *Fires and Human Behavior*, D. Canter (ed.), John Wiley & Sons, Ltd, UK, 1980, pp. 83-95.

[20] T. Jin, “Visibility through Fire Smoke,” in *Journal of Fire and Flammability*, vol. 9, 1978, pp. 135-155.

[21] T. Jin and T. Yamada, “Experimental Study of Human Behavior in Smoke Filled Corridors,” in *Proceedings of the Second International Symposium on Fire Safety Science*, T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. Seeger, P. Pagni, and C. Grant (eds.), Tokyo, Japan, 1989, pp. 511-520.

[22] R. Muhdi, J. Davis, and T. Blackburn, “Improving Occupant Characteristics in Performance-based Evacuation Modeling,” in *Proceedings of the HFES 50th Annual Meeting*, San Francisco, CA, 2006, pp. 1199-2003.

[23] R. Nagai, M. Fukamachi, and T. Nagatani, “Evacuation of Crawlers and Walkers from Corridor through an Exit,” in *Physica A*, vol. 367, 2006, pp.449–460.

[24] R. Nagai, M. Fukamachi, and T. Nagatani, “Experiment and Simulation for Counterflow of People Going on All Four,” in *Physica A*, vol. 358, 2005, pp. 516–528.

[25] Center for Disease Control and Prevention. (2006). Retrieved April 6, 2007, from CDC Web site http://www.cdc.gov/nccdphp/dnpa/bmi/adult_BMI/about_adult_BMI.htm

[26] K.M. Robinette, S. Blackwell, H. Daanen, M. Boehmer, S. Fleming, T. Brill, D. Hoeferlin, and D. Burnsides, “Civilian American and European Surface Anthropometry Resource (CAESAR) Final Report, Vol. I: Summary,” Wright-Patterson Air Force Base: Air Force Research Library, AFRL-HE-WP-TR-2002-0169, OH, 2002.

[27] K.M. Robinette, S. Blackwell, H. Daanen, M. Boehmer, S. Fleming, T. Brill, D. Hoeferlin, and D. Burnsides, “Civilian American and European Surface Anthropometry Resource (CAESAR) Final Report, Vol. II: Description,” Wright-Patterson Air Force Base: Air Force Research Library, AFRL-HE-WP-TR-2002-0173, OH, 2002.

CHAPTER FOUR

[1] R. Coté and G.E. Harrington, *Life Safety Code Handbook*®, National Fire Protection Association, Quincy, MA, 2006.

[2] E. Kuligowski and R.D. Peacock, “A Review of Building Evacuation Models,” National Institute of Standards and Technology, NIST Technical Note 1471, Gaithersburg, MD, 2005.

[3] V.O. Shestopal and S.J. Grubits, “Evacuation Model for Merging Traffic Flows in Multi-room and Multi-storey Buildings,” in *Proceedings of the Fourth International Symposium on Fire Safety Science*, T. Kashiwagi (ed.), Ontario, Canada, 1994, pp. 625-632.

[4] E. Kendik, “Methods of Design for Means of Egress: Towards a Quantitative Comparison of National Code Requirements,” in *Proceedings of the First International Symposium on Fire Safety Science*, C. Grant and P. Pagni (eds.), National Institute of Standard and Technology, Gaithersburg, MD, 1985, pp. 497-511.

[5] A.W. Heskestad and Ø.J. Meland, “Determination of Evacuation Times as a Function of Occupant and Building Characteristics and Performance of Evacuation Measures,” in *Proceedings of the 1st International Symposium on Human Behaviour in Fire*, T.J. Shields (ed.), Belfast, 1998, pp. 673-680.

[6] Combustion Science and Engineering, Egress models: EgressPro 2002, Retrieved: 27/7/06, available online http://www.firemodelsurvey.com/

[7] Z. Daoliang, Y. Lizhong, and L. Jian, “Exit Dynamics of Occupant Evacuation in an Emergency,” in *Physica A*, vol. 363, 2006, pp. 501-511.

[8] T. Kisko and R.L. Francis, “EVACNET+: A Computer Program to Determine Optimal Building Evacuation Plans,” in *Fire Safety Journal*, vol. 9, 1985, pp. 211-220.

[9] L.T. Buckmann and J. Leather, “Modeling Station Congestion the PEDROUTE Way,’ in *Traffic Engineering and Control*, vol. 35, 1994, pp. 373-377

[10] K. Takahashi, T. Tanaka, and S. Kose, “An Evacuation Model for Use in Fire Safety Design of Buildings,” in *Proceedings of the 2nd International Symposium on Fire Safety Science*, T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. Seeger, C. Grant, and P. Pagni (eds.), Tokyo, Japan, 1989, pp. 551-560.

[11] Matt McDonald Group, Ltd., STEPS Software, Retrieved: 28/7/06, Available online http://www.mottmac.com/skillsandservices/software/stepssoftware

[12] J.N. Fraser-Mitchell, "An Object Oriented Simulation (CRISP II) for Fire Risk Assessment," in *Proceedings of the 4th International Symposium of Fire Safety Science*, T. Kashiwaga (ed.), Ontario, Canada, 1994, pp. 793-804.

[13] G.K. Still, "Crowd Dynamics," PhD Dissertation, University of Warwick, Last updated: 7/2/07, Available online http://www.crowddynamics.com, Accessed January 2005.

[14] Crowd Dynamics, Myriad, Last updated: 24/8/06, available online http:/crowddynamics.com, Accessed July 2007.

[15] E. Galea and J.M.P. Galparsoro, "A Computer-based Simulation Model for the Prediction of Evacuation from Mass-transport Vehicle," in *Fire Safety Journal*, vol. 22, 1994, pp. 341-366.

[16] M. Owen, E.R. Galea, and P.J. Lawrence, "The EXODUS Evacuation Model Applied to Building Evacuation Scenarios," in *Journal of Fire Protection Engineering*, vol. 8, no. 2, 1996, pp. 65-86.

[17] H. Klupfel and T. Meyer-Konig, "Characteristics of the PedGo Software for Crowd Movement and Egress Simulation," in *Proceedings of the 2nd International Conference in Pedestrian and Evacuation Dynamics (PED)*, E. R. Galea (ed.), University of Greenwich, UK, 2003, pp. 331-340.

[18] P.A. Thompson and E.W. Marchant, "A Computer Model for the Evacuation of Large Building Populations," in *Fire Safety Journal*, vol. 24, 1995, pp. 131-148.

[19] M. Bensilum and D. Purser, "GridFlow: An Object-oriented Building Evacuation Model Combining Pre-movement and Movement Behaviours for Performance-based Design," in *7th International Symposium on Fire Safety Science*, D. Evans (ed.), Worcester Polytechnic Institute, MA , 2002, pp. 941-952.

[20] V. Schneider, "Application of the Individual-based Evacuation Model ASERI in Designing Safety Concepts," in *Proceedings of the Second International Symposium on Human Behavior in Fire*, T.J. Shields (ed.), Boston, MA, 2001, pp. 41-51.

[21] R. Fahy, "Exit 89-An Evacuation Model for High-rise Buildings: Model Description and Example Applications," in *Proceedings of the 4th International Symposium on Fire Safety Science*, T. Kashiwagi (ed.), Ontario, Canada, 1994, pp. 657-668.

[22] B.M. Levin, "EXITT: A Simulation Model of Occupant Decisions and Actions in Residential Fires," *Proceedings of the Second International Symposium on Fire*

Safety Science, T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. Seeger, C. Grant, and P. Pagni (eds.), Tokyo, Japan, 1989, pp. 561-570.

[23] J. Cappuccio, "Pathfinder: A Computer-based, Timed Egress Simulation," in *Fire Protection Engineering*, vol. 8, 2000, pp. 11-12.

[24] N. Ketchell, S. Cole, D.M. Webber, C.A. Marriott, P.J. Stephens, I.R. Brearley, J. Fraser, J. Dohney, and J. Smart, "The EGRESS Code of Human Movement and Behaviour in Emergency Evacuation," in *Proceedings of the International Conference on Engineering for Crowd Safety*, in R.A. Smith and J.F. Dickie (eds.), UK, 1993, pp. 361-370.

[25] AEA Technology Safety and Risk Management, A technical summary of the AEA EGRESS code, AEAT/NOIL/27812001/0029 (R) Issue 1, UK, 2001.

[26] S.M. Lo, Z. Fang, P. Lin, and G.S. Zhi, "An Evacuation Model: the SGEM Package," in *Fire Safety Journal*, vol. 39, 2004, pp. 169-190.

[27] K.M. Robinette, S. Blackwell, H. Daanen, M. Boehmer, S. Fleming, T. Brill, D. Hoeferlin, and D. Burnsides, "Civilian American and European Surface Anthropometry Resource (CAESAR) Final Report, Vol. I: Summary," Wright-Patterson Air Force Base: Air Force Research Library, AFRL-HE-WP-TR-2002-0169, OH, 2002.

[28] K.M. Robinette, S. Blackwell, H. Daanen, M. Boehmer, S. Fleming, T. Brill, D. Hoeferlin, and D. Burnsides, "Civilian American and European Surface Anthropometry Resource (CAESAR) Final Report, Vol. II: Description," Wright-Patterson Air Force Base: Air Force Research Library, AFRL-HE-WP-TR-2002-0173, OH, 2002.

CHAPTER FIVE

[1] E. Kuligowski and R.D. Peacock, “A Review of Building Evacuation Models,” National Institute of Standards and Technology, NIST Technical Note 1471, Gaithersburg, MD, 2005.

[2] V.M. Predtechenskii and A.I. Milinskii, *Planning for Foot Traffic in Buildings*, Amerind Publishing Co. Pvt. Ltd, New Delhi, 1978.

[3] J. Fruin, *Pedestrian Planning and Design*, Rev. Ed., Elevator World, Inc., Mobile, AL, 1987.

[4] B.D. Hankin and R.A. Wright, “Passenger Flow in Subways,” in *Operational Research Quarterly*, vol. 9, 1958, pp. 81-88.

[5] L.F. Henderson, “The Statistics of Crowd Fluids,” in *Nature*, vol. 229, pp. 381-383.

[6] S.J. Older, “Movement of Pedestrians on Footways in Shopping Streets,” in *Traffic Engineering and Control*, August, 1968, pp 160-163.

[7] A. Polus, L. Joseph, and A. Ushpiz, “Pedestrian Flow and Level of Service,” in *Journal of Transportation Engineering*, vol. 109, 1983, pp. 46-56.

[8] K. Ando, H. Ota, and T. Oki, “Forecasting the Flow of People,” in *Railway Research Review*, vol. 45, 1988, pp. 8-14.

[9] H.E. Nelson and H.A. MacLennan, “Emergency Movement. Section 3 / Chapter 14,” in *The SFPE Handbook of Fire Protection Engineering*, 2nd Ed., J. Dilenno, C. Beyer, R. Custer, W. Walton, J. Watts, D. Drysdale, and J. Hall (eds.), NFPA, Quincy, MA, 1995.

[10] J. Pauls, “Movement of People. Section 3 / Chapter 13,” in *The SPFE, Handbok of Fire Protection Engineering*, 2nd Ed., J. Dilenno, C. Beyer, R. Custer, W. Walton, J. Watts, D. Drysdale, and J. Hall (eds.), NFPA, Quincy, MA, 1995.

[11] E. Galea and J.M.P. Galparsoro, “A Computer-based Simulation Model for the Prediction of Evacuation from Mass-transport Vehicle,” in *Fire Safety Journal*, vol. 22, 1994, pp. 341-366.

[12] M. Owen, E.R. Galea, and P.J. Lawrence, “The EXODUS Evacuation Model Applied to Building Evacuation Scenarios,” in *Journal of Fire Protection Engineering*, vol. 8, no. 2, 1996, pp. 65-86.

[13] J.N. Fraser-Mitchell, "An Object Oriented Simulation (CRISP II) for Fire Risk Assessment," in *Proceedings of the 4th International Symposium of Fire Safety Science*, T. Kashiwaga (ed.), Ontario, Canada, 1994, pp. 793-804.

[14] E. Kendik, "Methods of Design for Means of Egress: Towards a Quantitative Comparison of National Code Requirements," in *Proceedings of the First International Symposium on Fire Safety Science*, C. Grant and P. Pagni (eds.), National Institute of Standard and Technology, Gaithersburg, MD, 1985, pp. 497-511.

[15] N. Ketchell, S. Cole, D.M. Webber, C.A. Marriott, P.J. Stephens, I.R. Brearley, J. Fraser, J. Dohney, and J. Smart, "The EGRESS Code of Human Movement and Behaviour in Emergency Evacuation," in *Proceedings of the International Conference on Engineering for Crowd Safety*, in R.A. Smith and J.F. Dickie (eds.), UK, 1993, pp. 361-370.

[16] T. Shen, "ESM: A Building Evacuation Simulation Model," in *Building and Environment*, vol. 40, 2005, pp. 671-680.

[17] L.S. Poon, "EvacSim: A Simulation Model of Occupants with Behavioural Attributes in Emergency Evacuation of High-rise Building Fires," in *Proceedings of the 4th International Symposium of Fire Safety Science*, T. Kashiwaga (ed.), Ontario, Canada, 1994, pp. 681-692.

[18] R. Fahy, "Exit 89-An Evacuation Model for High-rise Buildings: Model Description and Example Applications," in *Proceedings of the 4th International Symposium on Fire Safety Science*, T. Kashiwagi (ed.), Ontario, Canada, 1994, pp. 657-668.

[19] J. Cappuccio, "Pathfinder: A Computer-based, Timed Egress Simulation," in *Fire Protection Engineering*, vol. 8, 2000, pp. 11-12.

[20] P.A. Thompson and E.W. Marchant, "A Computer Model for the Evacuation of Large Building Populations," in *Fire Safety Journal*, vol. 24, 1995, pp. 131-148.

[21] J.L. Bryan, "Smoke as a Determinant of Human Behavior in Fire Situation," University of Maryland, College Park, 1977.

[22] P.G. Wood, "Survey of Behavior in Fires," in *Fires and Human Behavior*, D. Canter (ed.), John Wiley & Sons, Ltd, UK, 1980, pp. 83-95.

[23] T. Jin, "Visibility through Fire Smoke," in *Journal of Fire and Flammability*, vol. 9, 1978, pp. 135-155.

[24] T. Jin and T. Yamada, “Experimental Study of Human Behavior in Smoke Filled Corridors,” in *Proceedings of the Second International Symposium on Fire Safety Science*, T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. Seeger, P. Pagni, and C. Grant (eds.), Tokyo, Japan, 1989, pp. 511-520.

[25] R. Muhdi, J. Davis, and T. Blackburn, “Improving Occupant Characteristics in Performance-based Evacuation Modeling,” in *Proceedings of the HFES 50th Annual Meeting*, San Francisco, CA, 2006, pp. 1199-2003.

[26] R. Nagai, M. Fukamachi, and T. Nagatani, “Evacuation of Crawlers and Walkers from Corridor through an Exit,” in *Physica A*, vol. 367, 2006, pp.449–460.

[27] R. Nagai, M. Fukamachi, and T. Nagatani, “Experiment and Simulation for Counterflow of People Going on All Four,” in *Physica A*, vol. 358, 2005, pp. 516–528.

[28] R. Muhdi, S. Gwynne, and J. Davis, “The Incorporation and Validation of Empirical Data into The buildingEXODUS Model,” To appear in *Journal of Safety Science*, 2008.

[29] K.M. Robinette, S. Blackwell, H. Daanen, M. Boehmer, S. Fleming, T. Brill, D. Hoeferlin, and D. Burnsides, “Civilian American and European Surface Anthropometry Resource (CAESAR) Final Report, Vol. I: Summary,” Wright-Patterson Air Force Base: Air Force Research Library, AFRL-HE-WP-TR-2002-0169, OH, 2002.

[30] K.M. Robinette, S. Blackwell, H. Daanen, M. Boehmer, S. Fleming, T. Brill, D. Hoeferlin, and D. Burnsides, “Civilian American and European Surface Anthropometry Resource (CAESAR) Final Report, Vol. II: Description,” Wright-Patterson Air Force Base: Air Force Research Library, AFRL-HE-WP-TR-2002-0173, OH, 2002.

[31] R. Coté and G.E. Harrington, *Life Safety Code Handbook*®, National Fire Protection Association, Quincy, MA, 2006.

CHAPTER SIX

[1] R. Muhdi, S. Gwynne, and J. Davis, "The Incorporation and Validation of Empirical Data into the buildingEXODUS Model," To appear in *Journal of Safety Science*, 2008.

[2] S. Gwynne, R. Muhdi, and J. Davis, "Development and Validation of Crawling Model in Existing Computational Egress Tool," in *Proceedings of the 11th International Conference on Fire Science and Technology* (Interflam), London, UK, 2007.

[3] J.L. Bryan, "Smoke as a Determinant of Human Behavior in Fire Situation," University of Maryland, College Park, 1977.

[4] P.G. Wood, "Survey of Behavior in Fires," in *Fires and Human Behavior*, D. Canter (ed.), John Wiley & Sons, Ltd, UK, 1980, pp. 83-95.

[5] T. Jin, "Visibility through Fire Smoke," in *Journal of Fire and Flammability*, vol. 9, 1978, pp. 135-155.

[6] T. Jin and T. Yamada, "Experimental Study of Human Behavior in Smoke Filled Corridors," in *Proceedings of the Second International Symposium on Fire Safety Science*, T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. Seeger, P. Pagni, and C. Grant (eds.), Tokyo, Japan, 1989, pp. 511-520.

[7] R. Nagai, M. Fukamachi, and T. Nagatani, "Experiment and Simulation for Counterflow of People Going on All Four," in *Physica A*, vol. 358, 2005, pp. 516–528.

[8] R. Nagai, M. Fukamachi, and T. Nagatani, "Evacuation of Crawlers and Walkers from Corridor through an Exit," in *Physica A*, vol. 367, 2006, pp.449–460.

[9] R. Muhdi, J. Davis, and T. Blackburn, "Improving Occupant Characteristics in Performance-based Evacuation Modeling," in *Proceedings of the HFES 50th Annual Meeting*, San Francisco, CA, 2006, pp. 1199-2003.

[10] R. Coté and G.E. Harrington, *Life Safety Code Handbook*®, National Fire Protection Association, Quincy, MA, 2006.

[11] K.M. Robinette, S. Blackwell, H. Daanen, M. Boehmer, S. Fleming, T. Brill, D. Hoeferlin, and D. Burnsides, "Civilian American and European Surface Anthropometry Resource (CAESAR) Final Report, Vol. I: Summary," Wright-Patterson Air Force Base: Air Force Research Library, AFRL-HE-WP-TR-2002-0169, OH, 2002.

[12] K.M. Robinette, S. Blackwell, H. Daanen, M. Boehmer, S. Fleming, T. Brill, D. Hoeferlin, and D. Burnsides, “Civilian American and European Surface Anthropometry Resource (CAESAR) Final Report, Vol. II: Description,” Wright-Patterson Air Force Base: Air Force Research Library, AFRL-HE-WP-TR-2002-0173, OH, 2002.

[13] V.M. Predtechenskii and A.I. Milinskii, *Planning for Foot Traffic in Buildings*, Amerind Publishing Co. Pvt. Ltd, New Delhi, 1978.

[14] J. Fruin, *Pedestrian Planning and Design*, Rev. Ed., Elevator World, Inc., Mobile, AL, 1987.

[15] E.D. Kuligowski, “The Evaluation of A Performance-based Design Process for A Hotel Building: The Comparison of Two Egress Models, in *Masters Abstracts International*, 42(04), AAT 1417603, p. 1322, 2003.

[16] S.M. Olenick and D.J. Carpenter, “An Updated International Survey of Computer Models for Fire and Smoke,” in *Journal of Fire Protection Engineering*, vol. 13, no. 2, 2003, pp. 87-110.

[17] T. Kisko and R.L. Francis, “EVACNET+: A Computer Program to Determine Optimal Building Evacuation Plans,” in *Fire Safety Journal*, vol. 9, 1985, pp. 211-220.

[18] D. Helbing and P. Molnár, “Social Force Model for Pedestrian Dynamics,” in *Physical Review E*, vol. 51, no. 5, 1995, pp. 4282-4286.

[19] O. Khatib, “Real-time Obstacle Avoidance for Manipulators and Mobile Robots,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, St. Louis, MO, 1985, pp. 500-505.

[20] D. Helbing, I. Farkas, and T. Vicsek, “Simulating Dynamical Features of Escape Panic,” in *Nature*, vol. 407, 2000, pp. 487-490.

[21] J.A. Kirkland and A.A. Maciejewski, “A Simulation of Attempts to Influence Crowd Dynamics,” in *Proceedings of the IEEE International Conference Systems, Man, and. Cybernetics*, Washington, DC, 2003, pp. 4328-4333.

[22] S. Abraham, C.L. Johnson, and M.F. Najjar, *Weight and height of adults 18-74 years of age, United States, 1971-1974* (Vital and Health Statistics, Series 11, No. 211). US Department of Health Education and Welfare, Hyattsville, MD, 1979.

[23] S. Pheasant and C.M. Haslegrave, *Bodyspace: Anthropometry, Ergonomics, and the Design of Work*, 3rd Ed., Taylor & Francis, Inc., London, 2006.

[24] J. Eubanks and P. Hill, *Pedestrian Accident Reconstruction and Litigation*, 2nd Ed., Lawyers & Judges Publishing Co., Tucson, 1998.

[25] D.H. Sutherland, K.R. Kaufman, and J.R. Moitoza, J. R, "Kinematics of Normal Human Walking," in *Human Walking*, J. Rose and J. G. Gamble (eds.), Williams and Wilkinsore, Baltimore, MD, 1994, pp. 23-44.

[26] J. Pauls, "Building Evacuation: Research Methods and Case Studies," in *Fires and Human Behavior*, D. Canter (ed.), John Wiley & Sons, Ltd., London, UK, pp. 251-275.

[27] K. Ando, H. Ota, and T. Oki, "Forecasting the Flow of People," in *Railway Research Review*, vol. 45, 1988, pp. 8-14.

[28] E. Galea and J.M.P. Galparsoro, "A Computer-based Simulation Model for the Prediction of Evacuation from Mass-transport Vehicle," in *Fire Safety Journal*, vol. 22, 1994, pp. 341-366.

[29] M. Owen, E.R. Galea, and P.J. Lawrence, "The EXODUS Evacuation Model Applied to Building Evacuation Scenarios," in *Journal of Fire Protection Engineering*, vol. 8, no. 2, 1996, pp. 65-86.

[30] H.P.V. Cott and R.G. Kinkade, *Human Engineering Guide to Equipment Design*, Rev. Ed., McGraw Hill, American Institute for Research, Washington, DC, 1972.

[31] T. Barter, I. Emmauel, and B. Truett, *A Statistical Evaluation of Joint Range Data*, WADC Technical Note 53-311, Wright Patterson Aire Force Base, OH, 1957.

[32] J. Banks, J.S. Carson II, B.L. Nelson, and D.M. Nicol, *Discrete-Event System Simulation*, 4th Ed., Pearson Education, Inc., Upper Saddle River, NJ, 2005

[33] E. Galea and S. Gwynne, "Principles and Practice of Evacuation Modeling," Center for Numerical Modeling and Process Analysis, The University of Greenwich, London, Paper 04/IM/112, 2004.

[34] Matt McDonald Group, Ltd., STEPS Software, Retrieved: 28/7/06, Available online http://www.mottmac.com/skillsandservices/software/stepssoftware

[35] V. Schneider, "Application of the Individual-based Evacuation Model ASERI in Designing Safety Concepts," in *Proceedings of the Second International Symposium on Human Behavior in Fire*, T.J. Shields (ed.), Boston, MA, 2001, pp. 41-51.

[36] J.N. Fraser-Mitchell, “An Object Oriented Simulation (CRISP II) for Fire Risk Assessment,” in *Proceedings of the 4th International Symposium of Fire Safety Science*, T. Kashiwaga (ed.), Ontario, Canada, 1994, pp. 793-804.

[37] E. Kendik, “Methods of Design for Means of Egress: Towards a Quantitative Comparison of National Code Requirements,” in *Proceedings of the First International Symposium on Fire Safety Science*, C. Grant and P. Pagni (eds.), National Institute of Standard and Technology, Gaithersburg, MD, 1985, pp. 497-511.

[38] N. Ketchell, S. Cole, D.M. Webber, C.A. Marriott, P.J. Stephens, I.R. Brearley, J. Fraser, J. Dohney, and J. Smart, “The EGRESS Code of Human Movement and Behaviour in Emergency Evacuation,” in *Proceedings of the International Conference on Engineering for Crowd Safety*, in R.A. Smith and J.F. Dickie (eds.), UK, 1993, pp. 361-370.

[39] R. Fahy, “Exit 89-An Evacuation Model for High-rise Buildings: Model Description and Example Applications,” in *Proceedings of the 4th International Symposium on Fire Safety Science*, T. Kashiwagi (ed.), Ontario, Canada, 1994, pp. 657-668.

[40] K. Takahashi, T. Tanaka, and S. Kose, “An Evacuation Model for Use in Fire Safety Design of Buildings,” in *Proceedings of the 2nd International Symposium on Fire Safety Science*, T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. Seeger, C. Grant, and P. Pagni (eds.), Tokyo, Japan, 1989, pp. 551-560.

[41] V.O. Shestopal and S.J. Grubits, “Evacuation Model for Merging Traffic Flows in Multi-room and Multi-storey Buildings,” in *Proceedings of the Fourth International Symposium on Fire Safety Science*, T. Kashiwagi (ed.), Ontario, Canada, 1994, pp. 625-632.

[42] E. Galea and J.M.P. Galparsoro, “A Computer-based Simulation Model for the Prediction of Evacuation from Mass-transport Vehicle,” in *Fire Safety Journal*, vol. 22, 1994, pp. 341-366.

[43] M. Bensilum and D. Purser, “GridFlow: An Object-oriented Building Evacuation Model Combining Pre-movement and Movement Behaviours for Performance-based Design,” in *7th International Symposium on Fire Safety Science*, D. Evans (ed.), Worcester Polytechnic Institute, MA , 2002, pp. 941-952.

[44] P.A. Thompson and E.W. Marchant, “A Computer Model for the Evacuation of Large Building Populations,” in *Fire Safety Journal*, vol. 24, 1995, pp. 131-148.

[45] A.W. Heskestad and Ø.J. Meland, “Determination of Evacuation Times as a Function of Occupant and Building Characteristics and Performance of

Evacuation Measures," in *Proceedings of the 1st International Symposium on Human Behaviour in Fire*, T.J. Shields (ed.), Belfast, 1998, pp. 673-680.

[46] S.M. Lo, Z. Fang, P. Lin, and G.S. Zhi, "An Evacuation Model: the SGEM Package," in *Fire Safety Journal*, vol. 39, 2004, pp. 169-190.

[47] W.M. Spears, K.A. De Jong, T. Bäck, D.B. Fogel, and H. De Garis. "An Overview of Evolutionary Computation," in *Proceedings of the European Conference on Machine Learning (ECML-93)*, P.B. Brazdil (ed.), editor, Vienna, Austria, 1993, pp. 442-459.

[48] T. Back, U. Hammel, and H.P. Schwefel, "Evolutionary Computation: Comments on the History and Current State," in *IEEE Transactions on Evolutionary Computation*, vol. 1(1), 1997, pp. 3-17.

[49] P. Larranaga and J.A. Lozano, *Estimation of Distribution Algorithms: A New Tool for Evolutionary Computation*, Kluwer Academic Publishers, 2002.

[50] J.H. Holland, *Adaptation in Natural and Artificial Systems*, University of Michigan Press, Ann Arbor, MI, 1975.

[51] J. Kennedy and R. Eberhart, "Particle Swarm Optimization," in *Proceedings of the 1995 IEEE International Conference on Neural Networks*, Perth, Australia, 1995, pp. 1942-1948.

[52] J. Kennedy, "The Particle Swarm: Social Adaptation of Knowledge," in *Proceedings of the 1997 International Conference on Evolutionary Computation*, Indianapolis, IN, 1997, pp. 303-308.

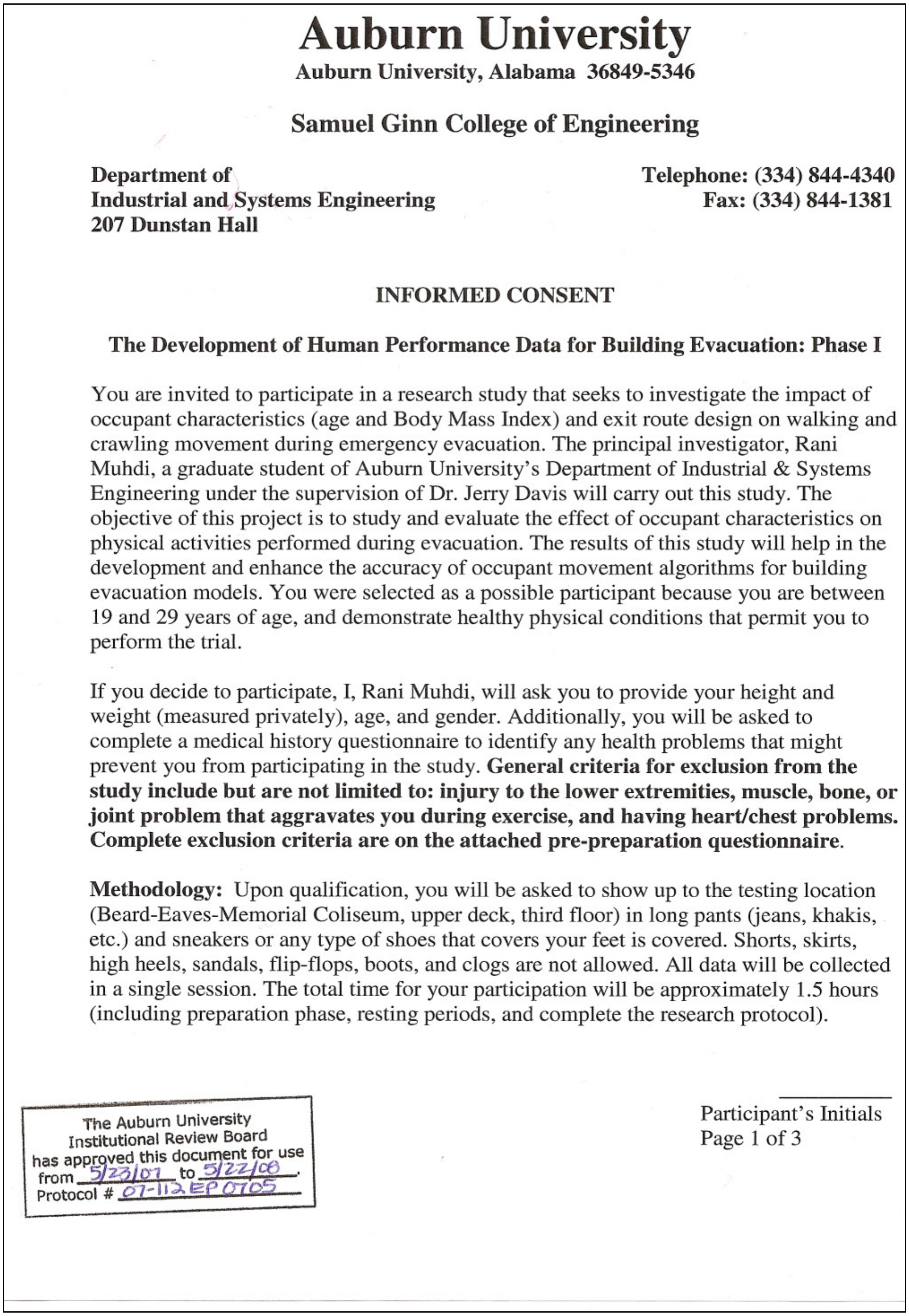
[53] A. Garrett, B. Carnahan, R. Muhdi, J. Davis, G. Dozier, M.P. SanSoucie, .P.V. Hull, and M.L. Tinker, "Evacuation Planning via Evolutionary Computation," in *Proceedings of the IEEE World Congress on Computational Intelligence*, Vancouver, BC, Canada, 2006.

[54] R. Muhdi, A. Garrett, R. Agarwal, J. Davis, G. Dozier, D. Umphress, "The Application of Evolutinary computation in evacuation planning," in *Proceedings of the 9th International IEEE Conference on Intelligent Transportation Systems*, Toronto, Canada, 2006.

APPENDICES

APPENDIX 3.1

INFORMED CONSENT



Auburn University
Auburn University, Alabama 36849-5346

Samuel Ginn College of Engineering

Department of
Industrial and Systems Engineering
207 Dunstan Hall

Telephone: (334) 844-4340
Fax: (334) 844-1381

INFORMED CONSENT

The Development of Human Performance Data for Building Evacuation: Phase I

You are invited to participate in a research study that seeks to investigate the impact of occupant characteristics (age and Body Mass Index) and exit route design on walking and crawling movement during emergency evacuation. The principal investigator, Rani Muhdi, a graduate student of Auburn University's Department of Industrial & Systems Engineering under the supervision of Dr. Jerry Davis will carry out this study. The objective of this project is to study and evaluate the effect of occupant characteristics on physical activities performed during evacuation. The results of this study will help in the development and enhance the accuracy of occupant movement algorithms for building evacuation models. You were selected as a possible participant because you are between 19 and 29 years of age, and demonstrate healthy physical conditions that permit you to perform the trial.

If you decide to participate, I, Rani Muhdi, will ask you to provide your height and weight (measured privately), age, and gender. Additionally, you will be asked to complete a medical history questionnaire to identify any health problems that might prevent you from participating in the study. **General criteria for exclusion from the study include but are not limited to: injury to the lower extremities, muscle, bone, or joint problem that aggravates you during exercise, and having heart/chest problems. Complete exclusion criteria are on the attached pre-preparation questionnaire**.

Methodology: Upon qualification, you will be asked to show up to the testing location (Beard-Eaves-Memorial Coliseum, upper deck, third floor) in long pants (jeans, khakis, etc.) and sneakers or any type of shoes that covers your feet is covered. Shorts, skirts, high heels, sandals, flip-flops, boots, and clogs are not allowed. All data will be collected in a single session. The total time for your participation will be approximately 1.5 hours (including preparation phase, resting periods, and complete the research protocol).

The Auburn University
Institutional Review Board
has approved this document for use
from 5/23/07 to 5/22/08.
Protocol # 07-112 EP 0705

____
Participant's Initials
Page 1 of 3

You will be asked to perform two physical activities (walk at your normal pace and crawl at your normal pace) on a horizontal straight surface and on an indirect horizontal surface for a distance of 100 ft. Prior to the crawling activity, you will be asked to put on knee pads and gloves. Time measurements will be taken in 6 locations along the track and recorded to a central computer. You will undergo a resting period before and after performing each activity. Your heart rate will be recorded to make sure you are fully rested before performing the next activity.

If you participate in this experiment and would like to be included in the second phase of this study, we <u>may</u> contact you again in the near future for this purpose.

Risks: The risks associated with this study are minimal.

1. Experience some discomfort or dizziness as a result of fatigue during the crawling activity.
2. The possibility to develop rug burns from the friction of rubbing your hands and knees on the surface during your crawling activity.
3. Risk of injury due to physical activity.

Precautions: The following precautions will be taken to reduce the risks described above.

1. You will complete a pre-preparation questionnaire prior to participating in this project.
2. Discomfort and dizziness:
    a. You can discontinue the trial or the study at any time and for any reason.
    b. A series of resting periods will be provided before each activity.
    c. You will remain at the testing site following the crawling activity until you feel comfortable to leave.

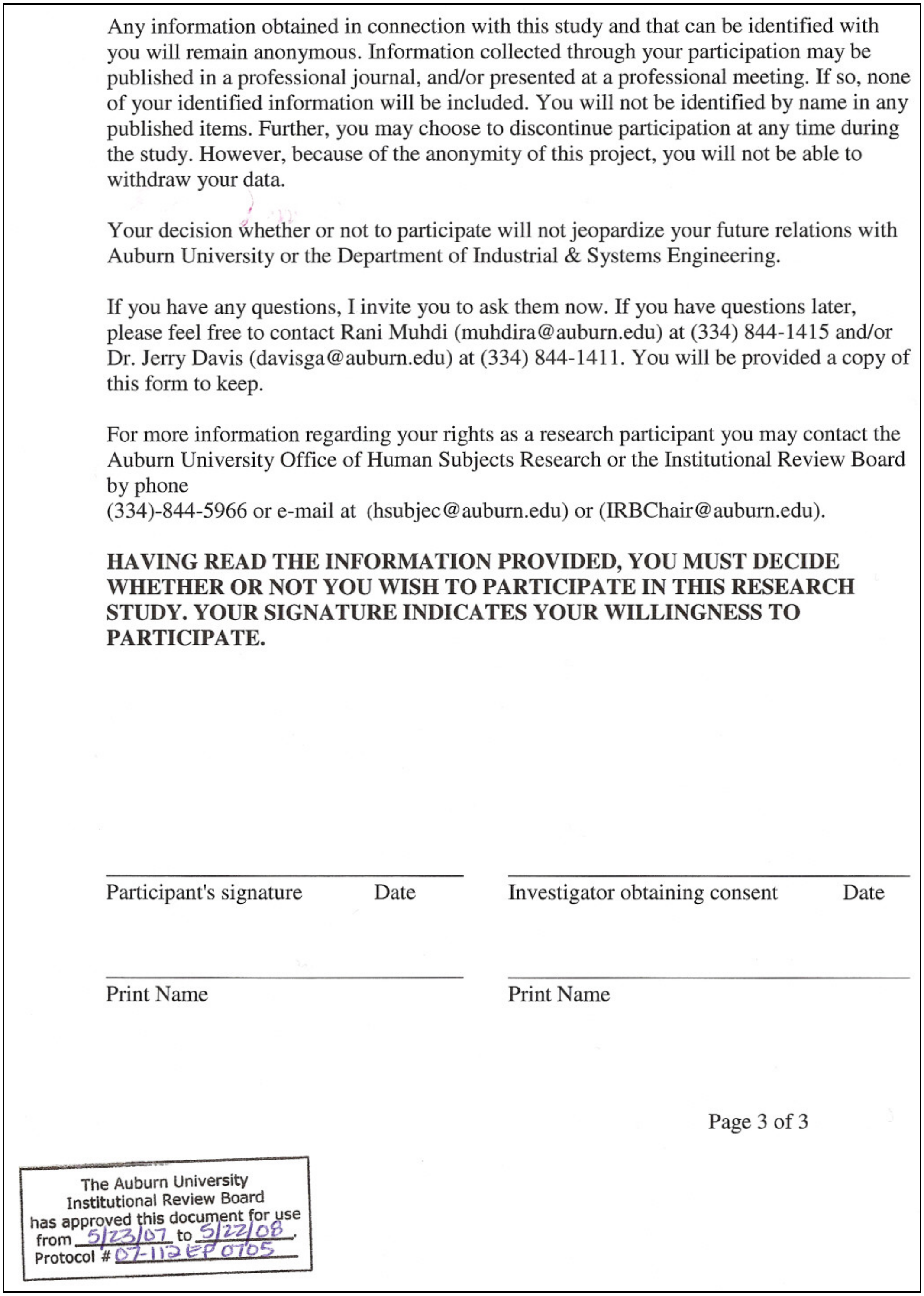
3. Developing rug burns:
    a. You will be asked to put on a set of knee pads and gloves before performing the crawling activity.
    b. You can discontinue the trial or the study at any time and for any reason.

Benefits: Although Auburn University cannot guarantee that you will receive any direct benefit from this study, your benefit from this study is the contribution of the data to assist researchers in developing procedures and techniques to minimize the injury and severity rates associated with building evacuation. Further, you will be compensated $25 for your time during the study.

The researcher will make every reasonable effort to insure your safety throughout your participation. Therefore, we ask you to follow all instructions and ask questions, if needed. In the event an accident or physical injury, follow the attached emergency action plan for the study location. You are responsible for any and all medical cost resulting from injury during or related to the study.

The Auburn University
Institutional Review Board
has approved this document for use
from 5/23/07 to 5/22/08.
Protocol # 07-112 EP 0705

____
Participant's Initials
Page 2 of 3



Any information obtained in connection with this study and that can be identified with you will remain anonymous. Information collected through your participation may be published in a professional journal, and/or presented at a professional meeting. If so, none of your identified information will be included. You will not be identified by name in any published items. Further, you may choose to discontinue participation at any time during the study. However, because of the anonymity of this project, you will not be able to withdraw your data.

Your decision whether or not to participate will not jeopardize your future relations with Auburn University or the Department of Industrial & Systems Engineering.

If you have any questions, I invite you to ask them now. If you have questions later, please feel free to contact Rani Muhdi (muhdira@auburn.edu) at (334) 844-1415 and/or Dr. Jerry Davis (davisga@auburn.edu) at (334) 844-1411. You will be provided a copy of this form to keep.

For more information regarding your rights as a research participant you may contact the Auburn University Office of Human Subjects Research or the Institutional Review Board by phone
(334)-844-5966 or e-mail at (hsubjec@auburn.edu) or (IRBChair@auburn.edu).

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

Participant's signature Date

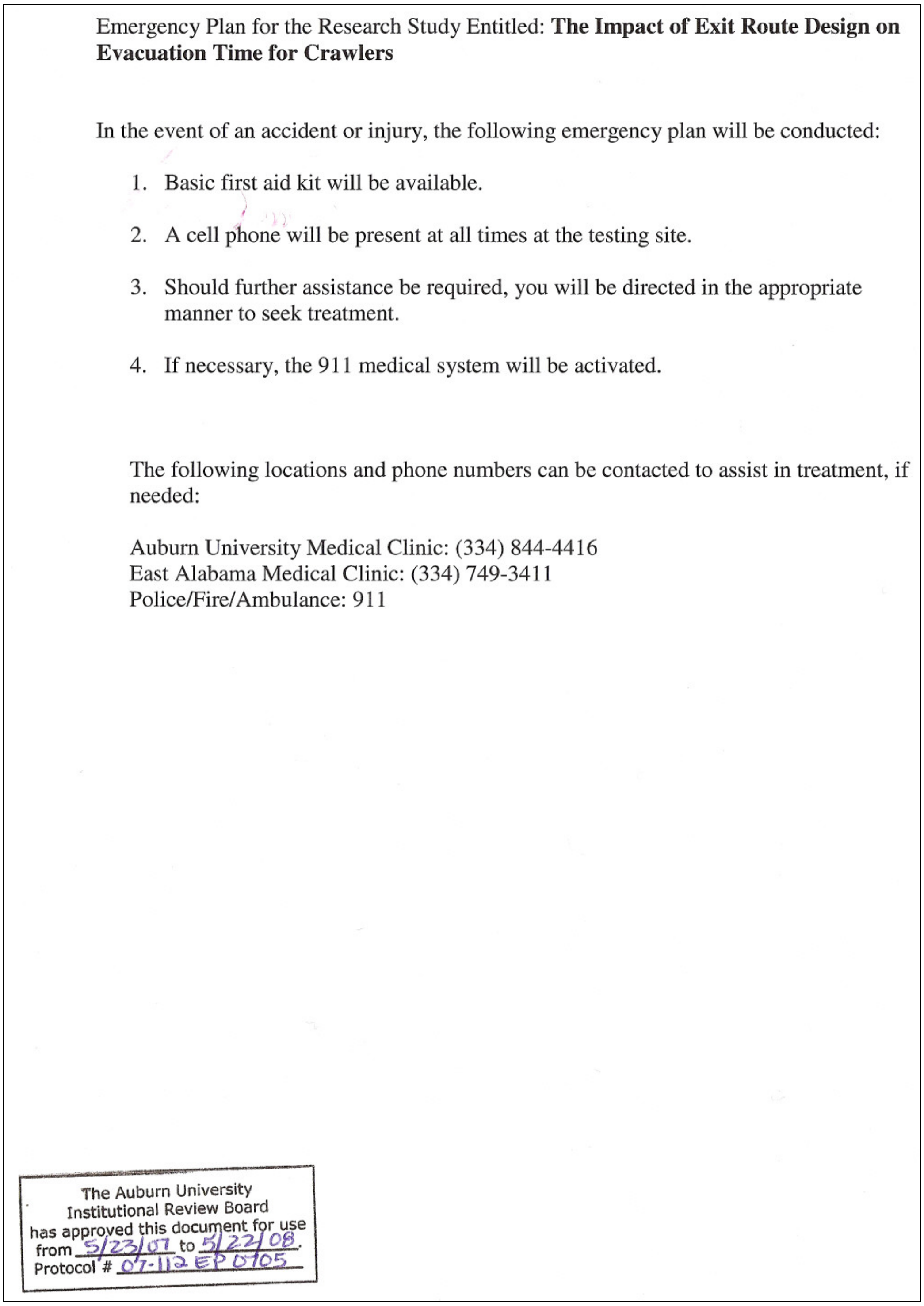
Investigator obtaining consent Date

Print Name

Print Name

Page 3 of 3

The Auburn University
Institutional Review Board
has approved this document for use
from 5/23/07 to 5/22/08.
Protocol # 07-112 EP 0705



Emergency Plan for the Research Study Entitled: **The Impact of Exit Route Design on Evacuation Time for Crawlers**

In the event of an accident or injury, the following emergency plan will be conducted:

1. Basic first aid kit will be available.
2. A cell phone will be present at all times at the testing site.
3. Should further assistance be required, you will be directed in the appropriate manner to seek treatment.
4. If necessary, the 911 medical system will be activated.

The following locations and phone numbers can be contacted to assist in treatment, if needed:

Auburn University Medical Clinic: (334) 844-4416
East Alabama Medical Clinic: (334) 749-3411
Police/Fire/Ambulance: 911

The Auburn University
Institutional Review Board
has approved this document for use
from 5/23/07 to 5/22/08.
Protocol # 07-112 EP 0705

APPENDIX 3.2

PHYSICAL ACTIVITY QUESTIONNAIRE

Confidential Document

Contact Information

Name	Age	Email (xxxxxxx@auburn.edu)	Cell phone number

Pre-Preparation Health Questionnaire

Please read the following questions and answer appropriately.

Participant code (provided by the researcher): _________

#	Question	Yes	No
	Note: If you answer yes to any of the following questions, please explain to the researcher in person.		
1.	Have you ever had surgery in your lower and/or upper extremities?	___	___
2.	Have you ever had pain in your hands, wrists, arms, neck, knees, legs, or back?	___	___
3.	Has your doctor ever informed you that you have a muscle, bone, or joint problem that has aggravated you during exercise?	___	___
4.	Have you ever felt faint, dizzy, or passed out, during or after exercise?	___	___
5.	Have you ever had trouble or problems related to exercise?	___	___
6.	Has your doctor ever told you that you have heart and/or chest problems?	___	___
7.	Have you been hospitalized in the last year?	___	___
8.	Are you currently on prescription medicine?	___	___
9.	Do you have any reason to believe that your participation in this study may put your health or well being at risk?	___	___

For Researcher to fill in:

Weight (lbs): __________ Height (cm): ________

Comments: ____

APPENDIX 3.3

INDIVIDUAL WALKING AND CRAWLING PROCEDURE

Purpose: To study and evaluate the effect of occupant characteristics on physical activities performed during evacuation.

Method:

1. Read and sign informed consent.
2. Allow researcher to measure and record your height and weight.
3. Allow researchers to explain the procedure (researcher's protocol).
4. Put on the Polar™ Heart Rate Monitor (female research assistant available)
5. Rest for 5 min.
6. When instructed, walk at your normal pace down the test track.
7. Rest until your heart rate reaches a resting level.
8. Put on knee pads and gloves.
9. When instructed, crawl at your normal pace (**Note:** the crawling position means that you are supported with your knees and flattened palms. Your arms and thighs should be perpendicular to the floor and your feet are comfortably extended and spaced).
10. Rest and remove the knee pads and gloves.
11. Conclude the trial.

APPENDIX 3.4

PARTICIPANTS DATA

Subject	Gender	BMI	Activity	Replicates			Average
				I	II	III	
1	Male	Normal	Walking	1.63	1.80	1.77	1.73
			Crawling	0.89	0.93	0.86	0.90
2	Male	Normal	Walking	1.67	1.77	1.68	1.70
			Crawling	0.84	0.85	0.90	0.86
3	Male	Normal	Walking	1.67	1.87	1.87	1.80
			Crawling	0.88	0.84	0.85	0.86
4	Male	Overweight	Walking	1.45	1.49	1.50	1.48
			Crawling	0.71	0.77	0.81	0.77
5	Male	Overweight	Walking	1.43	1.54	1.56	1.51
			Crawling	0.84	0.74	0.78	0.79
6	Male	Overweight	Walking	1.48	1.50	1.47	1.48
			Crawling	0.72	0.80	0.86	0.79
7	Male	Obese	Walking	1.35	1.38	1.29	1.34
			Crawling	0.74	0.74	0.75	0.74
8	Male	Obese	Walking	1.31	1.41	1.39	1.37
			Crawling	0.74	0.74	0.75	0.74
9	Male	Obese	Walking	1.35	1.34	1.38	1.36
			Crawling	0.76	0.78	0.75	0.76
10	Female	Normal	Walking	1.51	1.62	1.72	1.62
			Crawling	0.82	0.77	0.85	0.81
11	Female	Normal	Walking	1.68	1.66	1.67	1.67
			Crawling	0.76	0.86	0.88	0.83
12	Female	Normal	Walking	1.55	1.59	1.67	1.61
			Crawling	0.78	0.79	0.81	0.79
13	Female	Overweight	Walking	1.40	1.31	1.50	1.40
			Crawling	0.71	0.70	0.78	0.73
14	Female	Overweight	Walking	1.35	1.46	1.46	1.42
			Crawling	0.75	0.77	0.78	0.77
15	Female	Overweight	Walking	1.47	1.45	1.47	1.46
			Crawling	0.68	0.70	0.74	0.71
16	Female	Obese	Walking	1.33	1.25	1.30	1.29
			Crawling	0.64	0.63	0.67	0.65
17	Female	Obese	Walking	1.33	1.31	1.31	1.32
			Crawling	0.64	0.68	0.70	0.67
18	Female	Obese	Walking	1.23	1.28	1.30	1.27
			Crawling	0.54	0.70	0.69	0.65

APPENDIX 3.5

TEST FOR EQUAL VARIANCES AND TWO-SAMPLE T-TEST

Test for Equal Variances: Mean Walking, Mean Crawling

```
95% Bonferroni confidence intervals for standard deviations

                N     Lower       StDev       Upper
Mean Walking    18    0.117030    0.162172    0.259025
Mean Crawling   18    0.050901    0.070535    0.112660


F-Test (Normal Distribution)
Test statistic = 5.29, p-value = 0.001


Levene's Test (Any Continuous Distribution)
Test statistic = 10.67, p-value = 0.002
```

Two-Sample T-Test and CI: Mean Walking, Mean Crawling

```
Two-sample T for Mean Walking vs Mean Crawling

                N     Mean        StDev       SE Mean
Mean Walking    18    1.491       0.162       0.038
Mean Crawling   18    0.7689      0.0705      0.017


Difference = mu (Mean Walking) - mu (Mean Crawling)
Estimate for difference:  0.7217
95% CI for difference:  (0.6354, 0.8079)
T-Test of difference = 0 (vs not =): T-Value = 17.31  P-Value = 0.000  DF = 23
```

APPENDIX 3.6

GENERAL LINEAR MODEL: CRAWLING SPEED

General Linear Model: Crawling Speed versus G, BC, BLKs

```
Factor         Type       Levels     Values
G              fixed      2          1, 2
BC(G)          fixed      6          1, 2, 3, 1, 2, 3
BLKs(G BC)  fixed      18         1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15,
                                     16, 17, 18


Analysis of Variance for Crawling Speed, using Adjusted SS for Tests

Source         DF    Seq SS       Adj SS       Adj MS       F        P
G               1    0.066287     0.066287      0.066287    37.20    0.000
BC(G)           4    0.175055     0.175055     0.043764     24.56    0.000
BLKs(G BC)  12    0.014224     0.014224     0.001185     0.67     0.772
Error          36    0.064150     0.064150     0.001782
Total          53    0.319717


S = 0.0422132   R-Sq = 79.94%   R-Sq(adj) = 70.46%


Unusual Observations for Crawling Speed

     Crawling
Obs   Speed        Fit          SE Fit       Residual     St Resid
 16    0.722132    0.794130     0.024372     -0.071998    -2.09 R
 31    0.757424    0.829482     0.024372     -0.072058    -2.09 R
 52    0.542429    0.645986     0.024372     -0.103557    -3.00 R

R denotes an observation with a large standardized residual.
```

APPENDIX 4.1

INDIVIDUAL WALKING AND CRAWLING PROCEDURE

Purpose:	To study and evaluate the impact of exit route design and occupant characteristics on evacuation time for crawlers

Method:

1. Read and sign informed consent.
2. Allow researcher to measure and record your height and weight.
3. Allow researchers to explain the procedure (researcher's protocol).
4. Put on the Polar™ Heart Rate Monitor (female research assistant available)
5. Rest for 5 min.
6. When instructed, walk at your normal pace down the indirect test track.
7. Rest until your heart rate reaches resting level.
8. Put on knee pads and gloves.
9. When instructed, crawl at your normal pace down the indirect test track (**Note:** the crawling position means that you are supported with your knees and flattened palms. Your arms and thighs should be perpendicular to the floor and your feet are comfortably extended and spaced).
10. Rest and remove the knee pads and gloves.
11. Conclude the trial.

APPENDIX 4.2

PARTICIPANTS CAWLING DATA

Subject	Gender	BMI	Route Type	Replicates			Average
				I	II	III	
1	Male	Normal	Direct	34.26	32.66	35.31	34.08
			Indirect	37.23	36.18	39.66	37.69
2	Male	Normal	Direct	36.28	35.95	33.75	35.33
			Indirect	39.20	39.06	38.67	38.98
3	Male	Normal	Direct	34.50	36.09	35.95	35.51
			Indirect	37.21	35.54	35.65	36.13
4	Male	Overweight	Direct	42.78	39.54	37.46	39.93
			Indirect	43.35	40.34	42.48	42.06
5	Male	Overweight	Direct	36.14	41.28	38.85	38.76
			Indirect	44.17	43.34	45.72	44.41
6	Male	Overweight	Direct	42.21	38.23	35.32	38.59
			Indirect	43.20	41.32	44.75	43.09
7	Male	Obese	Direct	39.20	41.11	39.59	39.97
			Indirect	47.02	45.52	43.89	45.48
8	Male	Obese	Direct	41.04	41.42	40.53	41.00
			Indirect	44.59	46.83	48.77	46.73
9	Male	Obese	Direct	39.88	39.26	40.42	39.85
			Indirect	47.37	46.90	48.81	47.69
10	Female	Normal	Direct	37.24	39.35	35.99	37.53
			Indirect	38.38	41.26	38.70	39.45
11	Female	Normal	Direct	40.24	35.63	34.82	36.90
			Indirect	41.86	39.45	40.43	40.58
12	Female	Normal	Direct	39.28	38.58	37.71	38.52
			Indirect	40.14	41.49	40.61	40.75
13	Female	Overweight	Direct	43.04	43.40	38.86	41.77
			Indirect	44.33	45.10	43.98	44.47
14	Female	Overweight	Direct	40.73	39.48	38.93	39.71
			Indirect	42.30	45.20	44.27	43.92
15	Female	Overweight	Direct	44.79	43.49	41.40	43.23
			Indirect	45.04	45.65	43.97	44.89
16	Female	Obese	Direct	47.91	48.17	45.43	47.17
			Indirect	47.13	46.94	48.21	47.43
17	Female	Obese	Direct	47.57	44.84	43.30	45.24
			Indirect	46.23	47.85	47.76	47.28
18	Female	Obese	Direct	56.19	43.48	43.89	47.85
			Indirect	47.05	47.91	46.77	47.24

APPENDIX 4.3

TEST FOR EQUAL VARIANCES AND TWO-SAMPLE T-TEST

Test for Equal Variances: Straight, Indirect

```
95% Bonferroni confidence intervals for standard deviations

            N    Lower      StDev      Upper
Straight    54   3.54141    4.31554    5.49885
Indirect    54   3.02627    3.68779    4.69897


F-Test (Normal Distribution)
Test statistic = 1.37, p-value = 0.256


Levene's Test (Any Continuous Distribution)
Test statistic = 0.08, p-value = 0.776
```

Two-Sample T-Test and CI: Mean Straight, Mean indirect

```
Two-sample T for Mean Straight vs Mean indirect

                 N    Mean     StDev    SE Mean
Mean Straight    18   40.05    3.86     0.91
Mean indirect    18   43.24    3.61     0.85


Difference = mu (Mean Straight) - mu (Mean indirect)
Estimate for difference:  -3.19
95% CI for difference:  (-5.72, -0.65)
T-Test of difference = 0 (vs not =): T-Value = -2.56  P-Value = 0.015  DF = 34
Both use Pooled StDev = 3.7380
```

APPENDIX 4.4

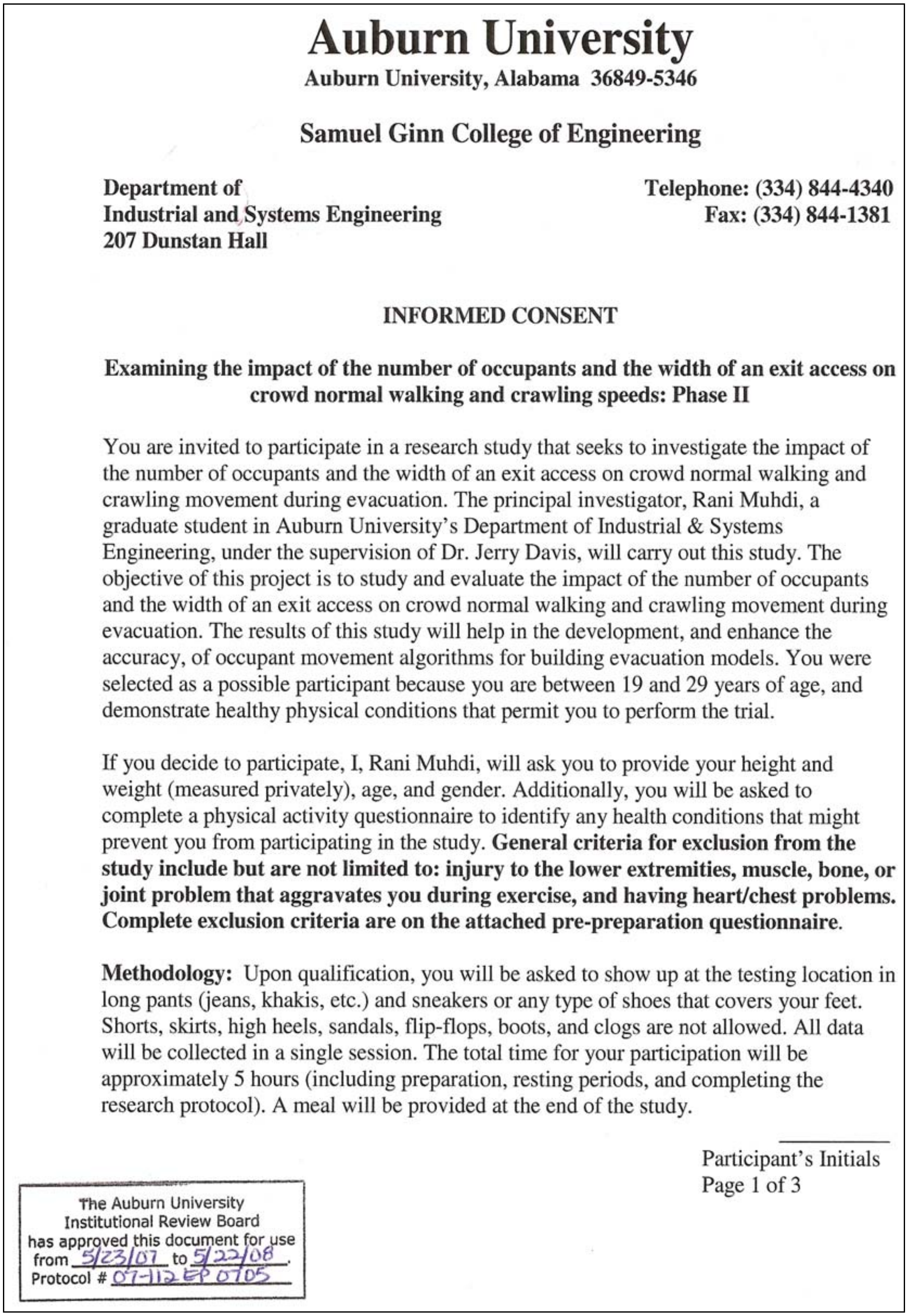
GENERAL LINEAR MODEL: TIMES TO EVACUATE IN AN INDIRECT ROUTE

General Linear Model: Indirect Route versus G, BC, BLKs

```
Factor        Type     Levels   Values
G             fixed    2        1, 2
BC(G)         fixed    6        1, 2, 3, 1, 2, 3
BLKs(G BC)    fixed    18       1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15,
                                16, 17, 18


Analysis of Variance for Indirect Route, using Adjusted SS for Tests

Source        DF   Seq SS     Adj SS     Adj MS     F       P
G             1    31.495     31.495     31.495     20.19   0.000
BC(G)         4    600.739    600.739    150.185    96.25   0.000
BLKs(G BC)    12   32.383     32.383     2.699      1.73    0.101
Error         36   56.171     56.171     1.560
Total         53   720.788


S = 1.24912   R-Sq = 92.21%   R-Sq(adj) = 88.53%


Unusual Observations for Indirect Route

     Indirect
Obs  Route     Fit       SE Fit    Residual   St Resid
22   44.5900   46.7300   0.7212    -2.1400    -2.10 R
24   48.7700   46.7300   0.7212    2.0400      2.00 R

R denotes an observation with a large standardized residual.
```

APPENDIX 5.1

INFORMED CONSENT



Auburn University

Auburn University, Alabama 36849-5346

Samuel Ginn College of Engineering

Department of
Industrial and Systems Engineering
207 Dunstan Hall

Telephone: (334) 844-4340
Fax: (334) 844-1381

INFORMED CONSENT

Examining the impact of the number of occupants and the width of an exit access on crowd normal walking and crawling speeds: Phase II

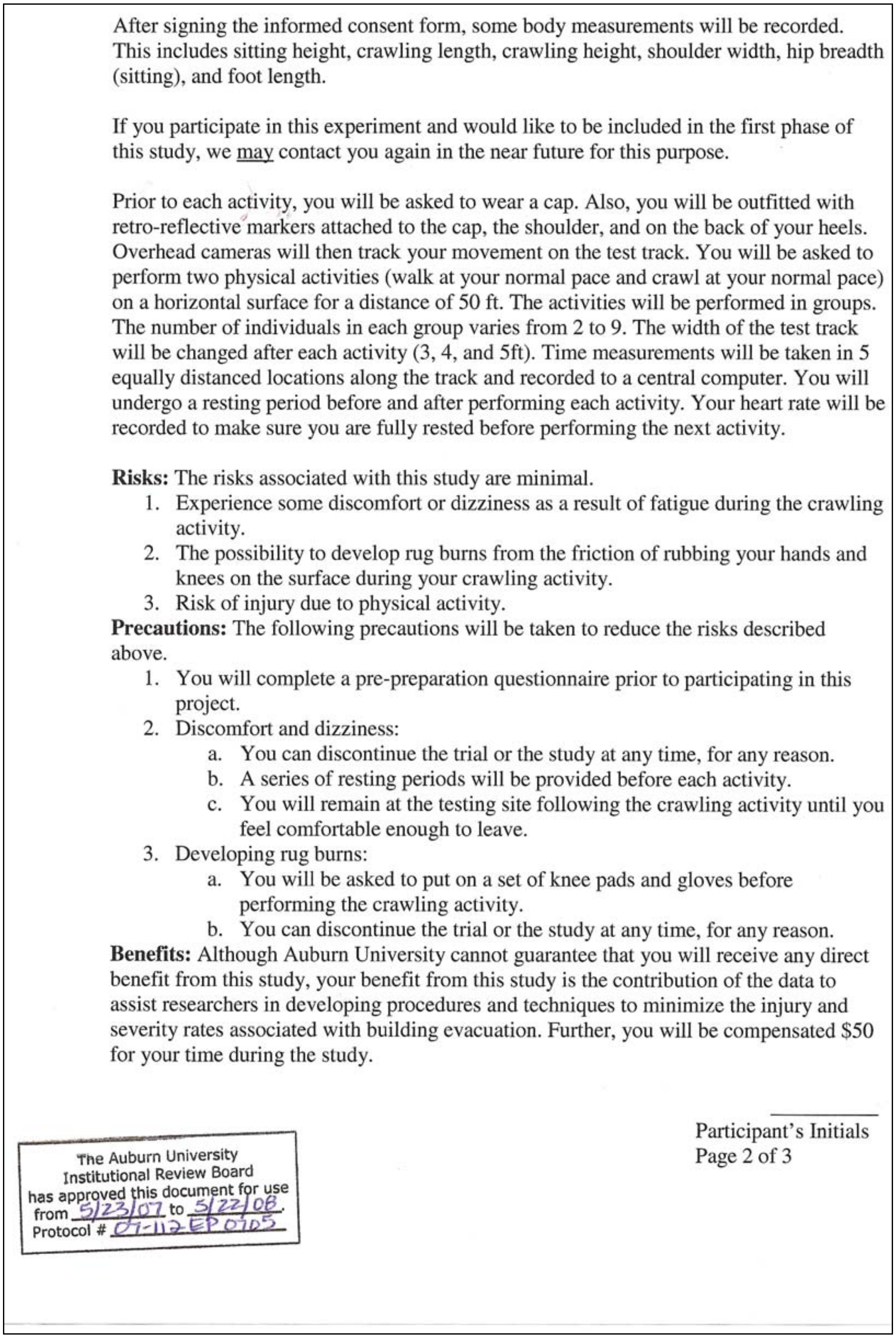
You are invited to participate in a research study that seeks to investigate the impact of the number of occupants and the width of an exit access on crowd normal walking and crawling movement during evacuation. The principal investigator, Rani Muhdi, a graduate student in Auburn University's Department of Industrial & Systems Engineering, under the supervision of Dr. Jerry Davis, will carry out this study. The objective of this project is to study and evaluate the impact of the number of occupants and the width of an exit access on crowd normal walking and crawling movement during evacuation. The results of this study will help in the development, and enhance the accuracy, of occupant movement algorithms for building evacuation models. You were selected as a possible participant because you are between 19 and 29 years of age, and demonstrate healthy physical conditions that permit you to perform the trial.

If you decide to participate, I, Rani Muhdi, will ask you to provide your height and weight (measured privately), age, and gender. Additionally, you will be asked to complete a physical activity questionnaire to identify any health conditions that might prevent you from participating in the study. **General criteria for exclusion from the study include but are not limited to: injury to the lower extremities, muscle, bone, or joint problem that aggravates you during exercise, and having heart/chest problems. Complete exclusion criteria are on the attached pre-preparation questionnaire**.

Methodology: Upon qualification, you will be asked to show up at the testing location in long pants (jeans, khakis, etc.) and sneakers or any type of shoes that covers your feet. Shorts, skirts, high heels, sandals, flip-flops, boots, and clogs are not allowed. All data will be collected in a single session. The total time for your participation will be approximately 5 hours (including preparation, resting periods, and completing the research protocol). A meal will be provided at the end of the study.

____
Participant's Initials
Page 1 of 3

The Auburn University
Institutional Review Board
has approved this document for use
from 5/23/07 to 5/22/08.
Protocol # 07-112 EP 0705



After signing the informed consent form, some body measurements will be recorded. This includes sitting height, crawling length, crawling height, shoulder width, hip breadth (sitting), and foot length.

If you participate in this experiment and would like to be included in the first phase of this study, we may contact you again in the near future for this purpose.

Prior to each activity, you will be asked to wear a cap. Also, you will be outfitted with retro-reflective markers attached to the cap, the shoulder, and on the back of your heels. Overhead cameras will then track your movement on the test track. You will be asked to perform two physical activities (walk at your normal pace and crawl at your normal pace) on a horizontal surface for a distance of 50 ft. The activities will be performed in groups. The number of individuals in each group varies from 2 to 9. The width of the test track will be changed after each activity (3, 4, and 5ft). Time measurements will be taken in 5 equally distanced locations along the track and recorded to a central computer. You will undergo a resting period before and after performing each activity. Your heart rate will be recorded to make sure you are fully rested before performing the next activity.

Risks: The risks associated with this study are minimal.

1. Experience some discomfort or dizziness as a result of fatigue during the crawling activity.
2. The possibility to develop rug burns from the friction of rubbing your hands and knees on the surface during your crawling activity.
3. Risk of injury due to physical activity.

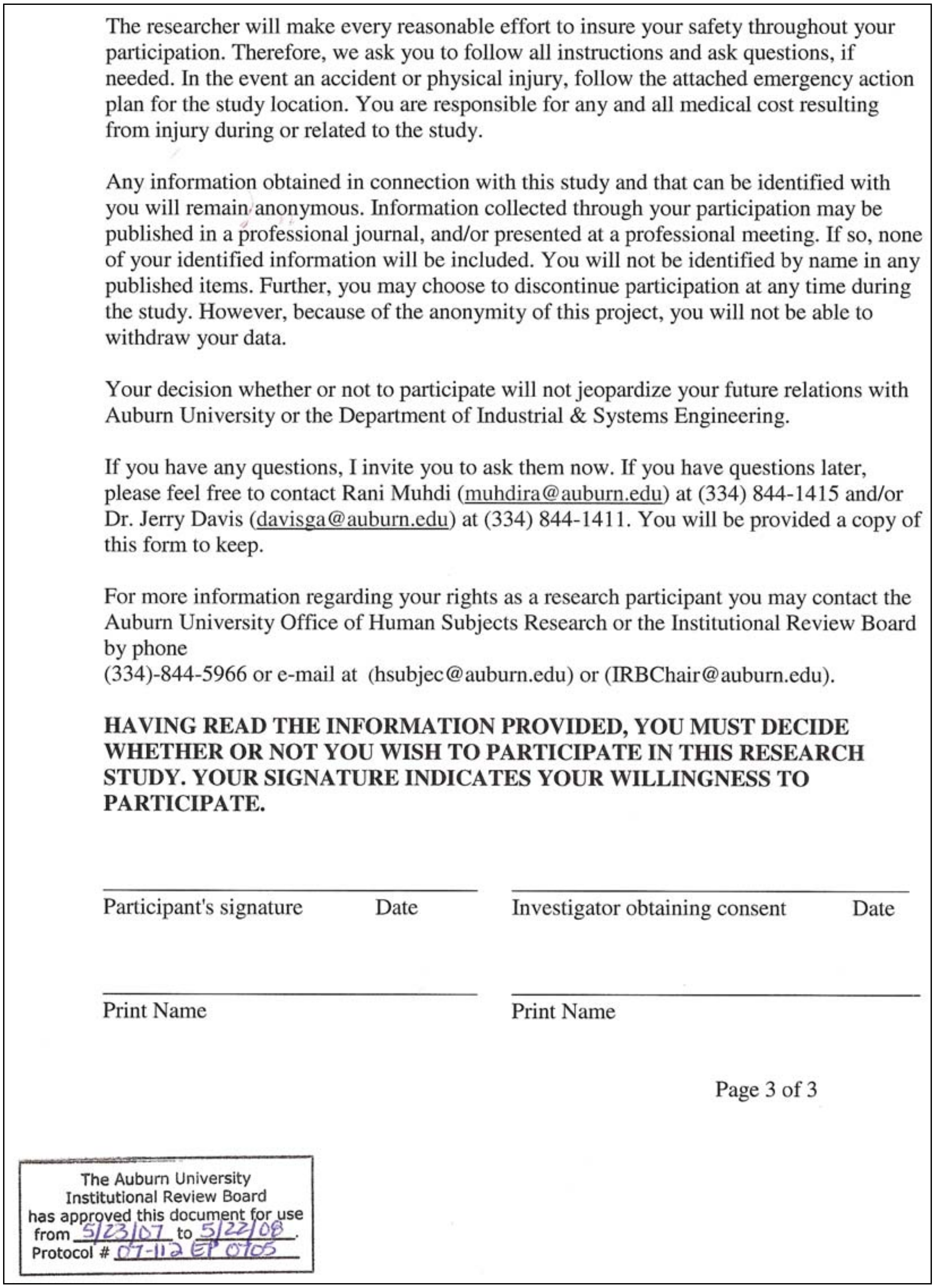
Precautions: The following precautions will be taken to reduce the risks described above.

1. You will complete a pre-preparation questionnaire prior to participating in this project.
2. Discomfort and dizziness:
    a. You can discontinue the trial or the study at any time, for any reason.
    b. A series of resting periods will be provided before each activity.
    c. You will remain at the testing site following the crawling activity until you feel comfortable enough to leave.
3. Developing rug burns:
    a. You will be asked to put on a set of knee pads and gloves before performing the crawling activity.
    b. You can discontinue the trial or the study at any time, for any reason.

Benefits: Although Auburn University cannot guarantee that you will receive any direct benefit from this study, your benefit from this study is the contribution of the data to assist researchers in developing procedures and techniques to minimize the injury and severity rates associated with building evacuation. Further, you will be compensated $50 for your time during the study.

The Auburn University
Institutional Review Board
has approved this document for use
from 5/23/07 to 5/22/08.
Protocol # 07-112 EP 0705

____
Participant's Initials
Page 2 of 3



The researcher will make every reasonable effort to insure your safety throughout your participation. Therefore, we ask you to follow all instructions and ask questions, if needed. In the event an accident or physical injury, follow the attached emergency action plan for the study location. You are responsible for any and all medical cost resulting from injury during or related to the study.

Any information obtained in connection with this study and that can be identified with you will remain anonymous. Information collected through your participation may be published in a professional journal, and/or presented at a professional meeting. If so, none of your identified information will be included. You will not be identified by name in any published items. Further, you may choose to discontinue participation at any time during the study. However, because of the anonymity of this project, you will not be able to withdraw your data.

Your decision whether or not to participate will not jeopardize your future relations with Auburn University or the Department of Industrial & Systems Engineering.

If you have any questions, I invite you to ask them now. If you have questions later, please feel free to contact Rani Muhdi (muhdira@auburn.edu) at (334) 844-1415 and/or Dr. Jerry Davis (davisga@auburn.edu) at (334) 844-1411. You will be provided a copy of this form to keep.

For more information regarding your rights as a research participant you may contact the Auburn University Office of Human Subjects Research or the Institutional Review Board by phone
(334)-844-5966 or e-mail at (hsubjec@auburn.edu) or (IRBChair@auburn.edu).

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

Participant's signature Date

Investigator obtaining consent Date

Print Name

Print Name

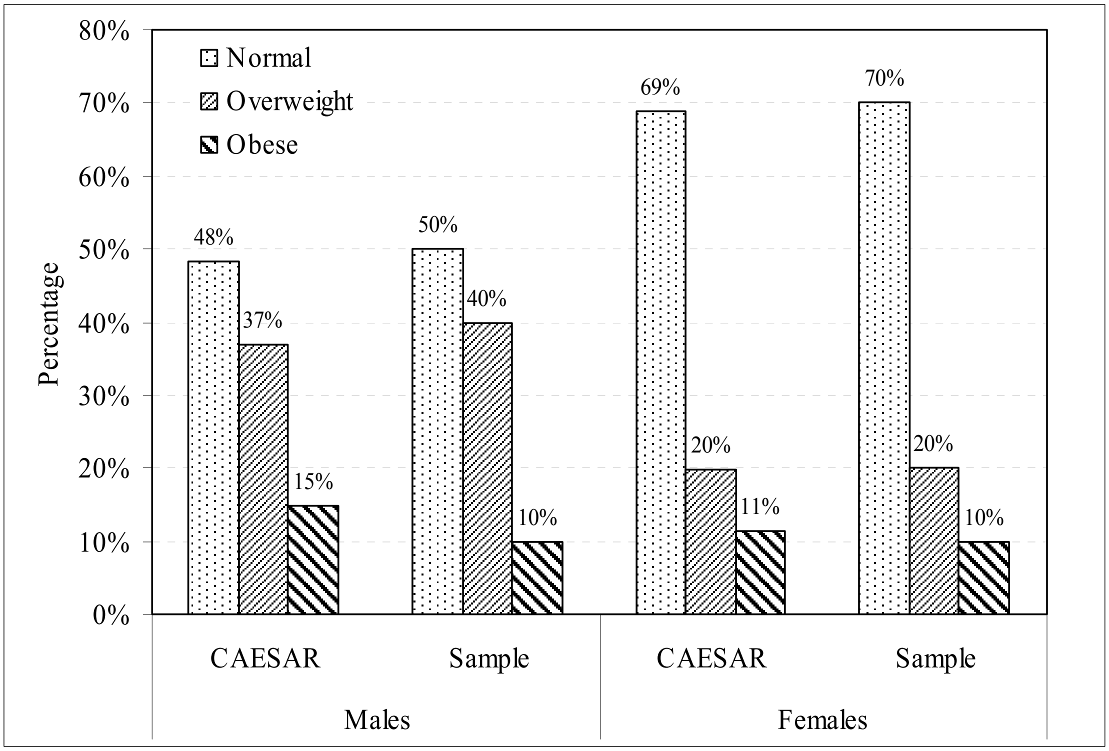
Page 3 of 3

The Auburn University
Institutional Review Board
has approved this document for use
from 5/23/07 to 5/22/08.
Protocol # 07-112 EP 0705

APPENDIX 5.2

A PROPORTIONAL COMPARISON BETWEEN CAESAR AND THE STUDY SAMPLE

BMI	CAESAR (563 subjects)		Sample (20 subjects)	
	271 males (48%)	292 females (52%)	10 males (50%)	10 females (50%)
Normal	131 (48%)	201 (69%)	5 (50%)	7 (70%)
Overweight	100 (37%)	58 (20%)	4 (40%)	2 (20%)
Obese	40 (15%)	33 (11%)	1 (10%)	1 (10%)



APPENDIX 5.3

CROWD WALKING AND CRAWLING PROCEDURE

Purpose: To study and evaluate the impact of the number of occupants and the width of an exit access on crowd normal walking and crawling speeds.

Method:

1. Read and sign informed consent.
2. Allow researcher to measure and record your height and weight.
3. Allow researchers to explain the procedure (researcher's protocol).
4. Put on the Polar™ Heart Rate Monitor (female research assistant available)
5. Rest for 5 min.
6. When instructed, walk, in a group, at your normal pace down the test track.
7. Rest until your heart rate reaches a resting level.
8. When instructed, walk again, in a group, at your normal pace down the test track (different track width).
9. Rest until your heart rate reaches a resting level.
10. Put on knee pads and gloves.
11. When instructed, crawl at your normal pace (**Note:** the crawling position means that you are supported with your knees and flattened palms. Your arms and thighs should be perpendicular to the floor and your feet are comfortably extended and spaced).
12. Rest until your heart rate reaches a resting level.
13. When instructed, crawl again, in a group, at your normal pace (different track width)
14. Rest and remove the knee pads and gloves.
15. Conclude the trial.

APPENDIX 5.4

GENERAL LINEAR MODEL: CROWD WALKING SPEED VS. OCCUPANT CONFIGURATION AND EXIT ACCESS WIDTH

General Linear Model: Walking versus Occupant Configuration, Exit Access Width

Factor	Type	Levels	Values
Conf	fixed	5	1, 2, 3, 4, 5
W	fixed	3	1, 2, 3

Analysis of Variance for Walking, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Conf	4	0.0040533	0.0040533	0.0010133	1.04	0.420
W	2	0.0379800	0.0379800	0.0189900	19.44	0.000
Conf*W	8	0.0287867	0.0287867	0.0035983	3.68	0.014
Error	15	0.0146500	0.0146500	0.0009767		
Total	29	0.0854700				

S = 0.0312517   R-Sq = 82.86%   R-Sq(adj) = 66.86%

Tukey Simultaneous Tests
Response Variable Walking
All Pairwise Comparisons among Levels of Conf
Conf = 1 subtracted from:

Conf	Difference of Means	SE of Difference	Adjusted T-Value	P-Value
2	-0.01000	0.01804	-0.554	0.9797
3	-0.01333	0.01804	-0.739	0.9438
4	-0.03167	0.01804	-1.755	0.4327
5	0.00000	0.01804	0.000	1.0000

Conf = 2 subtracted from:

Conf	Difference of Means	SE of Difference	Adjusted T-Value	P-Value
3	-0.00333	0.01804	-0.185	0.9997
4	-0.02167	0.01804	-1.201	0.7510
5	0.01000	0.01804	0.554	0.9797

Conf = 3 subtracted from:

```
                Difference          SE of       Adjusted
Conf            of Means            Difference  T-Value     P-Value
4               -0.01833            0.01804     -1.016      0.8441
5               0.01333             0.01804     0.739       0.9438

Conf = 4  subtracted from:

        Difference  SE of       Adjusted
Conf    of Means    Difference  T-Value     P-Value
5       0.03167     0.01804     1.755       0.4327


Tukey Simultaneous Tests
Response Variable Crawling
All Pairwise Comparisons among Levels of W
W = 1  subtracted from:

        Difference  SE of       Adjusted
W       of Means    Difference  T-Value     P-Value
2       0.07800     0.01327     5.879       0.0001
3       -0.02300    0.01327     -1.734      0.2255


W = 2  subtracted from:

        Difference  SE of       Adjusted
W       of Means    Difference  T-Value     P-Value
3       -0.1010     0.01327     -7.613      0.0000
```

APPENDIX 5.5

GENERAL LINEAR MODEL: CROWD CRAWLING SPEED VS. OCCUPANT CONFIGURATION AND EXIT ACCESS WIDTH

General Linear Model: Crawling versus Occupant Configuration, Exit Access Width

```
Factor      Type      Levels     Values
Conf        fixed     5          1, 2, 3, 4, 5
W           fixed     3          1, 2, 3


Analysis of Variance for Crawling, using Adjusted SS for Tests

Source      DF    Seq SS      Adj SS      Adj MS      F      P
Conf        4     0.0018867   0.0018867   0.0004717   0.54   0.712
W           2     0.0560467   0.0560467   0.0280233   31.84  0.000
Conf*W      8     0.0078533   0.0078533   0.0009817   1.12   0.406
Error       15    0.0132000   0.0132000   0.0008800
Total       29    0.0789867


S = 0.0296648   R-Sq = 83.29%   R-Sq(adj) = 67.69%


Unusual Observations for Crawling

Obs   Crawling    Fit         SE Fit      Residual    St Resid
  9   0.700000    0.755000    0.020976    -0.055000   -2.62 R
 10   0.810000    0.755000    0.020976     0.055000   2.62 R

R denotes an observation with a large standardized residual.


Tukey Simultaneous Tests
Response Variable Crawling
All Pairwise Comparisons among Levels of Conf
Conf = 1  subtracted from:

            Difference  SE of       Adjusted
Conf        of Means    Difference  T-Value     P-Value
2           0.00667     0.01713     0.3892      0.9946
3           0.00167     0.01713     0.0973      1.0000
```

4	-0.00500	0.01713	-0.2919	0.9982
5	-0.01667	0.01713	-0.9731	0.8630

Conf = 2 subtracted from:

Conf	Difference of Means	SE of Difference	Adjusted T-Value	P-Value
3	-0.00500	0.01713	-0.292	0.9982
4	-0.01167	0.01713	-0.681	0.9576
5	-0.02333	0.01713	-1.362	0.6590

Conf = 3 subtracted from:

Conf	Difference of Means	SE of Difference	Adjusted T-Value	P-Value
4	-0.00667	0.01713	-0.389	0.9946
5	-0.01833	0.01713	-1.070	0.8185

Conf = 4 subtracted from:

Conf	Difference of Means	SE of Difference	Adjusted T-Value	P-Value
5	-0.01167	0.01713	-0.6812	0.9576

APPENDIX 5.6

CROWD DENSITY AND CRAWLING SPEED DATA

# Occupant	W (ft)	L (ft)	Area (m^2)	Density (occ/m^2)	Time (sec)	Speed (m/s)
1	3	6	1.67	0.60	1.90	0.96
1	3	6	1.67	0.60	2.00	0.91
1	3	6	1.67	0.60	1.90	0.96
2	3	8	2.23	0.90	3.00	0.81
2	3	8	2.23	0.90	2.73	0.89
2	3	6	1.67	1.20	1.90	0.96
2	3	6	1.67	1.20	1.97	0.93
2	3	6	1.67	1.20	1.90	0.96
2	3	6	1.67	1.20	2.07	0.88
2	3	6	1.67	1.20	1.87	0.98
3	3	8	2.23	1.35	2.57	0.95
3	3	8	2.23	1.35	2.73	0.89
2	3	4	1.11	1.79	1.37	0.89
4	3	8	2.23	1.79	3.27	0.75
4	3	8	2.23	1.79	2.67	0.91
4	3	8	2.23	1.79	2.80	0.87
2	4	6	2.23	0.90	2.00	0.91
3	4	6	2.23	1.35	1.93	0.95
4	4	8	2.97	1.35	2.83	0.86
5	4	8	2.97	1.68	2.83	0.86
4	5	6	2.79	1.44	1.87	0.98
7	5	8	3.72	1.88	3.47	0.70

APPENDIX 5.7

REGRESSION ANALYSIS: CROWD CRAWLING SPEED VS. CROWD DENSITY

Polynomial Regression Analysis: Crowd Crawling Speed (m/s) versus Crowd Crawling Density (occ/m^2)

The regression equation is
Crowd Crawling Speed = 0.7973 + 0.2909 Crowd Density - 0.1503 Crowd Density^2

S = 0.0593124   R-Sq = 42.7%   R-Sq(adj) = 37.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	0.052397	0.0261983	7.45	0.004
Error	20	0.070359	0.0035180		
Total	22	0.122756			

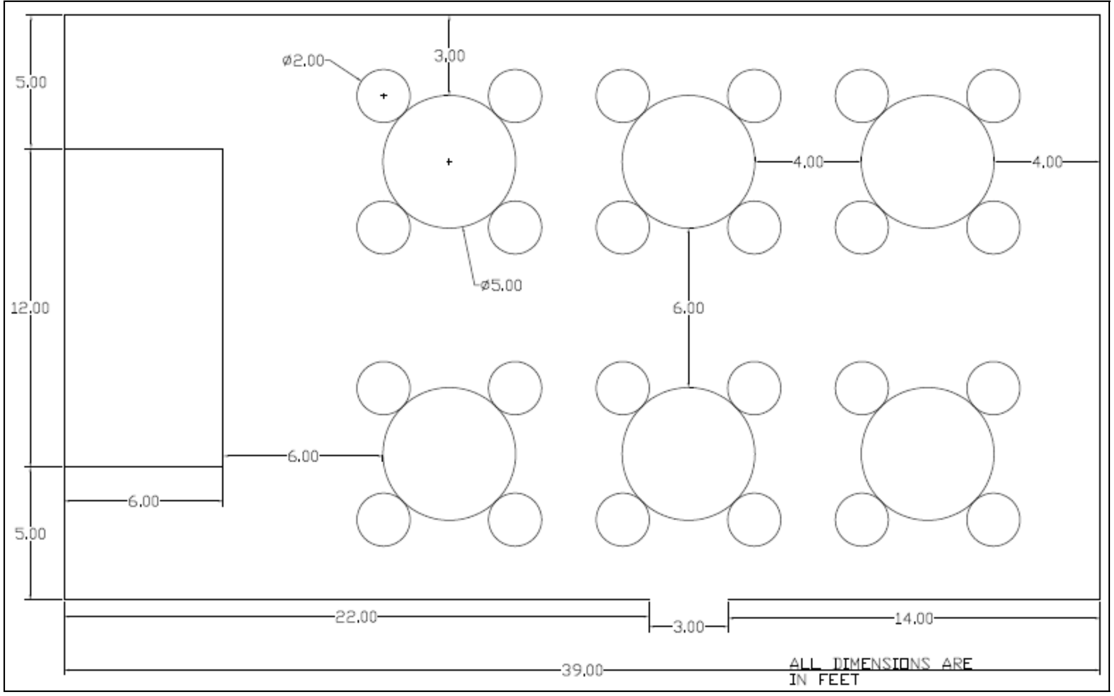
Sequential Analysis of Variance

Source	DF	SS	F	P
Linear	1	0.0356769	8.60	0.008
Quadratic	1	0.0167197	4.75	0.041

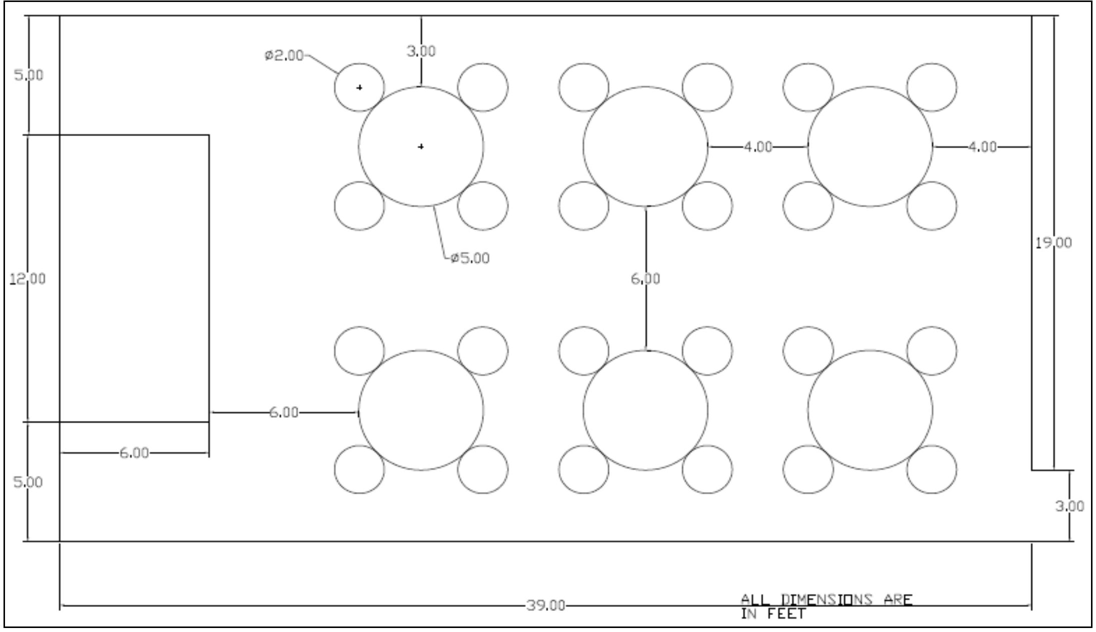
APPENDIX 6.1

LAYOUT DESIGNS FOR THE VALIDATION PROCESS

Scenario (1)



Scenario (2)



APPENDIX 6.2

TOTAL EVACUATION TIMES FOR ASERI AND THE POTENTIAL FIELD MODEL

Run #	Scenario 1			Scenario 2		
	ASERI	Potential Field	Diff.	ASERI	Potential Field	Diff.
1	11.6	9.0	2.6	14	15.2	-1.2
2	11.6	8.3	3.3	12	12.4	-0.4
3	11.2	10.2	1.0	12.8	12.9	-0.1
4	10.8	9.1	1.7	14	13.4	0.6
5	11.2	9.1	2.1	13.6	14.9	-1.3
6	11.2	8.7	2.5	13.6	13.1	0.5
7	10.4	8.7	1.7	13.2	14.9	-1.7
8	11.2	13.1	-1.9	12.8	12.5	0.3
9	10.4	8.8	1.6	12	11.8	0.2
10	10.8	10.0	0.8	12.4	14.5	-2.1
11	10.4	8.3	2.1	13.6	12.9	0.7
12	11.6	9.3	2.3	12.4	12.2	0.2
13	12.0	8.7	3.3	12.8	13.6	-0.8
14	10.8	8.0	2.8	12.4	16	-3.6
15	10.8	9.3	1.5	14	12.5	1.5
16	10.8	11.3	-0.5	13.2	14.9	-1.7
17	10.8	10.2	0.6	12.8	15.4	-2.6
18	11.6	10.2	1.4	12.8	14.2	-1.4
19	10.4	7.5	2.9	12.4	13.4	-1
20	11.2	10.1	1.1	12.8	13.8	-1
21	12.0	8.4	3.6	12.8	13.1	-0.3
22	11.2	9.5	1.7	12.4	13.2	-0.8
23	11.6	10.0	1.6	13.6	12.5	1.1
24	11.6	9.0	2.6	12.8	12.9	-0.1
25	10.0	9.6	0.4	13.2	11.9	1.3
26	11.6	9.3	2.3	12.8	12.3	0.5
27	10.8	8.7	2.1	13.6	13	0.6
28	10.8	9.5	1.3	13.2	16.6	-3.4
29	11.6	8.2	3.4	12.4	12.7	-0.3
30	10.8	9.7	1.1	14.4	15.3	-0.9
31	10.8	10.0	0.8	14.4	11.7	2.7
32	10.4	10.0	0.4	12.8	14.3	-1.5
33	11.2	8.1	3.1	12.8	14.9	-2.1
34	10.8	9.1	1.7	12	12.9	-0.9
35	11.6	8.8	2.8	12.4	13.1	-0.7
36	11.6	8.1	3.5	13.6	12.6	1
37	10.8	9.2	1.6	12.8	15.3	-2.5
38	11.2	10.2	1.0	12.8	13.3	-0.5
39	11.6	9.1	2.5	14	12.8	1.2
40	9.6	8.8	0.8	13.2	13.3	-0.1
41	11.2	10.9	0.3	12	12.2	-0.2
42	10.0	10.3	-0.3	12.4	14.3	-1.9
43	10.8	9.4	1.4	12.4	13.9	-1.5
44	10.0	9.6	0.4	14	12.7	1.3
45	11.2	9.7	1.5	11.6	14.9	-3.3
46	10.4	8.8	1.6	12.8	14.9	-2.1
47	10.4	8.6	1.8	12	13.8	-1.8
48	11.6	10.4	1.2	12.8	13.8	-1
49	11.2	8.8	2.4	12	12.3	-0.3
50	10.8	9.3	1.5	12.8	11.6	1.2
51	10.8	10.1	0.7	12.8	13.3	-0.5
52	10.4	9.0	1.4	14	14.7	-0.7
53	9.2	9.1	0.1	13.2	13.1	0.1
54	11.2	8.7	2.5	13.2	15.3	-2.1
55	10.8	9.1	1.7	12.8	11.9	0.9
56	10.8	10.9	-0.1	12.8	13.9	-1.1
57	12.0	8.9	3.1	13.2	14.9	-1.7
58	12.0	8.7	3.3	12.4	13.1	-0.7
59	10.4	13.9	-3.5	12.4	15.5	-3.1
60	11.2	8.7	2.5	12.8	14.5	-1.7
61	11.6	8.5	3.1	12.8	14.1	-1.3
62	11.2	10.3	0.9	13.2	13.1	0.1
63	12.0	9.3	2.7	12	14.9	-2.9
64	9.2	8.9	0.3	12.4	15.3	-2.9
65	10.8	13.7	-2.9	12	16.4	-4.4
66	12.0	11.6	0.4	12.4	13	-0.6
67	12.0	10.1	1.9	12.4	14	-1.6
68	10.4	7.9	2.5	13.2	13.7	-0.5
69	11.2	11.8	-0.6	12	15.7	-3.7
70	10.8	9.0	1.8	13.2	13.6	-0.4
71	10.4	8.3	2.1	12.8	12.9	-0.1
72	10.8	11.9	-1.1	12	12.8	-0.8
73	10.4	8.9	1.5	12.8	13.1	-0.3
74	9.6	11.7	-2.1	12.8	14.6	-1.8
75	10.8	9.8	1.0	13.6	14.3	-0.7
76	11.2	14.8	-3.6	12.8	13.1	-0.3
77	10.4	8.3	2.1	14	12.3	1.7
78	11.2	9.2	2.0	12.8	16.3	-3.5
79	11.6	8.5	3.1	12	13.8	-1.8
80	10.8	9.7	1.1	12.4	14.2	-1.8
81	11.6	9.7	1.9	12.8	14.6	-1.8
82	10.4	9.3	1.1	12.4	13.1	-0.7
83	11.6	12.5	-0.9	12.4	12.6	-0.2
84	12.8	9.2	3.6	12.8	15.4	-2.6
85	11.2	8.6	2.6	13.2	13.8	-0.6
86	11.2	9.0	2.2	12.4	14.1	-1.7
87	11.2	10.5	0.7	13.2	14	-0.8
88	12.4	13.0	-0.6	13.2	16.5	-3.3
89	11.6	8.4	3.2	12.4	14.8	-2.4
90	10.0	7.4	2.6	13.2	13.8	-0.6
91	10.4	8.0	2.4	14	11.3	2.7
92	11.6	8.0	3.6	12.8	13.9	-1.1
93	10.8	10.1	0.7	13.2	14.9	-1.7
94	11.2	10.0	1.2	13.2	11.4	1.8
95	11.2	10.1	1.1	12	14.2	-2.2
96	10.8	10.2	0.6	12.8	15.5	-2.7
97	12.4	8.7	3.7	12.4	13.4	-1
98	11.6	7.9	3.7	13.6	13.2	0.4
99	10.8	10.3	0.5	13.6	12.8	0.8
100	11.6	8.6	3.0	12.4	14.9	-2.5

APPENDIX 6.3

BASELINE EVACUATION RUNS FOR A SINGLE-EXIT CONFIGURATION

Run #	Evacuation Time in milliseconds	
	Walking	Crawling
1	9100	31000
2	7400	28500
3	8200	27800
4	8400	29100
5	8100	29300
6	8700	28600
7	8700	28700
8	9200	29800
9	7900	30500
10	7500	28900
11	8900	29400
12	7900	33200
13	7500	29300
14	8200	32300
15	8900	32900
16	8300	32600
17	8300	29900
18	9200	31900
19	8900	29000
20	7900	28000
21	8400	31000
22	7200	30200
23	7800	30000
24	8500	30000
25	8800	28200
26	8000	27500
27	7800	29500
28	7500	30400
29	8800	32700
30	7900	28200
31	7800	31300
32	8900	30300
33	7600	32800
34	8900	30200
35	7900	28700
36	7600	27900
37	8700	29600
38	8100	29500
39	8400	31300
40	7700	26800
41	7900	29300
42	8000	27400
43	8700	28200
44	8400	30700
45	9100	30500
46	8600	27200
47	8400	29400
48	9000	26600
49	7800	27900
50	8200	28500
51	7600	28500
52	8600	26400
53	8700	32000
54	7500	27200
55	8100	33600
56	8300	28100
57	8500	27500
58	7900	27700
59	8100	29400
60	8100	29100
61	7900	29800
62	8300	32300
63	9400	29600
64	7900	30500
65	8700	27700
66	8500	28500
67	8600	29700
68	7500	29800
69	8100	29000
70	8400	28900
71	7900	31700
72	8200	27400
73	7900	29000
74	7900	26600
75	8700	28600
76	9400	28500
77	9300	32900
78	7900	30700
79	8100	25700
80	8700	26200
81	7400	32200
82	7200	27800
83	9000	33000
84	8400	27300
85	8000	31400
86	8600	29500
87	8400	28100
88	8000	26700
89	8100	32200
90	8300	30000
91	9300	28500
92	7900	27600
93	7600	25600
94	9400	26300
95	8200	26500
96	8700	27900
97	9000	32300
98	8900	29100
99	8300	31800
100	8300	29600

$$\mu_{walking} = 8293$$

$$\sigma_{walking} = 533.6$$

$$\mu_{walking} + 3\sigma_{walking} = 9893.7$$

$$\mu_{crawling} = 29385$$

$$\sigma_{crawling} = 1904.4$$

$$\mu_{crawling} + 3\sigma_{crawling} = 35098.2$$

APPENDIX 6.4

EC RESULTS OF EDA, GGA, AND PSO FOR WALKING

Run	EDA			GGA			PSO		
	Function Evaluation	Fitness Value	Exit Location (0 - 39)	Function Evaluation	Fitness Value	Exit Location (0 - 39)	Function Evaluation	Fitness Value	Exit Locations (0 - 39)
1	1353	16914	(3,30)	2496	16914	(3,19,28)	2200	22897	(18,23,30)
2	2337	15324	(14,18)	2574	13260	(11,19)	2200	**17409.1**	**(10,17,21)**
3	2460	15374	(13,19)	2340	9849	(15,16)	2500	27776.9	(1,10,15,20)
4	2460	15314	(13,18)	2418	16557	(15,18)	2000	36271.5	(16,17,27,28,33)
5	2091	15354	(16,17)	2574	13399	(14, 18)	1700	42215.8	(1,7,10,22,23)
6	2214	15323	(16,17)	2418	17155	(4,15,21)	2300	38808	(6,16,29,35)
7	1845	9712	(14,17)	2184	18968	(17,30)	2100	35444.8	(2,12,16,39)
8	1968	16827	(16,17)	2574	**8248**	**(13,19)**	2400	35157.3	(1,6,7,21,28)
9	2583	15343	(14,17)	2262	15320	(15,18)	1200	46440.8	(0,4,6,8,10,14)
10	2460	17451	(14,17)	2106	20046	(5,17)	2200	44936.4	(1,14,24,25,26,35)
11	2583	15379	(11,18)	2574	13599	(14,17)	2300	46029.3	(8,9,11,13,29,30)
12	2460	16562	(15,17)	2028	17531	(17,21)	2100	37266.5	(3,8,16,18,33)
13	1968	20255	(5,10)	2106	16580	(15,18)	2000	45403.2	(4,16,19,24,27,38)
14	1353	**8753**	**(13,19)**	2262	17406	(15,30)	1800	23189.6	(10,15,16)
15	2583	15400	(13,21)	1404	19071	(13,17,19)	2500	22832.3	(5,8,13)
16	1845	15392	(13,19)	1248	13525	(13,21)	2300	27068.3	(1,3,8,9)
17	1722	18490	(11,15)	2106	13620	(15,18)	2500	17818.7	(12,17,18)
18	1722	8802	(13,19)	2262	15000	(5,13)	2100	37734	(3,4,10,24)
19	2583	9184	(13,19)	1872	15376	(19,29)	1900	36535.9	(0,5,13,29)
20	2583	9849	(13,19)	2496	13656	(15,16)	1400	37341.6	(11,17,22,27,33)
21	2337	18575	(5,11)	2262	15335	(13,18)	2000	34665.7	(4,6,12,24,28)
22	1476	13313	(13,19)	936	15340	(15,16)	1600	36708.3	(8,10,20,22,24)
23	2583	16238	(5,13,28)	2496	15337	(2,29)	2300	22410.9	(5,15,27)
24	1107	13131	(13,21)	1794	15323	(13,19)	2300	45466.8	(6,7,17,26,36)
25	1968	15499	(11,19)	2418	13283	(14,18)	1300	50523.6	(3,6,12)
26	2091	18663	(15,18)	1638	17615	(14,17,30)	1800	36654.3	(3,29,37,39)
27	1353	16913	(11,19)	936	17926	(2,29)	1900	35985.7	(8,13,25,27,31)
28	2214	18903	(16,22)	2028	23123	(13,22,25)	1900	43244.1	(3,22,30,31,35)
29	2583	15257	(15,17)	2106	17668	(12,17,18)	1900	26023.1	(7,10,18,22)
30	1353	20072	(2,27)	1248	13160	(13,19)	900	53023.9	(5,13,14,16,17,38)
μ	2074.6	15252.1		2072.2	15639.7		1986.7	35442.8	
σ	467.8	3212.2		485.5	2947.9		397.2	9622.9	

EC RESULTS OF EDA, GGA, AND PSO FOR CRAWLING

Run	EDA			GGA			PSO		
	Function Evaluation	Fitness Value	Exit Locations (0 - 39)	Function Evaluation	Fitness Value	Exit Locations (0 - 39)	Function Evaluation	Fitness Value	Exit Locations (0 - 39)
1	1845	23979	(11,18)	2106	20194	(11,19)	1800	88702.2	(14,16,18,22)
2	2214	24955	(1,29)	1560	20978	(11,18)	2100	157439.8	(9,10,13,14,28,33)
3	1353	23628	(13,21)	2574	21758	(13,18)	800	147439.1	(3,16,22,27,35)
4	1722	21906	(2,31)	2496	22583	(14,21)	1200	89368.35	(9,26,39)
5	2583	21562	(2,29)	2184	23950	(14,18)	1000	161090.3	(20,25,27,28,29,35)
6	1353	21910	(3,28)	1950	19979	(14,18)	2200	56996.02	(2,9,13)
7	1230	21083	(3,28)	1560	22571	(11,21)	2400	255171.7	(4,6,8,11,17,19,25,26,38)
8	1599	19789	(13,19)	2184	23550	(15,22)	1200	121905	(1,8,9,11,30)
9	2337	21039	(2,30)	1638	**18765**	**(19,29)**	1300	220956.3	(0,4,7,12,15,18,26,32)
10	1722	20728	(3,13)	1950	19959	(3,29)	1300	115330.3	(6,7,15,25,38)
11	2460	**18310**	**(3,13)**	2574	20381	(3,30)	1400	122422.1	(3,10,11,29,38)
12	2583	24792	(15,17)	2574	22547	(10,17)	1100	181892.5	(3,4,9,19,27,30)
13	1722	21947	(3,29)	2184	19235	(13,29)	2000	113173.7	(5,12,13,34)
14	2583	18759	(3,13)	2418	19496	(3,19)	2500	153062.6	(7,15,19,25,26,30)
15	1599	21168	(4,28)	2184	20838	(13,18)	1800	186765	(5,6,10,15,19,21,22)
16	1845	19776	(13,29)	2574	23403	(15,18)	2500	187481.7	(3,7,15,24,25,33)
17	1599	20271	(13,19)	1950	29199	(15,21)	900	81313.64	(1,16,20)
18	2583	19231	(3,13)	1638	24241	(14,17)	1900	128457.2	(3,4,30,36,38)
19	2214	25583	(15,17)	2184	22244	(10,18)	1500	82126.51	(7,22,28,33)
20	2460	43467	(19,30)	2574	25604	(15,17)	2300	57459.17	(12,14,19)
21	2583	23780	(14,17)	2028	24854	(14,17)	1100	189783.9	(2,6,10,12,19,32,33)
22	2460	23812	(14,22)	2418	20560	(3,13)	2500	188662.7	(2,6,9,15,32,35)
23	1599	19314	(13,19)	2418	23889	(15,18)	2500	181302.4	(5,9,13,20,28,35)
24	1599	20901	(13,19)	1638	19833	(11,21)	2400	92469.21	(14,24,25,29)
25	1599	20728	(1,13)	2340	22278	(15,22)	2300	88358.79	(10,11,18,22)
26	1968	19877	(19,28)	2340	21614	(14,18)	2100	122185.7	(15,16,18,23,24)
27	1599	19133	(13,19)	2574	19774	(11,21)	2100	154812.5	(3,14,24,31,34,39)
28	2583	18589	(13,19)	2496	24175	(15,17)	2200	**54719.33**	**(12,17,21)**
29	2583	21982	(16,22)	2340	23065	(14,21)	1600	228525.3	(3,8,9,10,28,34,35,39)
30	2583	19211	(13,19)	2418	24358	(15,18)	1800	159528.5	(15,18,19,27,29,30)
μ	2025.4	22040.4		2202.2	22195.8		1793.3	138963.4	
σ	468.9	4526.8		335.1	2303.9		549.6	53256.9	

APPENDIX 6.5

BEST LOCATION PROBABILITIES OF EXIT LOCATIONS

Exit Location	Walking		
	EDA	GGA	PSO
0	0.00	0.00	0.07
1	0.00	0.00	0.17
2	0.03	0.07	0.03
3	0.03	0.03	0.20
4	0.00	0.03	0.13
5	0.10	0.07	0.13
6	0.00	0.00	0.20
7	0.00	0.00	0.13
8	0.00	0.00	0.23
9	0.00	0.00	0.07
10	0.03	0.00	0.27
11	0.17	0.03	0.07
12	0.00	0.03	0.13
13	0.37	0.27	0.17
14	0.13	0.13	0.10
15	0.13	0.30	0.10
16	0.13	0.10	0.23
17	0.27	0.23	0.20
18	0.13	0.27	0.13
19	0.30	0.23	0.03
20	0.00	0.00	0.10
21	0.07	0.10	0.07
22	0.03	0.03	0.17
23	0.00	0.00	0.07
24	0.00	0.00	0.20
25	0.00	0.03	0.07
26	0.00	0.00	0.07
27	0.03	0.00	0.17
28	0.03	0.03	0.10
29	0.00	0.10	0.13
30	0.03	0.10	0.10
31	0.00	0.00	0.07
32	0.00	0.00	0.00
33	0.00	0.00	0.10
34	0.00	0.00	0.00
35	0.00	0.00	0.10
36	0.00	0.00	0.03
37	0.00	0.00	0.07
38	0.00	0.00	0.07
39	0.00	0.00	0.07
Max	**0.37**	**0.30**	**0.27**

Exit Location	Crawling		
	EDA	GGA	PSO
0	0.00	0.00	0.03
1	0.07	0.00	0.07
2	0.10	0.00	0.10
3	0.23	0.13	0.23
4	0.03	0.00	0.13
5	0.00	0.00	0.10
6	0.00	0.00	0.17
7	0.00	0.00	0.17
8	0.00	0.00	0.10
9	0.00	0.00	0.27
10	0.00	0.07	0.20
11	0.03	0.17	0.13
12	0.00	0.00	0.17
13	0.47	0.13	0.13
14	0.07	0.23	0.17
15	0.07	0.27	0.27
16	0.03	0.00	0.13
17	0.10	0.17	0.07
18	0.03	0.33	0.17
19	0.30	0.10	0.27
20	0.00	0.00	0.10
21	0.03	0.20	0.07
22	0.07	0.07	0.17
23	0.00	0.00	0.03
24	0.00	0.00	0.13
25	0.00	0.00	0.20
26	0.00	0.00	0.13
27	0.00	0.00	0.13
28	0.13	0.00	0.17
29	0.13	0.10	0.13
30	0.07	0.03	0.17
31	0.03	0.00	0.03
32	0.00	0.00	0.10
33	0.00	0.00	0.20
34	0.00	0.00	0.07
35	0.00	0.00	0.17
36	0.00	0.00	0.03
37	0.00	0.00	0.00
38	0.00	0.00	0.13
39	0.00	0.00	0.10
Max	**0.47**	**0.33**	**0.27**

APPENDIX 6.6

T-TEST COMARISONS OF MEAN FUNCTION EVALUATIONS AND FITNESS VALUES FOR WALKING

Two-Sample T-Test and CI: Fun. Eval. (W-EDA), Fun. Eval. (W-GGA)

```
Two-sample T for Fun. Eval. (W-EDA) vs Fun. Eval. (W-GGA)

                                              SE
                    N     Mean  StDev         Mean
Fun. Eval. (W-EDA)  30    2075  468           85
Fun. Eval. (W-GGA)  30    2072  485           89


Difference = mu (Fun. Eval. (W-EDA)) - mu (Fun. Eval. (W-GGA))
Estimate for difference:  2
95% CI for difference:  (-244, 249)
T-Test of difference = 0 (vs not =): T-Value = 0.02  P-Value = 0.985  DF = 58
Both use Pooled StDev = 476.7106
```

Two-Sample T-Test and CI: Fun. Eval. (W-EDA), Fun. Eval. (W-PSO)

```
Two-sample T for Fun. Eval. (W-EDA) vs Fun. Eval. (W-PSO)

                                              SE
                    N  Mean       StDev       Mean
Fun. Eval. (W-EDA)  30  2075      468         85
Fun. Eval. (W-PSO)  30  1987      397         73


Difference = mu (Fun. Eval. (W-EDA)) - mu (Fun. Eval. (W-PSO))
Estimate for difference:  88
95% CI for difference:  (-136, 312)
T-Test of difference = 0 (vs not =): T-Value = 0.78  P-Value = 0.436  DF = 58
Both use Pooled StDev = 433.9231
```

Two-Sample T-Test and CI: Fun. Eval. (W-GGA), Fun. Eval. (W-PSO)

```
Two-sample T for Fun. Eval. (W-GGA) vs Fun. Eval. (W-PSO)
```

```
                                   SE
                    N     Mean  StDev  Mean
Fun. Eval. (W-GGA)  30    2072  485    89
Fun. Eval. (W-PSO)  30    1987  397    73


Difference = mu (Fun. Eval. (W-GGA)) - mu (Fun. Eval. (W-PSO))
Estimate for difference:  86
95% CI for difference:  (-144, 315)
T-Test of difference = 0 (vs not =): T-Value = 0.75  P-Value = 0.458  DF = 58
Both use Pooled StDev = 443.5210
```

Two-Sample T-Test and CI: Fit. Val. (W-EDA), Fit. Val. (W-GGA)

```
Two-sample T for Fit. Val. (W-EDA) vs Fit. Val. (W-GGA)

                    N   Mean    StDev        SE Mean
Fit. Val. (W-EDA)   30  15252   3212         586
Fit. Val. (W-GGA)   30  15640   2948         538


Difference = mu (Fit. Val. (W-EDA)) - mu (Fit. Val. (W-GGA))
Estimate for difference:  -388
95% CI for difference:  (-1981, 1206)
T-Test of difference = 0 (vs not =): T-Value = -0.49  P-Value = 0.628  DF = 58
Both use Pooled StDev = 3082.8921
```

Two-Sample T-Test and CI: Fit. Val. (W-EDA), Fit. Val. (W-PSO)

```
Two-sample T for Fit. Val. (W-EDA) vs Fit. Val. (W-PSO)

                    N   Mean    StDev        SE Mean
Fit. Val. (W-EDA)   30  15252   3212         586
Fit. Val. (W-PSO)   30  35443   9623         1757


Difference = mu (Fit. Val. (W-EDA)) - mu (Fit. Val. (W-PSO))
Estimate for difference:  -20191
95% CI for difference:  (-23951, -16431)
T-Test of difference = 0 (vs not =): T-Value = -10.90  P-Value = 0.000  DF = 35
```

Two-Sample T-Test and CI: Fit. Val. (W-GGA), Fit. Val. (W-PSO)

```
Two-sample T for Fit. Val. (W-GGA) vs Fit. Val. (W-PSO)
```

```
                     N   Mean       StDev           SE Mean
Fit. Val. (W-GGA)    30  15640      2948            538
Fit. Val. (W-PSO)    30  35443      9623            1757


Difference = mu (Fit. Val. (W-GGA)) - mu (Fit. Val. (W-PSO))
Estimate for difference:  -19803
95% CI for difference:  (-23537, -16069)
T-Test of difference = 0 (vs not =): T-Value = -10.78  P-Value = 0.000  DF = 34
```

APPENDIX 6.7

T-TEST COMARISONS OF MEAN FUNCTION EVALUATIONS AND FITNESS VALUES FOR CRAWLING

Two-Sample T-Test and CI: Fun. Eval. (C-EDA), Fun. Eval. (C-GGA)

```
Two-sample T for Fun. Eval. (C-EDA) vs Fun. Eval. (C-GGA)

                                                    SE
                      N     Mean  StDev           Mean
Fun. Eval. (C-EDA)  30     2025   469             86
Fun. Eval. (C-GGA)  30     2202   335             61

Difference = mu (Fun. Eval. (C-EDA)) - mu (Fun. Eval. (C-GGA))
Estimate for difference:  -177
95% CI for difference:  (-388, 34)
T-Test of difference = 0 (vs not =): T-Value = -1.68  P-Value = 0.099  DF = 52
```

Two-Sample T-Test and CI: Fun. Eval. (C-EDA), Fun. Eval. (C-PSO)

```
Two-sample T for Fun. Eval. (C-EDA) vs Fun. Eval. (C-PSO)

                      N     Mean  StDev           SE Mean
Fun. Eval. (C-EDA)  30     2025   469             86
Fun. Eval. (C-PSO)  30     1793   550             100


Difference = mu (Fun. Eval. (C-EDA)) - mu (Fun. Eval. (C-PSO))
Estimate for difference:  232
95% CI for difference:  (-32, 496)
T-Test of difference = 0 (vs not =): T-Value = 1.76  P-Value = 0.084  DF = 58
Both use Pooled StDev = 510.8316
```

Two-Sample T-Test and CI: Fun. Eval. (C-GGA), Fun. Eval. (C-PSO)

```
Two-sample T for Fun. Eval. (C-GGA) vs Fun. Eval. (C-PSO)

                      N     Mean  StDev           SE Mean
```

```
Fun. Eval. (C-GGA)  30    2202   335           61
Fun. Eval. (C-PSO)  30    1793   550           100


Difference = mu (Fun. Eval. (C-GGA)) - mu (Fun. Eval. (C-PSO))
Estimate for difference:  409
95% CI for difference:  (172, 645)
T-Test of difference = 0 (vs not =): T-Value = 3.48  P-Value = 0.001  DF = 47
```

Two-Sample T-Test and CI: Fit. Val. (C-EDA), Fit. Val. (C-GGA)

```
Two-sample T for Fit. Val. (C-EDA) vs Fit. Val. (C-GGA

                    N     Mean      StDev     SE Mean
Fit. Val. (C-EDA)   30    22040     4527      826
Fit. Val. (C-GGA    30    22196     2304      421


Difference = mu (Fit. Val. (C-EDA)) - mu (Fit. Val. (C-GGA)
Estimate for difference:  -155
95% CI for difference:  (-2026, 1715)
T-Test of difference = 0 (vs not =): T-Value = -0.17  P-Value = 0.868  DF = 43
```

Two-Sample T-Test and CI: Fit. Val. (C-EDA), Fit. Val. (C-PSO)

```
Two-sample T for Fit. Val. (C-EDA) vs Fit. Val. (C-PSO)

                    N     Mean      StDev     SE Mean
Fit. Val. (C-EDA)   30    22040     4527      826
Fit. Val. (C-PSO)   30    138963    53257     9723


Difference = mu (Fit. Val. (C-EDA)) - mu (Fit. Val. (C-PSO))
Estimate for difference:  -116923
95% CI for difference:  (-136881, -96965)
T-Test of difference = 0 (vs not =): T-Value = -11.98  P-Value = 0.000  DF = 29
```

Two-Sample T-Test and CI: Fit. Val. (C-GGA), Fit. Val. (C-PSO)

```
Two-sample T for Fit. Val. (C-GGA vs Fit. Val. (C-PSO)

                    N     Mean      StDev     SE Mean
```

```
Fit. Val. (C-GGA      30      22196          2304           421
Fit. Val. (C-PSO)     30      138963         53257          9723


Difference = mu (Fit. Val. (C-GGA) - mu (Fit. Val. (C-PSO))
Estimate for difference:  -116768
95% CI for difference:  (-136673, -96863)
T-Test of difference = 0 (vs not =): T-Value = -12.00  P-Value = 0.000  DF = 29
```

APPENDIX 6.8

T-TEST COMARISONS OF MEAN TOTAL EVACUATION TIME AND NUMBER OF CASUALTIES FOR WALKING SIMULATION RUNS

Two-Sample T-Test and CI: Evac. Time_1, Evac. Time_2

```
Two-sample T for Evac. Time_1 vs Evac. Time_2

                                                SE
                N      Mean        StDev        Mean
Evac. Time_1    1000   7767        562          18
Evac. Time_2    1000   6684        505          16


Difference = mu (Evac. Time_1) - mu (Evac. Time_2)
Estimate for difference:  1084.0
95% CI for difference:  (1037.1, 1130.9)
T-Test of difference = 0 (vs not =): T-Value = 45.34  P-Value = 0.000  DF = 1973
```

Two-Sample T-Test and CI: Casualties_1, Casualties_2

```
Two-sample T for Casualties_1 vs Casualties_2

               N     Mean        StDev       SE Mean
Casualties_1   1000  0.222       0.457       0.014
Casualties_2  1000   0.471       0.618       0.020


Difference = mu (Casualties_1) - mu (Casualties_2)
Estimate for difference:  -0.2488
95% CI for difference:  (-0.2965, -0.2011)
T-Test of difference = 0 (vs not =): T-Value = -10.23  P-Value = 0.000  DF = 1841
```

APPENDIX 6.9

T-TEST COMARISONS OF MEAN TOTAL EVACUATION TIME AND NUMBER OF CASUALTIES FOR CRAWLING SIMULATION RUNS

Two-Sample T-Test and CI: Evac. Time_3, Evac. Time_4

```
Two-sample T for Evac. Time_3 vs Evac. Time_4

                                                SE
                 N     Mean       StDev         Mean
Evac. Time_3     1000  17691      1219          39
Evac. Time_4     1000  17760      1288          41


Difference = mu (Evac. Time_3) - mu (Evac. Time_4)
Estimate for difference:  -68.7
95% CI for difference:  (-178.7, 41.3)
T-Test of difference = 0 (vs not =): T-Value = -1.22  P-Value = 0.221  DF = 1998
Both use Pooled StDev = 1254.3708
```

Two-Sample T-Test and CI: Evac. Time_3, Evac. Time_5

```
Two-sample T for Evac. Time_3 vs Evac. Time_5

                                                SE
                 N     Mean       StDev         Mean
Evac. Time_3     1000  17691      1219          39
Evac. Time_5     1000  18878      1779          56


Difference = mu (Evac. Time_3) - mu (Evac. Time_5)
Estimate for difference:  -1186.7
95% CI for difference:  (-1320.5, -1052.9)
T-Test of difference = 0 (vs not =): T-Value = -17.40  P-Value = 0.000  DF = 1768
```

Two-Sample T-Test and CI: Evac. Time_4, Evac. Time_5

```
Two-sample T for Evac. Time_4 vs Evac. Time_5
```

```
                                                  SE
                   N      Mean          StDev     Mean
Evac. Time_4       1000   17760         1288      41
Evac. Time_5       1000   18878         1779      56


Difference = mu (Evac. Time_4) - mu (Evac. Time_5)
Estimate for difference:  -1118.0
95% CI for difference:  (-1254.2, -981.8)
T-Test of difference = 0 (vs not =): T-Value = -16.10  P-Value = 0.000  DF = 1820
```

Two-Sample T-Test and CI: Casualties_3, Casualties_4

```
Two-sample T for Casualties_3 vs Casualties_4

                   N      Mean          StDev     SE Mean
Casualties_3       1000   0.314         0.538     0.017
Casualties_4       1000   0.336         0.584     0.018


Difference = mu (Casualties_3) - mu (Casualties_4)
Estimate for difference:  -0.0220
95% CI for difference:  (-0.0713, 0.0273)
T-Test of difference = 0 (vs not =): T-Value = -0.88  P-Value = 0.381  DF = 1984
```

Two-Sample T-Test and CI: Casualties_3, Casualties_5

```
Two-sample T for Casualties_3 vs Casualties_5

                   N      Mean          StDev     SE Mean
Casualties_3       1000   0.314         0.538     0.017
Casualties_5       1000   0.105         0.310     0.0098


Difference = mu (Casualties_3) - mu (Casualties_5)
Estimate for difference:  0.2090
95% CI for difference:  (0.1705, 0.2475)
T-Test of difference = 0 (vs not =): T-Value = 10.64  P-Value = 0.000  DF = 1595
```

Two-Sample T-Test and CI: Casualties_4, Casualties_5

```
Two-sample T for Casualties_4 vs Casualties_5
```

```
              N     Mean        StDev       SE Mean
Casualties_4  1000  0.336       0.584       0.018
Casualties_5  1000  0.105       0.310       0.0098


Difference = mu (Casualties_4) - mu (Casualties_5)
Estimate for difference:  0.2310
95% CI for difference:  (0.1900, 0.2720)
T-Test of difference = 0 (vs not =): T-Value = 11.04  P-Value = 0.000  DF = 1519
```