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# RETRACTED: Evacuation Simulation Focusing on Modeling of Disabled People Movement

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**Abstract:** All building users should have the right to safe evacuation. However, evacuation becomes a big challenge when it concerns people with disabilities. Nowadays, computer programs are used to plan escape routes. Therefore, the manuscript deals with the issues of modeling evacuation with particular emphasis on people with disabilities. A review of different evacuation modeling software is presented. The research is performed mainly to see what the limitations of different programs are and how they regard occupants with disabilities. The analyses contain a study of six cases of the evacuation from a building. In this study the three following programs—SIMULEX, STEPS and Pathfinder—are considered. Different populations of people with mobility impairments are modeled. The comparison of the methodology when using these three programs is presented in the following sections. Research has shown that despite the same input data, the results obtained with the three programs differ significantly. In the case of the total evacuation time, the differences reach up to 8%.

**Keywords:** evacuation; simulation; disabled occupants; evacuation modelling; egress models



**Citation:** Żydek, K.; Król, M.; Król, A. RETRACTED: Evacuation Simulation Focusing on Modeling of Disabled People Movement. *Sustainability* **2021**, *13*, 2405. https://doi.org/10.3390/su13042405

Academic Editor: Gabriele Bernardini

Received: 25 January 2021
Accepted: 20 February 2021
Published: 23 February 2021
Retracted: 15 July 2021



## 1. Introduction

The most crucial aspect of building safety in case of a fire is the possibility of safe escape. It must be provided for all occupants and is included in law regulations. Safe evacuation depends on the conditions of the escape routes. Therefore, the time of evacuation is important for the proper design of the system ensuring good conditions at every section of the evacuation route. Currently, since real evacuation experiments are inconvenient to carry out, computer programs are used to determine the time of the evacuation of people from the building.

In case of fire in the building, safe evacuation conditions must be provided for each occupant, regardless of their physical and mental characteristics. Since nowadays disabled people naturally participate in the common life, their likely presence in a building makes it necessary to anticipate the evacuation of disabled people from buildings. It is obvious that the evacuation of people with disabilities will last longer. This time will depend on the degree of disability. For a realistic estimation of the evacuation time it is all the more important to take such people into account. Therefore, there is a need to include disabled people in commonly used evacuation programs.

The study of building evacuation has been continued since the start of the 20th century. Several important studies of movement in corridors, through doorways and on stairs are described in the literature by Fruin [1], Predtechenskii and Milinski [2] and Kobes [3]. Research on movement characteristics in a staircase was conducted by Fang et al. in 2012 [4]. In that research, the authors indicate that the downward velocity is determined mainly by visibility in the staircase, occupants' strength and the merging behavior entering the staircase.



This paper has been retracted. A retraction notice was published on 15 July 2021 in *Sustainability* **2021**, *13*, 7912. https://doi.org/10.3390/su13147912

The National Institute of Standards and Technology (NIST) has been collecting data from fire drill evacuations [5]. These data can be considered for developing new standards and used in evacuation modeling. Peacock et al. [6] have reviewed movement speeds from building evacuation drills and presented new data to ensure a better understanding of fire evacuations and the influence of human behavior on movement speeds and the total evacuation time.

A factor that has a major influence on the total evacuation time is the delay in actions taken by people. These actions can be, for instance, notifying others, collecting belongings, helping others, getting dressed, etc. In 2009 Zhao et al. presented results from a survey that was carried out to investigate the pre-evacuation behavior in a multi-storey office building [7]. Delay times and travel speeds derived from actual fires and evacuation exercises are reported in the literature and collected in a brief database by Fahy and Proulx [8].

In literature, there is research on human behavior commenced by Bryan in 1956 [9] and followed by many researchers—Woods [10], Sime [11] and Bryan [12]. Researchers consider different aspects of human behavior and its influence on fire evacuation. For instance, in her studies Fahy has described the aspects of panic and its proper interpretation [13].

A selected historical review of the occupants' behavior during a fire is presented by Bryan [14]. There are many studies on evacuation from different types of buildings. Nilsson and Johansson presented an analysis of the evacuation in a cinema theatre [15]. Likewise, they focus on mutual social influence in human behavior. Proulx [16] in 1995 presented the results of evacuation time and occupant movement in apartment buildings. The experiment contained an analysis of four buildings which had an average population of 150 occupants, including children, adults and people with disabilities.

The development of research in this field allowed to assume that human behavior during a fire is an important factor in terms of survival. A review of crowd behavior and motion experiments is described by Haghani and Sarvi [17]. In one of her articles, Kobes indicated the critical factors which determine occupants' response, and presented a review of human behavior in buildings during fire [3]. In many studies, it is also concluded that people move to familiar places or people. In general, during evacuation people select routes or exits they know even if the distance to the exit is greater. This assumption was described by Sime in 1983 and can be found in many current studies [18]. Kinateder et al. [19] have described the influence of neighbors' behavior and exit familiarity.

In 2012 Heliovaara [20] presented the results of the analysis of human behavior in a corridor and exit selection. In this research, the authors identify the manner of pedestrian behavior—cooperative and egoistic, and how it affects the egress outcome.

Except for human behavior analysis, previous fire incidents provide information about people's movements and actions as well.

The data on the average pre-evacuation time and walking speed, including results of disabled occupants, derived from fire investigation and evacuation drill are reported by Shi et al. [21]. The latest database including pre-evacuation times collected from case studies of incidents and evacuation drills was provided by Gwynne and Boyce in 2016 [22] and its expanded version by Lovreglio et al. [23] in 2019.

Many factors, including the characteristics of the occupants and physical ability, have a major impact on the movement speed. Tancogne and Laclemence have done research about fire risk perception and evacuation by vulnerable people [24]. Through this research, the understanding of the building evacuation process has been improved.

Karen Boyce [25] signalized that it is very important to understand the capabilities of the evacuation of people with disabilities, and the necessity of performance-based design to provide a safe indoor environment for all occupants.

The walking speeds of adults with disabilities and the impact of disabled occupants on the building evacuation have been described in several studies. Sharifi et al. [26] described walking speeds in different indoor environments.

To ensure safe evacuation for people with disabilities some of the following solutions are used.

Kuligowski et al. [27] described the average speeds of older occupants and occupants with mobility impairments who need assistance during an evacuation. In this research, we can find information about the local speed of an occupant assisted by others, using an evacuation chair, and older adults during evacuation on stairways.

In large buildings and when the geometry is complicated, there is a necessity of using alternative solutions that provide safe evacuation for all occupants, including people with disabilities. In some countries, the fire codes define the necessity of using refuge areas, especially in high-rise buildings. In his paper, Chow [28] has described regulations for using refuge areas and floors in buildings. In other research, there is a description of emergency lift use for the evacuation of people, including people with disabilities. Koo et al. [29], Bukowski et al. [30]. Chen et al. [31] indicate that lifts can be used to assist ultra high-rise building evacuation, however, only lifts with special requirements can be used.

The presented manuscript provides an overview of research on evacuation modeling, paying particular attention to the evacuation of disabled people. In the literature, we can find studies that show the comparison between results from simulations and egress drill data [32], standards [33], or various egress models [34,35]. In general, these studies contain complex building geometry including several floors and staircases. This research aims to provide information from a simple model with simple geometry, setting equal input parameters, and show the differences in results from different software. The analysis of these simple cases can lead to the conclusion that even in simplistic models the differences can be noticeable. In this paper, three of the most popular programs are selected and used for the analysis—STEPS, SIMULEX and Pathfinder. Six cases were examined, differing in the number of disabled people, the number of people in general and their distribution in the model. The results show the total evacuation time and the number of people who completed evacuation at a particular time. The results from these simple cases performed using three programs are compared to each other to show that the selection of the simulation tool can affect the results. The differences in results from STEPS, SIMULEX and Pathfinder differ depending on the analyzed case and reach maximum values up to 8% for total evacuation time and about 9% for the second parameter.

The manuscript is organized as follows. The state of knowledge on modeling the evacuation of disabled people is presented. The method of calculating the evacuation time is presented. Section 4 describes the programs that were used for the analyses. The analyzed cases are described in detail in the next section. In the section after, the results are presented and analyzed. The manuscript is completed with the conclusions.

## 2. Evacuation Modeling—State of Art

Experiments involving humans and evacuation drills usually are complicated and difficult to perform. For this reason, computer evacuation modeling software is used. Evacuation models enable users to analyze many different scenarios, including the more complex ones. The analysis must be prepared based on data collected in the past. The data available in the literature can be used as input parameters for evacuation models or a model validation process.

A review of methodologies used in evacuation modeling and available computer evacuation models is provided by Gwynne et al. [36]. This research has been continued and complimented in the following years by Kuligowski in her first and second evacuation models review [37,38]. Many studies about evacuation models, evacuation simulation and model validation can be found in the literature. The validation procedure described by Lovreglio et al. [39]. In 2006 Lo et al. indicated that most of the models have focused on modeling the flow of evacuees [40]. In that study, they have focused on one aspect of people's behavior—the choice of exit. They proposed an exit selection model based on a game theory.

In general, human behavior can be simulated in evacuation models by using distributions and probabilistic variables. Pre-evacuation behavior has the main impact on the total evacuation time. In computational models, there are different approaches to simulate the pre-evacuation behavior and decision-making process. Among them is a model introduced by Lovreglio et al. [41], which can be implemented in any existing software.

There are two main methods to simulate occupant behavior, which was described by Kuligowski [42]. In the work, she indicates that evacuation models do not simulate occupants' behavior but only represent some types of activities and their duration.

A comparison between measured and predicted evacuation time is provided by Olsson and Regan [32]. In their study, the Simulex model was used. In other research, one can find information about effective tools used to analyze evacuation in complex buildings. For instance, Oven et al. [43] described the possibility of using EXODUS to model evacuation in a high-rise building.

It is important to remember that the results derived from models always have some uncertainties, among others due to the stochastic nature of human behavior. The issue of a proper interpretation of the results derived from models has been widely described by Ronchi et al. [44].

In 2013 Kuligowski indicated that there is a lack of data on human behavior during evacuation and the uncertainties can be caused by simplifications and assumptions [45].

To provide safe evacuation for all occupants, it is important to include people with disabilities in a model. This option is not always available. In some models, there is only the possibility to vary occupants by their movement speeds. Some models provide the possibility to set some criteria or model movement with special equipment such as wheelchairs, canes, or walkers, while other models enable to model occupants behavior, for instance, helping people with mobility impairments to reach the exit or in a staircase. Christensen et al. [46] indicated that many evacuation models do not address residents with disabilities appropriately. In 2018 Christensen presented an agent-based simulation model called BUMMPEE. This model addresses various criteria for the heterogeneous population such as individual speed, size, perception, assistance, ability to negotiate terrain and psychological profile [47]. However, this model is not fully tested for a large scale, it was validated only in a small office complex [29,48,49]. An extended version of the BUMMPEE model for a large-scale simulation was presented by Manley et al. in 2011 [50]. This model was tested for evacuation at an airport. To consider new strategies for evacuation Manley and Kim [51] presented the model called Exitus, which demonstrates the strategy of assisted evacuation for people with disabilities and elevator use. This shows that there are better solutions than a strategy to wait for assistance at the designed refuge areas.

## 3. Main Assumptions of Evacuation Modeling

Nowadays, to analyze the level of life safety in buildings, computer modeling software is used. Computer models allow achieving a more realistic and efficient solution compared to hand calculations. Evacuation models are used to calculate the time that is required for occupants to safely evacuate from a building. The required safe egress time (RSET) is the time needed for all occupants to leave the dangerous zone. RSET is the sum of the detection time, the alarm time and the evacuation time. Evacuation time is a sum of the pre-evacuation time and the movement time. In general, RSET can be calculated as [52]:

$$RSET = t_d + t_a + t_{pre\text{-}evac} + t_{mov} \tag{1}$$

where:

$t_d$—detection time,
$t_a$—alarm time,
$t_{pre\text{-}evac}$—pre-evacuation time, a sum of recognition time $t_{rec}$ and response time $t_{res}$,
$t_{mov}$—movement time.

The conditions of safe evacuation are provided when the available safe egress time (ASET) is greater than RSET. It means that the time required to safely evacuate from a dangerous zone cannot be greater than the time of deteriorating the conditions under the critical values. This relationship is shown in Figure 1.

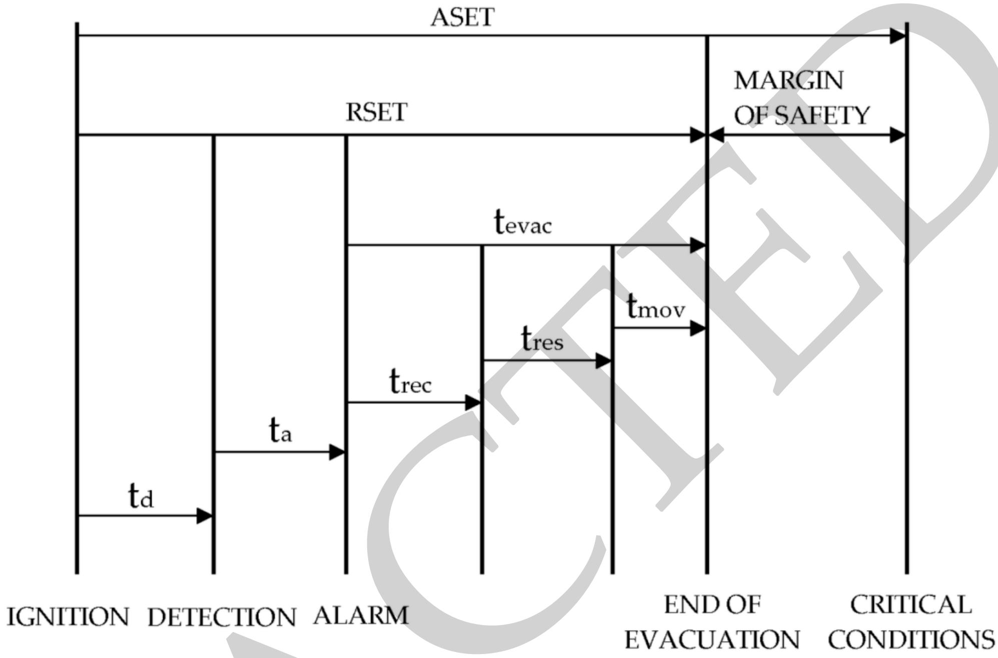



**Figure 1.** Components of required safe egress time [52].

Due to different human reactions, especially in stressful situations, and a lack of collected data, evacuation modeling requires making some assumptions that can affect the total evacuation time. In some models, the representation of human behavior may be difficult, due to specific model characteristics and limited options. In general, it is assumed that in low-density evacuations, the total evacuation time depends on pre-evacuation time, and in high-density evacuations, the total evacuation time depends mainly on movement time [53].

## 4. A Brief Review of Selected Evacuation Models

There is a multiplicity of evacuation models that are used in Fire Safety Engineering. These models have various characteristics and can be used for different purposes, from very simple to complex analysis. In reviews provided by Gwynne et al. [36] and Kuligowski et al. [37,38] various available models comparison can be found. Models are divided into several groups depending on different parameters. The categories include, among others, model availability, used modeling methodology, methods for simulating movement and behaviors, if the model cooperates with other software, for instance, CAD or FDS, or how the model is validated.

To model building evacuations users can choose software from about 26 computer programs available on the market [38]. Some of them are available on a consultancy basis for instance EGRESS or ALLSAFE and some models are available to the public such as STEPS, EVACNET, Simulex, PEDFLOW, EXODUS, Pathfinder, WAYOUT, PEDROUTE, SimWalk, Legion or MassMotion. In this study, according to the criteria described by Kuligowski and Gwynne [54] and Castle and Paul [55] three popularly used programs are chosen. The main criteria for the selection of SIMULEX, STEPS and Pathfinder are the availability and popularity of these models.

### 4.1. SIMULEX

Simulex is a part of the Virtual Environment Application software and enables to define occupants in a building and simulate the escape movement of people from large, complex buildings. Originally, Simulex was developed as a part of Peter Thompson's PhD thesis [56] and it has been improved since then. Simulex allows creating 3D models of buildings, including floors and staircases. It also allows importing building geometry from CAD files. In this program, the travel distance is calculated automatically. The movement algorithms are based on data collected by observing real evacuations and people's movement in a building. Occupants move towards pre-defined exits with individual walking speeds [57]. The walking velocity for a person depends on individual characteristics and the proximity of other occupants. One person in front of another will reduce the velocity, as shown in Figure 2. Interpersonal distance represents the distance between the centre of two people's bodies.

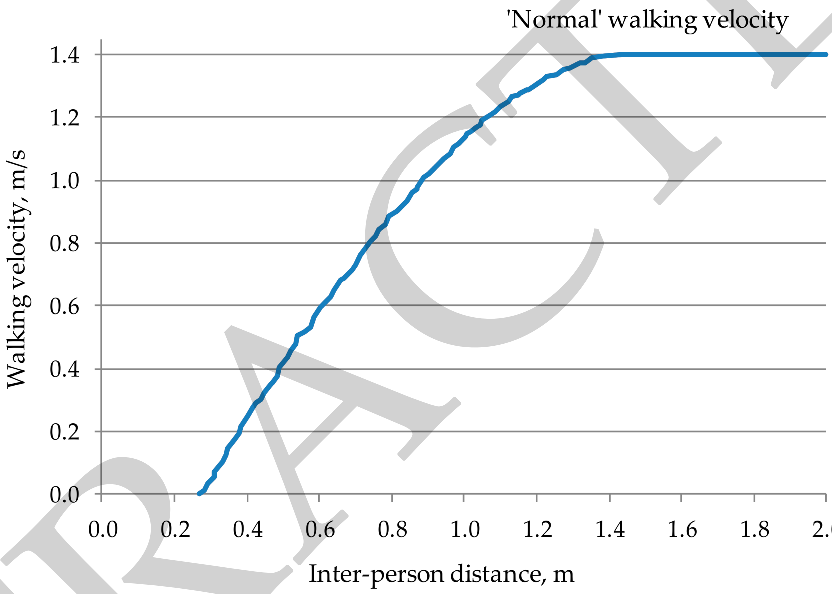



**Figure 2.** The relationship between walking velocity and interpersonal distance [57].

The normal unimpeded walking velocity for each person is randomly chosen in the interval between 0.8–1.7 m/s. The velocity on stairs is reduced compared to the velocity for horizontal surfaces. The velocity of descending a staircase is 0.5 times the horizontal velocity and the velocity of ascending a staircase is 0.35 times the horizontal velocity [57].

The characteristics of the occupants must be defined. The occupants can be added as a group or separately. When a group of people is added, the occupant type governs the distribution of body sizes. The distribution of different body types for different groups is shown in Table 1.

**Table 1.** Distribution of body types for different occupant groups [57].

| Occupant Type | Average, % | Male, % | Female, % | Child, % |
|---|---|---|---|---|
| Office Staff | 30 | 40 | 30 | 0 |
| Commuters | 30 | 30 | 30 | 10 |
| Shoppers | 30 | 20 | 30 | 20 |
| School Children | 10 | 10 | 10 | 70 |
| Elderly | 50 | 20 | 30 | 0 |
| All Male | 100 | 0 | 0 | 0 |
| All Female | 0 | 0 | 100 | 0 |
| All Children | 0 | 0 | 0 | 100 |

Simulating characteristics of a population, the response time of each person or a group can be defined using one of three distributions: random, triangular or normal distribution and the mean response time and the limits can be specified.

Each person is represented mathematically as three circles. Simulex contains 4 different body types, containing the dimensions given in Table 2.

**Table 2.** Body dimensions for the body type in Simulex [57].

| Body Type | Radius Torso Circle | Radius Shoulder Circle | Offset of the Centre of the Shoulder from the Centre of the Body |
|---|---|---|---|
| Average | 0.25 | 0.15 | 0.10 |
| Male | 0.27 | 0.17 | 0.11 |
| Female | 0.24 | 0.14 | 0.09 |
| Child | 0.21 | 0.12 | 0.07 |

Simulex allows for defining population groups with combinations of features like walking speed, body size, or time to respond to an alarm. All these aspects can be changed to model any type of occupants, with different disabilities as well.

Simulex makes several assumptions which concern methods of individual movement and geometry of escape. Each person heads towards an exit by taking a direction that is at right angles to the contours shown on the chosen distance map. Each person is assigned a normal, unimpeded walking speed and the walking speeds are reduced as people get closer together [57].

The crowd areas can occur as a result of the behavior because people slow down and stop when they reach a congested area. To prevent a model from crowds of people, the authors use an algorithm which demands to decide to rotate an individual's body and shuffle sideways through the narrow space available [57].

Simulex uses a fine network approach. The network plan of the building can be easily produced by importing drawings from CAD programs. This approach usually consumes a considerable amount of computation time. However, the fine network approach can represent the geometry precisely. Generally, the more complex the building, the longer it takes to compute.

The main problem observed during the simulation is when two or more occupants try to walk through a narrow space like a door.

### *4.2. STEPS*

STEPS is a software tool for simulating pedestrian dynamics under normal and emergency conditions. This program allows simulating pedestrian movement and behavior in different buildings, including very large populations and complex building geometry. It is a movement and partial behavior model, which is capable of evaluating any building type. Enclosure and occupant are represented using an individual perspective [58]. In evacuation mode, the algorithm defines that people look for exits and their priority is to leave the building as quickly as possible. In normal conditions, it is possible to model complex routes, additional movement and use of lifts or vehicles. It is an agent-based model with a fine network geometry. The grid is made of squares. One person occupies one cell at any given time and moves if the next cell is empty [59]. People can move from cell to cell using eight different directions and choose those which allow moving to the target. In this program, the user can define various parameters to represent people. Individuals have unique characteristics defined by size, walking speed, patience, pre-movement delay, awareness, route choice and environment familiarity. The patience factor allows modifying occupant's perception of queues at targets. Occupants can make an initial decision to select an exit and change it if the conditions change, for instance, when the exit is closed or there is a queue. The delay before people start moving can be expressed directly in seconds or through distribution. The distribution can be chosen from uniform, normal, lognormal, probability density, or cumulative probability distribution. STEPS contains a large library of people models, including individuals with reduced mobility. In version 5.4 there are several 3D models of individuals, among others schematic, a person, a person in a wheelchair, a person with a walking stick, or a person with a trolley [60]. It allows diversifying the population in the simulation. Each type of person can have different walking speeds. All walking speeds can be expressed directly in meters per second as the maximum walking speed or can be derived from distributions. The input value can be specified by the user in four ways: fixed, speed distance curve, speed density curve, or speed/smoke. The walking speed in each way depends on a different factor. STEPS provides more flexibility than a traditional cell-based model. Building geometry can be imported from CAD files and STEPS can tessellate irregular-shaped building geometries including curved surfaces and allows different cell sizes in different sections of the model [61]. STEPS was validated by comparing results with codes, standards and both full-scale tests and real-life observations [62]. It is a well-known evacuation model and its basis has been frequently described in many other studies, therefore it is not described in this paper. For instance, Hoffmann and Henson [63] have described the usage of STEPS for simulating evacuation in stations. In another paper, they have also described the usage of this model to analyze evacuation from the train in a tunnel [33]. STEPS was used to model evacuation in the International Centre for Life in Newcastle which was described by Rhodes and Hoffmann [64] and Wall and Waterson [65] compared results from STEPS with the NFPA standards.

### 4.3. Pathfinder

Pathfinder is a software developed by Thunderhead Engineering. It is a continuous, partial behavioral model with a microscopic refinement of the population [66]. Pathfinder is an agent-based evacuation model that enables the analysis of various buildings, with large and complex geometry as well. In this model, the building's geometry can be imported from CAD files, like in the previously described programs. In the model, each person has an individual profile and behavior. The user can define the occupants' characteristics (size, walking speed and a choice of exit). Based on the characteristics, occupants decide on exit paths which can dynamically change under the following conditions, for instance, to avoid queues, response to door openings or closures. The parameters are defined using profiles and can be described by various distributions—constant, normal, lognormal and uniform. Similarly, populations can be described by different behaviors, for instance, have different exit goals or pre-evacuation behavior. Pathfinder enables modeling an assisted evacuation for occupants with special needs. Mobility impaired occupants can be modeled with wheelchairs or hospital beds. Specific groups of people or individuals can be modeled to help others, and the disabled occupants can have assigned behaviors, for example waiting for help in a specific place in the model or the current location. In this model, the user can also connect familiar occupants into a group, who will seek each other and maintain minimum distance apart [67].

In Pathfinder, walls and other areas where occupants cannot move are represented as gaps in the navigation mesh. Doors and stairways are represented as special navigation mesh edges and triangles. Doors provide a mechanism for joining rooms and tracking occupant flow and may also be used to control occupant flow. Occupants cannot pass between two rooms unless they are joined by a door. Moreover, the simulator requires that each occupant must have a path to at least one exit door. Occupant movement speed in the staircase is reduced and depends on the incline of the stairway.

Occupants can be represented as a cylindrical or a polygonal shape. The diameter of the cylinder is a parameter used for path planning and collision testing. This value will affect how many occupants can be added to a room without overlapping. The default value is 45.58 cm and is based on the average measurements of male and female persons [68]. The polygonal shape is used to select the vehicle shape, for instance, a wheelchair or bed used in the assisted evacuation.

Pathfinder is a well-validated model. It has been validated against codes, fire drills and experiments, past experiments described in the literature and against other models [62]. A brief comparison of applied programs is presented in Table 3.

**Table 3.** Basic features of the analyzed programs.

| Feature | SIMULEX | STEPS | Pathfinder |
|---|---|---|---|
| CAD file import | X | X | X |
| Moving speed parameterization | - | X | X |
| Individual occupant profile | - | X | X |
| Coupling with CFD software | - | X | X |
| Disable persons/wheelchairs | - | X | X |
| Lifts | - | X | X |
| Stairs/ramps | X | X | X |

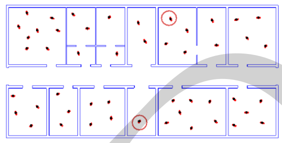
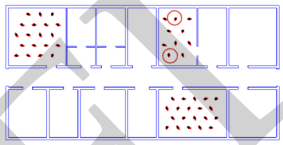
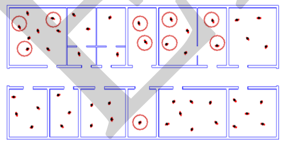
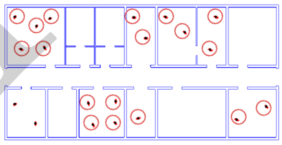
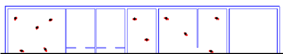
Based on the features presented in Table 3, it can be concluded that Simulex gives fewer options and it is a simple tool to analyze mainly people movement in a model—occupants routes, queuing or the total evacuation time. The other two programs give more options, for instance to simulate complex evacuation scenarios with variable populations, to model selected people behaviors or interact with dangerous fire conditions such as smoke.

Choosing the right tool must be dictated by the complexity of the analyzed case and required output variables in particular. It must be said that different softwares can be more or less user-friendly. Sometimes more options can confuse and impede model preparation, but fewer options can prove insufficient.

## 5. Case Study

A simple case study is performed to analyze the possibilities of modeling disabled occupants using different programs. The same case study is performed using SIMULEX, STEPS and Pathfinder. The building geometry in each program is downloaded from the CAD file. A simple evacuation model represents the geometry of one floor in an office building. The analysis is performed using one floor without any stairs or lifts. The simple geometry is adopted to avoid additional factors which could affect the results. Six different cases are analyzed. These cases differ according to the total number of evacuees and their distribution in the model. The floor geometry and the occupants' distribution in each case are presented in Table 4. Disabled occupants are marked with a red circle. In every analyzed model for each case, the modeling conditions—geometry and occupants' distribution—are comparable. For the population, the pre-evacuation time of 120 s using normal distribution was set. Occupants had stayed in the position for about 120 s and then started to move.

**Table 4.** The examined cases, disabled people are in circles.

| Cases | Total Number of Evacuees | Number of People "Office Staff" | Number of Disabled People | Occupants Distribution |
|---|---|---|---|---|
| Case 1 | 49 | 47 | 2 |  |
| Case 2 | 49 | 47 | 2 |  |
| Case 3 | 49 | 39 | 10 |  |
| Case 4 | 20 | 2 | 18 |  |
| Case 5 | 20 | 20 | 0 |  [redacted] |
| Case 6 | 20 | 18 | 2 | [redacted] |

The walking speeds are set according to data collected in the literature. The maximum walking speed of occupants without disabilities was set as 1.19 m/s. The value is chosen due to SFPE Handbook of Fire Protection Engineering guidelines [69] for exit route elements such as corridors and doorways. By analyzing the data collected by Sharifi et al. [26] and Fahy and Prolux [8], the walking speed of people with disabilities was set as average 0.5 m/s. The value was assumed as the average because of the large variation of the results. The data [8,26] also show that walking speeds vary depending on the analyzed case, therefore the minimum walking speed for occupants without disabilities was set as 0.9 m/s.

In SIMULEX the distance map was calculated automatically. One distance includes two exits at the ends of the corridor. The building population was defined using the option "group people". People without any impairments were simulated according to characteristics of the body type as a group of "office staff" and people with disabilities were simulated using the same option as an occupant type "all disabled". Using the occupant type option, the program distributes different body types for the group with the following distribution for "office staff": 30% as "average", 30% as "female" and 40% as "male". The walking speeds were set as default.

In Pathfinder, the population was defined using two profiles—default and disabled. These two profiles were varied by different walking speeds. For the default profile, the walking speed value was set in the range from 0.9 m/s to 1.19 m/s, and for disabled as a constant value of 0.5 m/s. Other characteristics were set as default. The behavior mode was set as

"Steering"—that means occupants interact with each other and avoid collisions. This mode, compared to SFPE mode, gives results more similar to experimental data.

In STEPS, two people types with default size distribution were defined—"Office staff" and "disabled", which were distinct by walking speeds and 3D model. "Office staff" had a directly defined m/s maximum walking speed of 1.19 m/s and "disabled" of 0.5 m/s. It means that a particular people type will move with a walking speed different for each person due to the proper representation of the natural variety of people movement but no higher than the specified maximum walking speed.

In STEPS, setting the distribution of occupants in a building is not as easy as in other programs. One occupant cannot be added individually. To add people in a model, avoiding spreading people on the entire surface, specific locations must be set. To configure a selected group of occupants in a relevant location, the user must follow a few steps before setting. Selected groups of people can be positioned only using the option "people events" in created locations, which means that every room or area where occupants are in a model, has a defined location and event. This procedure elongates the time to create a simulation. In comparison, using Pathfinder or Simulex, occupants can be added individually in every selected area in the model, which is faster and easier.

## 6. Results and Discussion

In this section, the results from the six cases performed in three programs are presented. In Table 5 the evacuation time results are presented.

**Table 5.** The evacuation times for all cases calculated with three programs.

| Cases | Total Number of Evacuees | Number of People "Office Staff" | Number of Disabled People | Delay Time, min | Total Evacuation Time, min/s | | |
|---|---|---|---|---|---|---|---|
| | | | | | SIMULEX | Pathfinder | STEPS |
| Case 1 | 49 | 47 | 2 | | 2:37 | 2:35 | 2:35 |
| Case 2 | 49 | 47 | 2 | | 2:29 | 2:39 | 2:27 |
| Case 3 | 49 | 39 | 10 | 2 | 2:36 | 2:39 | 2:35 |
| Case 4 | 20 | 2 | 18 | | 2:36 | 2:39 | 2:34 |
| Case 5 | 20 | 20 | 0 | | 2:18 | 2:21 | 2:15 |
| Case 6 | 20 | 18 | 2 | | 2:39 | 2:50 | 2:36 |

In these six simple cases, the total evacuation time depends mainly on the delay time and the presence of disabled people in the population. The lowest value of evacuation time in every program is received for Case 5 where the population consisted of 20 people without any mobility impairments. Other factors that affect the results are the total number of evacuees and their distribution in the building. Evacuation time in Case 6, where the population was less than half of the population in Case 1 and located in one room, is comparable. It shows that grouping people in a limited space will affect the total evacuation time due to crowding through doors and narrow spaces. Similar conclusions are observed in Koo's research [48]. Sometimes occupants can be blocked in a model doorway due to model specifications and its limitations, for instance, blocking grid cells by some of the model's compartments. It can occur in STEPS, for example when wall boundaries touch or cross grid cells are in the doorway. In this case, some cells are blocked and the door width is limited. At worst, when the geometry and grid are not adjusted, the movement can be fully blocked and occupants will not be able to escape. The simulation will run endlessly and cause false results.

Every simulation was run several times. The mean evacuation times were calculated as a simple average. The mean values and the deviations (error bars) are presented in Figure 3. SIMULEX has the biggest error bars compared to the other two models. That may be caused by the differences in population in every run of the simulation. As described in previous sections, the population is distributed within an algorithm and in the following runs, the walking speeds for each person can be slightly different. Results from STEPS have smaller error bars compared to SIMULEX. The difference in walking speeds in the following runs shows that the total evacuation time for the same conditions can be slightly different. Despite the random distribution of evacuees' speed, for each subsequent simulation, with the same settings, Pathfinder gives the same results. This is because the seed of the random number generator cannot be modified. In Table 6 the differences between these three analyzed models of the total evacuation times are presented.

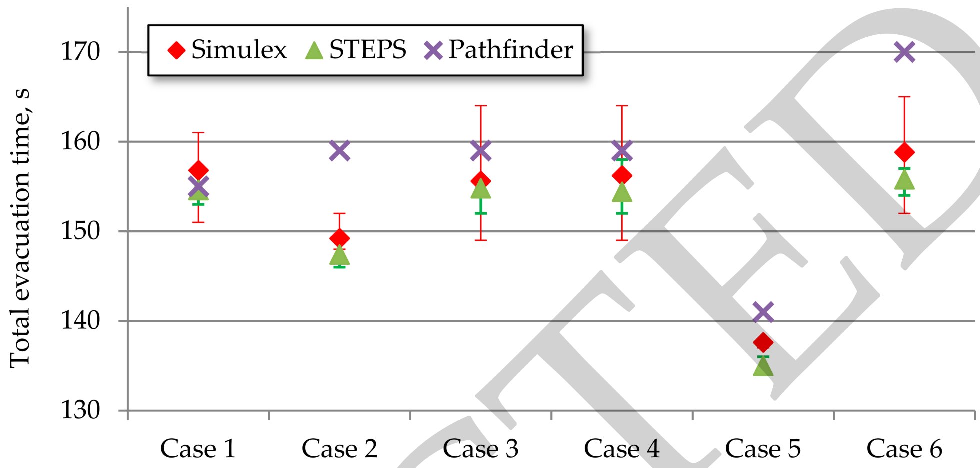



**Figure 3.** Total evacuation time from the three analyzed programs.

**Table 6.** Total evacuation time differences between programs.

| | Differences between Results From | | |
|---|---|---|---|
| | **STEPS—Simulex** | **Simulex—Pathfinder** | **STEPS—Pathfinder** |
| Case 1 | 1.27% | 1.27% | 0.65% |
| Case 2 | 1.34% | 6.29% | 7.55% |
| Case 3 | 0.64% | 1.89% | 2.52% |
| Case 4 | 1.28% | 1.89% | 3.14% |
| Case 5 | 2.17% | 2.13% | 4.26% |
| Case 6 | 1.89% | 6.47% | 8.24% |

The differences between results depend on the analyzed case. The maximum difference between results reaches 8.24% and can be observed in Case 6, between STEPS and Pathfinder.

It must be said that in every analyzed model the input parameters were equal and the differences in results are observed. It can be concluded that in more complex cases containing much more criteria, the differences may be much higher. In general, various occupants in the population are differed mostly by the walking speeds. As it is suggested by Christensen [47] the group of disabled occupants should be differed considering more criterias. This approach seems to be much accurate, but it can lead to higher differences in the results.

As shown in Figure 3 results from the three programs slightly differ from each other, however, they are generally comparable. It can be concluded that the differences may occur due to model characteristics and used algorithms, for instance to map people interactions, avoiding queues, etc. It is also noticeable that STEPS gives the lowest values in every case, and Pathfinder, except Case 1, gives the highest values of evacuation time. Results from SIMULEX usually are between the other two programs. It can be concluded that some programs may over- or underestimate the results and it should be taken into account.

Another parameter that was analyzed for these three programs is the number of people, who completed evacuation. The comparison of this parameter for each program is presented in Figure 4. Figure 4a–c presents the results respectively for Case 1, Case 2 and Case 3 where the population of 49 people was analyzed.

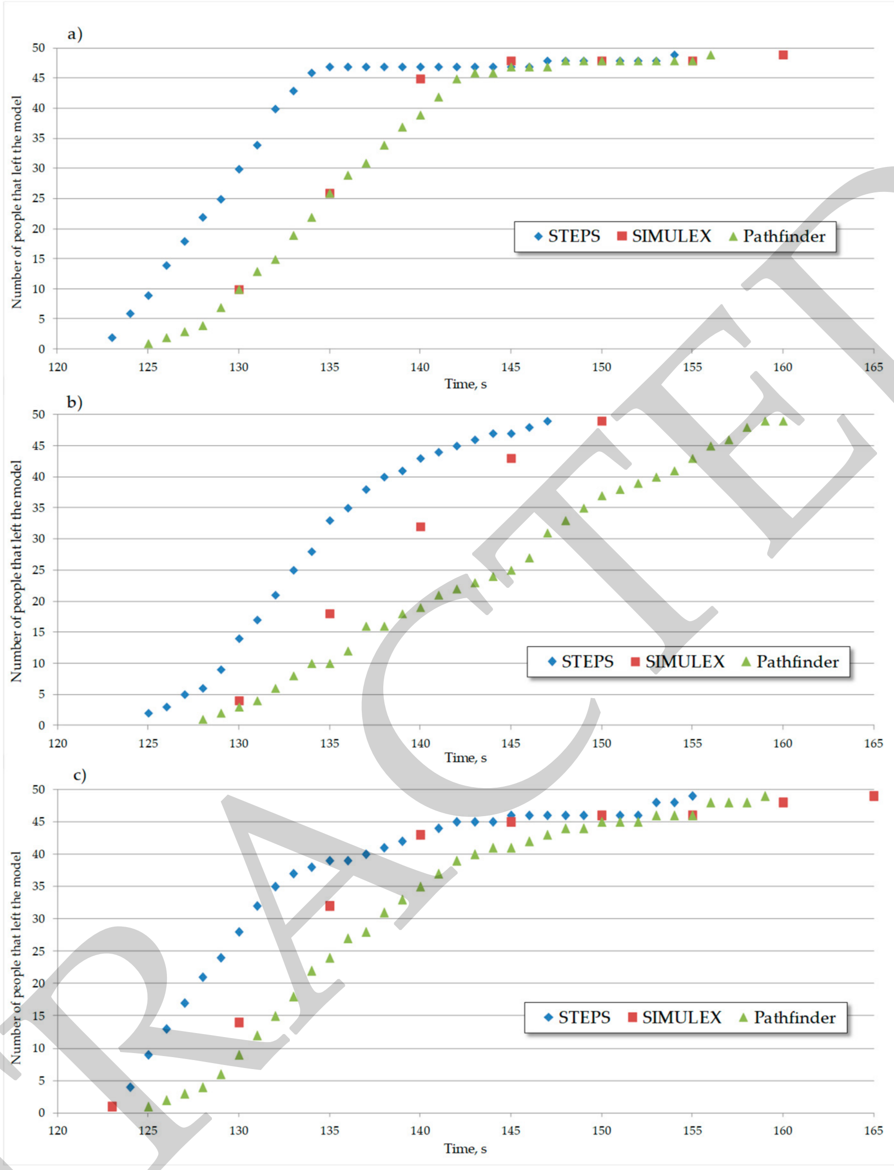



**Figure 4.** The number of people who completed evacuation at a particular time (**a**) Case 1, (**b**) Case 2, (**c**) Case 3.

The results for another three cases where the population of 20 people was analyzed—Case 4, Case 5 and Case 6 are presented in Figure 5a–c.

STEPS and Pathfinder provide the results of the number of people who completed evacuation in the time step of 1 s, and SIMULEX in the time step of 5 s.

As shown in Figures 4 and 5, occupants in analyzed cases leave the model at different times in each program. STEPS predicted the fastest evacuation, Pathfinder the slowest, meanwhile the results provided by SIMULEX were between them—with results varying more towards either side of the spectrum or staying in the center. It might be caused by a specific feature of Pathfinder—the so-called steering mode, which enables a realistic simulation of the crowd trying to pass a door.

In Table 7 the differences in the number of people who completed evacuation at the particular times are presented.

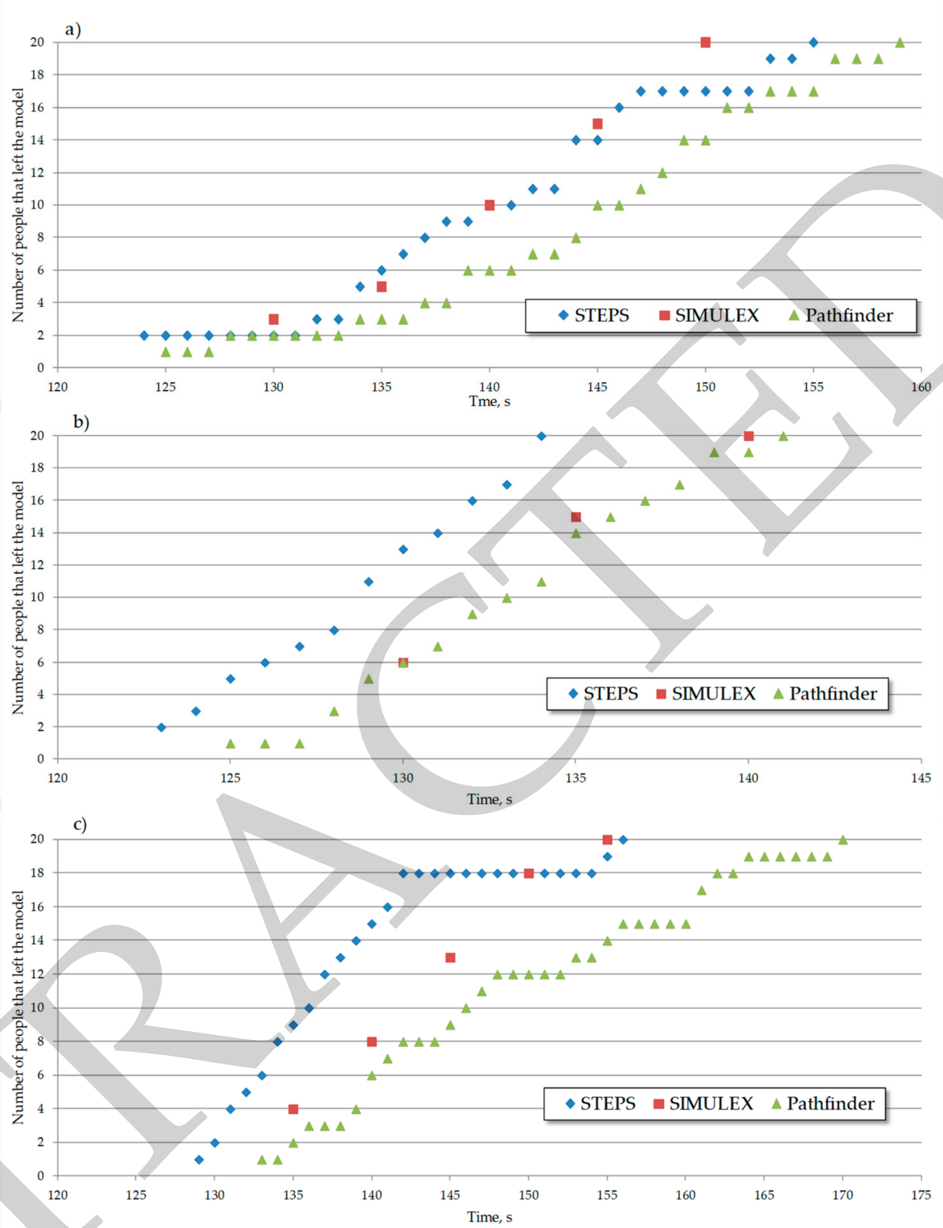



**Figure 5.** The number of people who completed evacuation at a particular time (**a**) Case 4, (**b**) Case 5, (**c**) Case 6.

**Table 7.** A number of people who completed evacuation in a particular time—differences between results from the analyzed models.

| | Differences between Results from: | | |
|---|---|---|---|
| | **STEPS—Simulex** | **Simulex—Pathfinder** | **STEPS—Pathfinder** |
| Case 1 | 3.75% | 2.50% | 1.28% |
| Case 2 | 2.00% | 6.25% | 8.13% |
| Case 3 | 6.06% | 3.64% | 2.52% |
| Case 4 | 3.23% | 5.66% | 2.52% |
| Case 5 | 4.29% | 0.71% | 4.96% |
| Case 6 | 0.64% | 8.82% | 8.24% |

The analysis of these very simple models shows the differences in the results. The initial assumption was that the results should be comparable, because of the models' validation and verification. Due to the different characteristics of selected programs, we have expected that the results could differ slightly. The results confirm our suppositions. The analysis of these simple models shows that different software can give different values of various parameters, even if the geometry and inputs are equal. It leads to the conclusion that the differences in more complex models can be much higher. In the literature, we can find some studies where researchers model evacuation using different software and compare the predicted results to actual evacuation times. We aimed to indicate the fact of the differences in results from different programs, which was observed also by Forell [70] and Ko [71].

It is important to remember that the choice of the software can affect the received results and it should be considered when selecting the software.

## 7. Conclusions

Ensuring people's safety in a building is a serious challenge and must involve all occupants, with disabilities as well. The latter issue is of great importance because modern society is obliged to ensure the same living conditions for all groups of citizens. The paper presents an extensive literature review on evacuation modeling with particular emphasis on disabled people. Three popular evacuation modeling programs were selected and used to consider six cases. The proposed geometry of the building was simple and the same in all cases. The number of evacuees and the number of disabled people changed. It allowed to observe how the evacuation time changes depending on the number of people, including people with disabilities. The results obtained with each program varied. There were also differences in individual cases. The biggest differences were found between the STEPS and Pathfinder programs for case 6, they were 8.24%. The use of three programs also was a means to compare them in terms of use.

Simulex is a program that is a simple tool to analyze people's movement in a building. The operation of the software and building the model is easy and fast, especially when building a simple model without complex geometry and population. In contrast, STEPS is a more complex program where users can set and analyze various parameters. Building a model is more complicated and requires following a few steps that elongate the process and can sometimes be confusing. Pathfinder offers a convenient interface and the possibility of almost freely modeling evacuees' behavior including disabled people, who need assistance.

Despite the fact that the outputs provided by the examined software slightly differed, they are regarded as consistent in general. The choice of proper software can be difficult, but it must always be dictated by the needs. It is also important to remember that models have some assumptions and simplifications.

In the near future, research on the evacuation of people with disabilities using the evacuation chair is planned. The obtained evacuation times will be implemented into the selected simulation program.

**Author Contributions:** Conceptualization, M.K. and K.Ż.; methodology, K.Ż.; formal analysis, K.Ż. and A.K.; investigation, K.Ż., M.K. and A.K.; data curation, K.Ż.; writing—original draft preparation, K.Ż.; writing—review and editing, K.Ż. and A.K.; visualization, K.Ż.; supervision, M.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** The work was supported by the Polish Ministry of Science and Higher Education within the research subsidy.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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