HOSPITAL EVACUATION PLANNING TOOL FOR ASSISTANCE DEVICES (HEPTAD)

Michael Joyce, Peter J Lawrence & Edwin R Galea, Fire Safety Engineering Group, University of Greenwich, UK

ABSTRACT

A new software tool, called HEPTAD (Hospital Evacuation Planning Tool for Assistance Devices), designed to aid evacuation planning in hospitals is described and demonstrated in this paper. The software can identify regions within the hospital geometry that are inappropriate for patients who require the use of specific movement assist devices in the event of an emergency evacuation. Using the software, Hospital Emergency Coordinators (HECs) are able to ensure that all patients are allocated a bed from which they can be evacuated within a safe period of time. In addition, HEPTAD has been designed as a proof of concept for algorithms that will later be incorporated within the EXODUS egress model. HEPTAD utilises several techniques from autonomous robotics to generate the fastest viable egress route for assistance devices from every location in the geometry while taking into account device spatial and kinematic constraints. It then takes this egress time along with factors from space syntax (isovist and spaciousness) to analyse the "emergency vulnerability" of every location within the geometry.

INTRODUCTION

In 2016/17, there were approximately 650 primary fires in hospitals and medical care facilities in England alone and on average one fire-related casualty in every 10 of these fires [1]. Due to the mobility requirements of many of the patients within hospitals, the success of an evacuation depends greatly on assistance from staff and their use of assistance devices [2]. It is widely agreed that evacuation plans and the layout of hospital facilities should be designed with assistance devices in mind [3,4]. It is therefore critical to fully understand the variety of devices in use to develop effective evacuation plans. These devices, such as evacuation chairs, hospital beds, wheelchairs, rescue sheets and stretchers, vary significantly in terms of their spatial constraints (size and shape) and kinematic constraints (movement speed, acceleration and manoeuvrability) [5–7]. This means that the route with the smallest evacuation time from each room may differ depending on the device in use. In addition, the impact of fire hazards on viable exit routes may be dependent on the nature of the device employed due to various performance constraints associated with the device. Patients who require the use of specific movement assistance devices during an evacuation must be located in areas where they can be manoeuvred to an exit / safe area using the device in less time than the ASET [8] (Available Save Egress Time) of the scenario. These appropriate areas can be determined by analysing the egress time required with the use of the device.

The research presented here, outlines a new technique for obtaining a "value of emergency vulnerability" (VEV) for every point on a building geometry. This has been implemented into a software tool named HEPTAD (Hospital Evacuation Planning Tool for Assistance Devices) that can aid Hospital Emergency Coordinators (HECs) by determining the areas of the geometry that are inappropriate for patients based on the assistance devices used. The VEV is calculated for each type of assistance device used by assessing the viable egress routes for the device from every point on the geometry. The tool could also be utilised to test "what if" scenarios as part of a risk assessment exercise (such as a Qualitative Design Review [4]). Furthermore, real-time applications of the methodology could be developed to identify alternative viable near optimal evacuation routes during an actual incident should the preferred evacuation route be compromised. In addition, HEPTAD provides a proof of concept for theoretical models that will later be incorporated into the EXODUS egress model [9].

BACKGROUND

Many patients may have specific medical constraints which limits the type of movement device that can be employed to take them to a place of safety during an emergency. As a result, guidance from Florida Department of Health [10] suggest conducting a "patient movement study, based on the number and type of patient to be moved from which locations" in order to determine the distribution of devices throughout the hospital. There is, however, no guarantee that because a patient is near an appropriate assistance device, their egress time will be below the ASET. It may be imperative to have one step before the patient movement study to first allocate beds to patients based on the expected egress time for an appropriate device from that location. To achieve this, it is essential to have a good understanding of the egress time for each device from every location within the geometry under likely evacuation scenarios. However, traditional methods to determine the egress time of assistance devices, such as drills or physical trials, can be costly, time consuming and potentially hazardous [4]. Furthermore, given that hospitals and care homes are occupied 24 hours a day, any physical trial is often constrained by the requirements of the occupants. One solution is to use a modelling approach; however, HECs currently rely on limited modelling tools to plan for the use and distribution of devices [3,11].

There are several hand calculation models that can aid with assisted evacuation planning. One such model by Childers et al [12] uses a mathematical optimisation approach as a way of determining patient prioritisation. Another model by Ünlü et al [13] takes a weighted sum of a number of Space Syntax variables to produce an overview of the vulnerability of each area on the geometry during an emergency. These models, however, do not differentiate between devices that may be utilised during an evacuation so cannot be used to determine which devices are suitable. There are currently only two hand calculation tools available to HECs to determine suitable assistance devices for a hospital. The first, by the United States Department of Homeland Security [14], provides a metric for analysing the performance of possible assistance devices based on a weighted sum of a number of subjective factors obtained from focus groups. Hunt et al [6,7] took this one step further by providing a metric that also includes empirically obtained performance factors such as horizontal and vertical movement speeds, number of operators and space occupied. Neither of these tools, however, identify the safe areas of the hospital for each patient based on their mobility requirements.

Another common set of tools utilised to determine the effectiveness of an evacuation plan are evacuation simulation models. The vast majority of these models, however, are unable to represent assistance devices [5,7]. Of the few models that can represent these devices, only two (Pathfinder [15] and EXODUS [7]) are able to explicitly represent some of the spatial and kinematic constraints that have an impact on the egress time and route finding of the device. Both Pathfinder and EXODUS take into account the size of assistance devices for route finding. They do this by analysing the width of each corridor and narrow gap in the geometry and marking it as impassable if its width is less than the width of the device. Unlike Pathfinder, EXODUS takes this one step further by also marking 90 degree corners as impassable for an object by analytically determining if the object can traverse it based on its length and width. It is not possible to represent the *holonomicity* [16] of devices in either model. That is, whether the device is capable of moving in any direction without first rotating. For example, a stretcher can move in any direction without the need to rotate, while a wheelchair will have to rotate to change direction (other than reversing). Thus the stretcher, a holonomic device, is not as constrained as the wheelchair, a non-holonomic device. These limitations may result in the prediction of unrealistic routes in certain geometries. These models, therefore, cannot guarantee an accurate prediction of the viable routes available to a device and so may produce unreliable qualitative and quantitative results. In addition to these limitations, neither model can predict the required egress time from every location in the geometry without individually simulating the movement from each location. This means that, although they may be used to verify an existing plan, they are inefficient at determining a safe distribution of patients within a hospital.

Ronchi et al [17] suggest that features based on fields of study outside of fire safety engineering are often relevant to evacuation modelling. Following this principal, this research has looked at methods from two external fields of study, autonomous robotics and space syntax, with the aim to solve limitations with existing models and add functionality to the EXODUS model. Particular interest has been placed on recent work in the field of Autonomous Robotics, where, through the use of a network embedded in C-Space, the most relevant spatial and kinematic constraints have been represented [18].

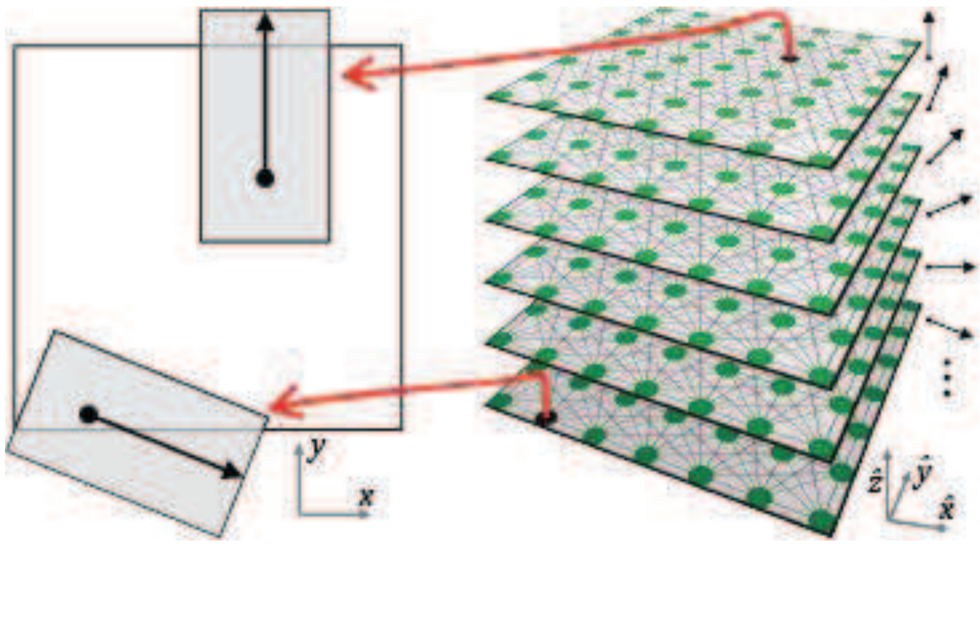
THEORETICAL MODEL

C-Space Network

The first method incorporated into the model is from the field of autonomous robotics and consists of representing each Degree Of Freedom (DOF) of the assistance device in a C-Space (configuration space) [16]. The C-Space represents the collection of points describing every possible position and orientation of a given object within a given geometry. The C-Space for an assistance device in a single floor geometry consists of an x and y co-ordinate describing the location of a reference point on the device and an angle representing the orientation of the device around that point and so is a three-dimensional space. For multi-floor structures, the C-Space is four dimensional. The method discretises this space into a network of nodes and arcs through which the device can navigate. This technique has been shown to work well when path planning for robots in close proximity environments (environments where the available space to move is not much larger than the size of the object), for example an improvised explosive device (IED) disposal robot [18]. This has an analogy to the movement of assistance devices through narrow corridors and doorways.

First, the geometry is represented as a collection of boundary lines that represent the walls and obstacles in the building. This version of HEPTAD is limited to single floor structures and so the C-Space described here is three dimensional with 3 DOF. These are the spatial co-ordinates of a reference point on the device (x and y position) and the angular orientation around this point (θ measured clockwise in degrees from the positive y axis). This means that any configuration (position and orientation) on the geometry can be represented by the three co-ordinates (x, y, θ). For an object with 3 DOF, its C-Space is the 3 dimensional space where each dimension represents one of the degrees of freedom [16]. A 3D C-Space can be constructed for each assistance device where every $(\hat{x}, \hat{y}, \hat{z})$ coordinate in this space represents exactly one (x, y, θ) configuration on the floorplan where $\hat{x} = x$ [in metres], $\hat{y} = y$ [in metres] and $\hat{z} = \theta$ [in degrees]. Note that the $\hat{z}$ axis is congruent to the unit circle S^1 and is modular 360.

Figure 1: Network in 3D C-Space (right) and Corresponding Configurations (left). For simplicity, each orientation is displayed as a separate layer in C-Space and arcs between layers are not shown.



To enable the incorporation of spatial and kinematic constraints into this space, some form of discretisation must be performed on the C-Space. To achieve this, a 3D network is embedded in the C-Space. Each node n in this network has a position $(\hat{x}, \hat{y}, \hat{z})$ in C-Space that corresponds to a configuration (x, y, θ) on the geometry as shown in Figure 1. The nodes are placed in a 3D grid with a spacing on the $\hat{x}, \hat{y}$ plane of 0.25×0.25 (as this provides twice the resolution of the default network in EXODUS and can be obtained from this network by performing a barycentric subdivision [19]). The $\hat{z}$ axis has a spacing of 22.5 to provide 16 possible orientations to match the 16 possible movement directions from each node (once the nodes are connected by arcs). Therefore, for a floorplan that can be contained in the rectangle $[E, W] \times [S, N] \subset \mathbb{R}^2$ on the real plane, a node is placed in C-Space at position $(0.25i, 0.25j, 22.5k)$ for all $i, j, k \in \mathbb{Z}$ such that $4E \leq i \leq 4W$, $4S \leq j \leq 4N$ and $0 \leq k < 16$. The nodes in the network form a 3D grid with an $\hat{x}$ spacing of 0.25, $\hat{y}$ spacing of 0.25 and $\hat{z}$ spacing of 22.5.

For all pairs of nodes n_1 and n_2 in the network that represent configurations (x_1, y_1, θ_1) and (x_2, y_2, θ_2) respectively, a directed arc $a = (n_1, n_2)$ is added between them if and only if $\sqrt{d(x_1, x_2)^2 + d(y_1, y_2)^2} < 0.7$ and $d(\theta_1, \theta_2) \leq 22.5$ where $d(s, r)$ is the distance between s and r in C-Space. Each node will then have arcs that point in 16 different directions (on the x, y plane). Figure 1 shows a portion of the 3D network in C-Space, and the corresponding configuration for two nodes.

Representing Constraints

The most relevant spatial constraints (size and shape) and kinematic constraints (turning radius and holonomicity) of the device can be represented by editing the C-Space network. Spatial constraints are commonly represented in C-Space by taking the Minkowski sum of the boundary lines with the device for each orientation [16]. This can be thought of as shrinking the device down into a single point while inflating the boundary lines. The result of doing this is a 3D volume in C-Space that marks out the invalid configurations, i.e., the configurations that would result in a collision with a boundary line. This method has been used by Lozano-Pérez et al [20] to produce a "slice projection" of C-Space for robot path planning. As the representation of C-Space has been discretised into a network, the nodes that now sit inside this Minkowski sum (and therefore represent an invalid configuration) can be removed from the network. All remaining nodes in the C-Space network now represent valid configurations, that is, configurations that do not cause a collision with a boundary line.

Representation of the kinematic constraints can be done in a similar fashion by removing all the arcs in the network that represent an invalid movement. If the device in unable to turn on the spot (has a non-zero minimum turning radius), all arcs that represent a rotation and no translation can be removed. That is, all arcs that go from configuration (x_1, y_1, θ_1) to (x_2, y_2, θ_2) such that $x_1 = x_2$ and $y_1 = y_2$ will be removed. To represent a non-holonomic device (in this context, a device whose movement direction must be equal to the direction it is facing), all arcs that cause a translation whose direction differs from the current orientation by more than some tolerance are removed. So, given a tolerance of ε degrees ($\varepsilon > 4.07$), an arc that goes from configuration (x_1, y_1, θ_1) to (x_2, y_2, θ_2) is removed if the inequality in Equation 1 is true.

$$d\left(\theta_1, tan^{-1}\left(\frac{d(x_1, x_2)}{d(y_1, y_2)}\right)\right) > \varepsilon \qquad [1]$$

Route Finding

One benefit of having a network embedded in C-Space is that route-finding is relatively simple. Given the target nodes (exits) and appropriate weights for each arc, Dijkstra's algorithm (shortest path) can be used to determine the egress time from each node in the network and the quickest route from that node to an exit. Since the nodes and arcs that represent invalid configurations and movements have been removed, the resulting route must abide by the spatial and kinematic constraints of the device.

The length of each arc takes into account the maximum translational speed s_t and rotational speed s_r of the device. The length of an arc a that goes from configuration (x_1, y_1, θ_1) to (x_2, y_2, θ_2) is determined by Equation 2.

$$L(a) = \sqrt{\left(\frac{d(x_1, x_2)}{s_t}\right)^2 + \left(\frac{d(y_1, y_2)}{s_t}\right)^2 + \left(\frac{d(\theta_1, \theta_2)}{s_r}\right)^2} \qquad [2]$$

The length of each arc is the time taken for the device to move from the first configuration to the second, moving at its maximum translational and rotational speeds. Acceleration and deceleration are also taken into account by reducing this speed when the device is changing direction to account for slowing when taking a corner. With these weightings, the resulting potential on each node from Dijkstra's algorithm will be the time for the device to get from the configuration represented by that node to the nearest exit. This is the egress time from that configuration.

Value of Emergency Vulnerability (VEV)

A Value of Emergency Vulnerability (VEV) can be calculated for every position on the geometry by utilising the egress time from this position (or nearest node) and two factors from Space Syntax. The concept of a VEV was first proposed by Ünlü et al [13] and took into account 5 factors; Real Integration (a measure of how isolated the location is), Isovist (area of geometry visible from the location), Distance (distance to an exit), Queuing Crowd (density of people in the location) and Spaciousness (how much space is available around the location i.e. the floor area of the room containing the location). Of these factors, only Isovist and Spaciousness are incorporated into HEPTAD. The Real Integration and Distance factors are not taken into account as they are replaced by the Egress Time factor. The Queuing Crowd factor is not currently represented in HEPTAD, as this will be replaced by the interactions with occupants when the HEPTAD algorithms are incorporated into EXODUS.

To gain a value for each of the three factors (Egress Time, Spaciousness and Isovist), the 2D floor plan is discretised into $0.25m \times 0.25m$ cells such that the centre of each cell has the same x, y position as the $\hat{x}, \hat{y}$ position of nodes in C-Space, i.e., at $(0.25i, 0.25j)$ for all $i, j \in \mathbb{Z}$ such that $4E \leq i \leq 4W$ and $4S \leq j \leq 4N$. This means that each cell corresponds to at most 16 nodes in C-Space with the same x, y coordinates (will be less than 16 if some have been deleted). The Egress Time T of a cell is the average egress time $[s]$ over these nodes. The Isovist I is the total area $[m^2]$ visible from the centre of the cell. This is calculated by casting rays from the centre of the cell and testing for intersections with boundary lines. Each ray has a maximum length equal to a maximum visibility distance v. The Spaciousness S is a measure of the proportion [%] of valid orientations at the position represented by the centre of the cell. This is calculated by taking the total number of nodes that correspond to the cell (that have not been deleted) and dividing by 16.

To calculate the VEV, a dimensionless value is constructed for each factor then a weighted sum is taken. The dimensionless values lie between 0 and 1 such that 0 is the least vulnerable for that factor and 1 is the most vulnerable. The dimensionless Egress Time is $\hat{T} = \frac{T}{ASET - Prep. - Resp.}$ where the "ASET" is the available safe egress time (obtained from fire models or risk assessments), "Prep." is the preparation time for the device and "Resp." is the worst possible response time of staff. The dimensionless Spaciousness is $\hat{S} = 1 - \frac{S}{100}$. Finally, the dimensionless Isovist is $\hat{I} = 1 - \frac{I}{\pi v^2}$ where v is the maximum visibility distance. With these values, the VEV is calculated with Equation 3 where the weights w_T, w_S and w_I are such that $w_T + w_S + w_I = 1$. These weights represent how much each factor influences the vulnerability of a location. Weights of $w_T = 0.7$, $w_S = 0.1$ and $w_I = 0.2$ have been used here for demonstration purposes.

$$V = w_T\hat{T} + w_S\hat{S} + w_I\hat{I} \qquad [3]$$

Hazards

Hazards (such as fire, smoke or debris) are represented in HEPTAD as regions of the geometry where the device cannot go. Once their position is defined on the geometry, they can be switched on and off and the egress routes and times are recalculated accordingly. Each hazard is given a probability value from 0 to 1 by the user. This value is the probability that the hazard is active given that there is an evacuation taking place. The model assumes that at most one hazard can be active at any time, so the sum of the probabilities of the hazards must be ≤ 1. Let there be n hazards $H_1, H_2, \dots, H_n$ with respective probabilities $P_1, P_2, \dots, P_n$. Then the empty hazard H_0 that represents no hazard (for example in a non-emergency evacuation) will have probability $P_0 = 1 - \sum_{i=1}^{n} P_i$.

With this probability measure, a weighted average of the VEV can be calculated called the averaged Value of Emergency Vulnerability (aVEV). For each cell, the aVEV over all hazards can be calculated using Equation 4 where V_i is the VEV with hazard i active.

$$\text{aVEV} = \sum_{i=0}^{n} V_i P_i \qquad [4]$$

In addition to the aVEV, another value that must be considered is the maximum Required Safe Egress Time (mRSET), that is, the total egress time (from alarm activation to escape) for the device in the worst case. In HEPTAD, this is calculated in each cell by taking the largest Egress Time over all the hazards and adding the preparation time of the device and the response time of the staff.

Result Interpretation

To determine the distribution of patients throughout the hospital, both the aVEV and the mRSET should be considered. No patient should be placed in an area whose mRSET is greater than the ASET for the device they require. In addition, patients should not be placed in an area with an aVEV of more than the Egress Time weighting w_T. In this case, although it is possible for the patient to evacuate in less time than the ASET, the contribution to VEV from Isovist and Spaciousness is sufficiently high to generate the same aVEV value as for the case where the egress time is equal to or greater than the ASET. For each device, zones in the geometry can be colour coded using the following heuristic:

- Areas with mRSET $\geq$ ASET are marked as RED-ZONES: patients requiring this device should never be placed in these areas.
- Areas that are not RED-ZONES but with aVEV $\geq w_T$ are marked as AMBER-ZONES: patients requiring this device should not be placed in these areas. However, they may if measures are put in place to improve the visibility of the patient (increase the Isovist) and/or provide a clearer path for the device to enter and exit the zone (to increase the Spaciousness).
- All areas that are not RED- or AMBER-ZONES can be marked as GREEN-ZONES: patients that require this device should, where possible, be located in these zones. Within these zones, areas with a lower mRSET and aVEV scores should be prioritised.

TEST CASE

To demonstrate the functionality of HEPTAD, a test case of a hypothetical hospital layout was constructed along with several scenarios. Only the ground floor of the building is considered as HEPTAD does not yet have functionality to include stairways. The floor plan is shown in Figure 2. The usable space in this geometry was input into HEPTAD with 16 rooms (R1-16), 4 external exists (E1-4) and an internal exit (E5). Three hazards were also added to the geometry each with its own probability of being active during an evacuation. For the scenarios represented by the hazards, an ASET of 150 seconds and a response time of 50 seconds are assumed. These scenarios were selected for demonstration purposes only. The hazards and room labelling are shown in Figure 3 and the hazard information is shown in Table 1.

Figure 2: Hypothetical Building Layout used in the Test Case.

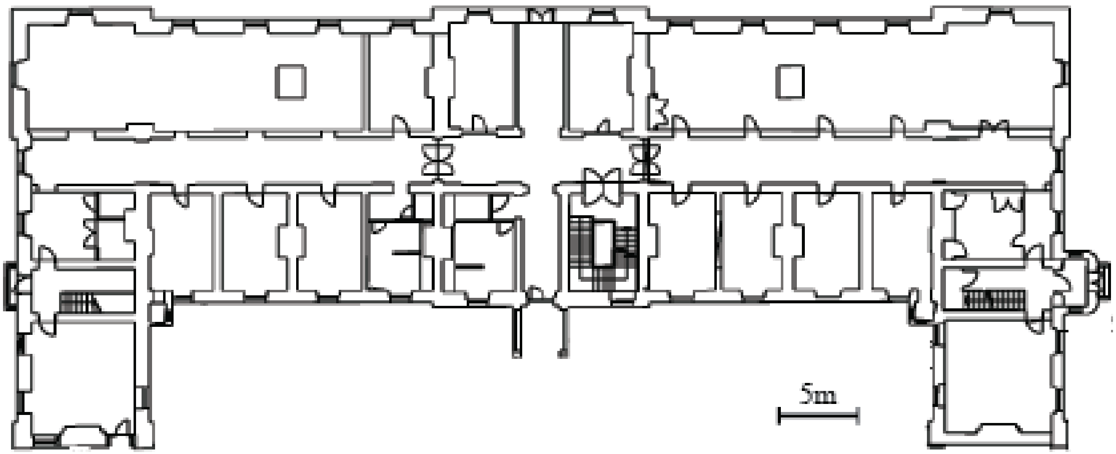


Figure 3: Geometry in HEPTAD with Rooms (R1-16), Exists (E1-5) and Hazards (red) (H1-3).

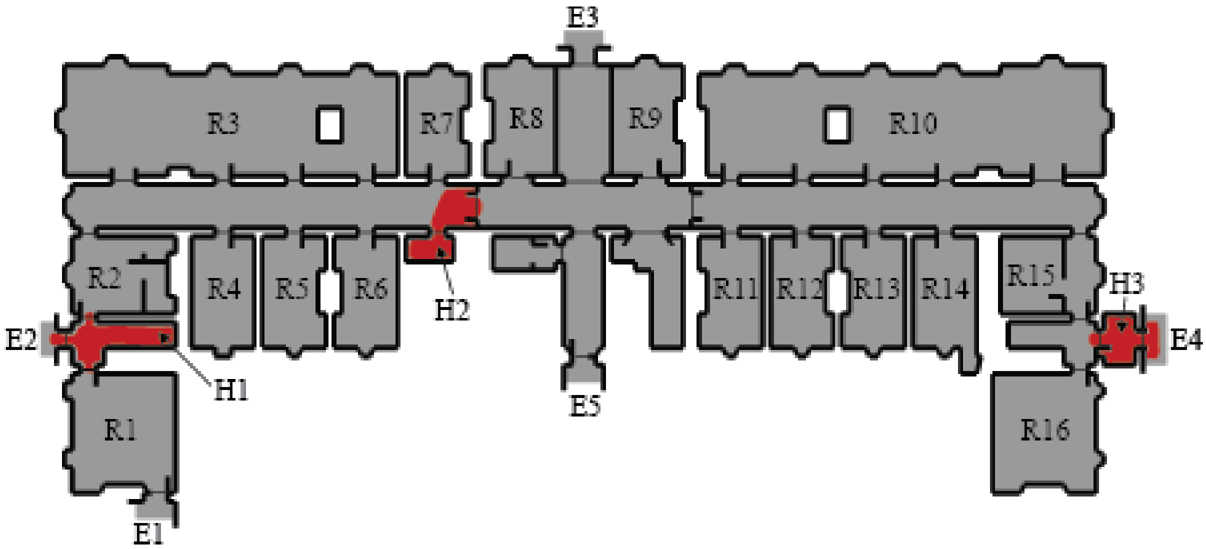
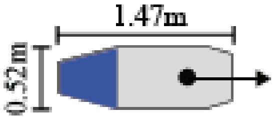
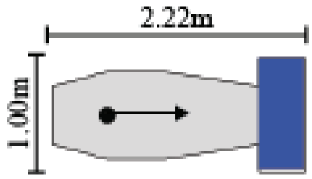


Table 1: Scenario, Probability and Size of Each Hazard.

Hazard	Scenario	Probability Active During Evacuation [%]	Floor area disrupted [m^2]
0	No hazard.	22	0.0
1	Fire between R1 and R2 blocking E2.	33	15.25
2	Fire in storage cupboard next to R6 blocking the main corridor.	25	11.0
3	Fire in storage cupboard next to E4 blocking this exit.	20	10.25

Within this geometry and set of scenarios, two different assistance devices were compared. These were an Evacuation Chair and Rescue Sheet (with male attendants) [5]. The majority of the parameters for these devices were either taken directly from data collected by Adams and Galea [5,6] or inferred from these data. The rest were estimated based on observations. These parameters are presented in Table 2.

Table 2: Properties of Assistance Devices with Male Handlers (for demonstration purposes only); * value inferred from data in reference; ** reasonable value obtained through observations.

Property	**Evacuation Chair**	**Rescue Sheet**
Max horizontal speed $[m/s]$ [6]	1.54	1.38
Max rotational speed $[°/s]$ [6*]	163.29	49.39
Acceleration rate $[m/s^2]$ **	0.4	0.5
Holonomic **	No	No
Min turning radius $[m]$ **	0.0	0.0
Preparation time $[s]$ [6]	29	53
Photograph of device [7]		
Size and shape of device (grey) with attendant(s) attached (blue). Arrow shows forward direction [6*]		

RESULTS

Base Case (No Hazards)

Table 3 Results from HEPTAD for the Base Case (no hazards). The Isovist, Spaciousness, Egress Time and VEV for each room (R1-16) for Evacuation Chair (EC) and Rescue Sheet (RS).

Room	**Isovist $[m^2]$**	**Spaciousness [%]**		**Egress Time $[s]$**		**VEV**	
		EC	**RS**	**EC**	**RS**	**EC**	**RS**
R1	51.7	81.4	61.9	6.1	11.4	0.334	0.459
R2	24.7	62.1	37.8	8.9	24.8	0.524	0.765
R3	81.7	83.3	65.4	19.6	34.8	0.372	0.669
R4	30.7	75.1	48.3	20.7	36.2	0.515	0.802
R5	29.0	71.7	44.7	23.6	33.0	0.557	0.786
R6	28.9	71.7	44.3	21.3	29.7	0.541	0.752
R7	26.8	71.0	43.7	18.3	26.9	0.524	0.732
R8	31.6	73.4	49.7	14.9	22.4	0.470	0.656
R9	34.4	73.4	49.7	14.9	22.4	0.466	0.651
R10	83.8	84.0	67.1	19.4	34.3	0.365	0.657
R11	29.2	71.7	44.6	18.4	27.2	0.519	0.727
R12	29.1	71.7	44.2	21.3	29.7	0.540	0.753
R13	29.2	71.7	44.6	24.2	33.1	0.562	0.787
R14	31.5	73.8	47.4	21.9	36.4	0.538	0.809
R15	22.8	64.3	32.7	11.1	47.5	0.523	0.940
R16	46.6	82.8	62.9	10.7	50.8	0.371	0.878

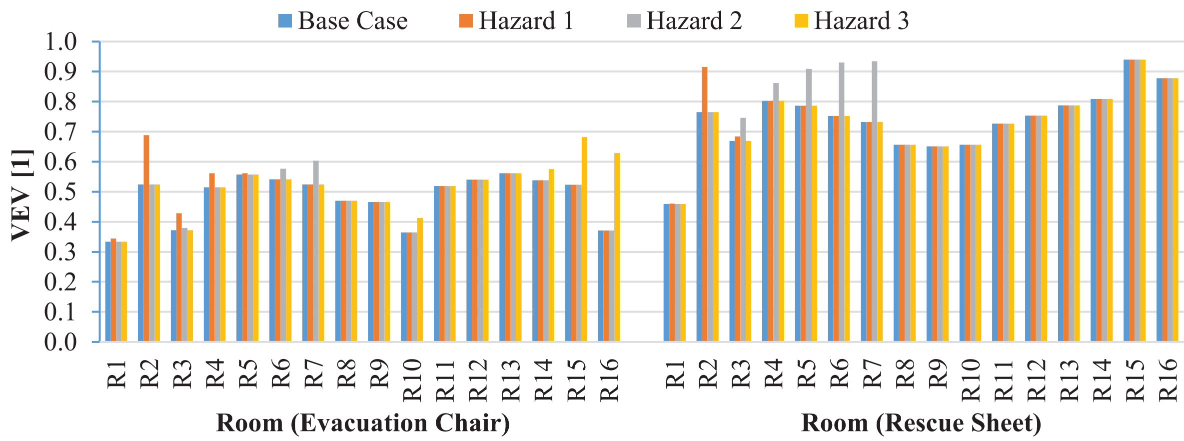
The Dreadnaught building geometry was input into HEPTAD along with the properties of the devices. The value of Isovist, Spaciousness, Egress Time and VEV were collected for each $0.25m \times 0.25m$ cell on the geometry. The average values in each room are shown in Table 3 for the scenario with no hazards. Note that the Isovist is identical for both devices so results are only shown once.

The data in Table 3 suggest that the Evacuation Chair performs better than the rescue sheet for all factors (Spaciousness, Egress Time and VEV) and all rooms. The Rescue Sheet has an especially large Egress Time for rooms R15 and R16 as, unlike the Evacuation Chair, it cannot manoeuvre through the small gap to E5 so must use a different exit. Based on the values produced by HEPTAD, all 16 rooms are GREEN-ZONES for a patient requiring an Evacuation Chair compared to only 5 rooms for those requiring a Rescue Sheet. The number of RED-, AMBER- and GREEN-ZONES differ, however, when hazards are considered.

Effect of Hazards

For each hazard entered into HEPTAD, egress routes from every location were recalculated giving different Egress Times and VEVs. Only areas of the geometry where the base case route travels through the location of a hazard are affected by that hazard. If the base case route travels through a hazard, the route of the device is altered to avoid the hazard and may end up using an alternative exit. Due to the different spatial and kinematic constraints of the devices, the route alteration differs depending on the device. Therefore, the effect of each hazard on the VEV of each room is also different for each device. The effect each hazard has on the VEVs is shown in Figure 4.

Figure 4: Bar Charts Comparing the VEV of Different Hazards for Each Room for Evacuation Chair (left) and Rescue Sheet (right).



To determine the appropriate ZONES for each room (R1-16) for each device, the mRSET and aVEV were calculated. These values with the corresponding ZONES are given in Table 4. The results obtained from HEPTAD suggest that all 16 rooms are appropriate for the use of an Evacuation Chair. By contrast, for the Rescue Sheet, only five rooms are appropriate (R1, R3, R8, R9 and R10), six rooms may be appropriate with the additional measures in place to ensure more visibility and spaciousness (R2, R4, R5, R11, R12, R13 and R14) and four rooms are inappropriate (R6, R7, R15 and R16). The ZONE colouring for the Rescue Sheet is shown in Figure 5 (the colouring is not shown for the Evacuation Chair as all rooms are GREEN-ZONES).

Taking all the factors into account, it is not surprising that the Rescue Sheet has much larger mRSET and aVEV values than the Evacuation Chair for all rooms. After the staff response and preparation phases of the evacuation, attendants of the Rescue Sheet only have 47 seconds to evacuate the patient compared to 71 seconds for the Evacuation Chair. This is due to the preparation times of 53 seconds and 29 seconds respectively. In addition to this, the Evacuation Chair has a maximum horizontal speed that is 1.12 times that of the Rescue Sheet and a maximum rotational speed that is 3.31 times that of the Rescue Sheet. Finally, the larger size of the Rescue Sheet decreases the value of Spaciousness in all rooms as well as causing it to take wider arcs around corners which increases the egress distance.

Table 4: The mRSET, aVEV and ZONE Colouring for the Evacuation Chair (EC) and Rescue Sheet (RS) for Each Room (R1-16).

Room	mRSET [*s*]		aVEV [1]		ZONE	
	EC	RS	EC	RS	EC	RS
R1	85.1	114.4	0.337	0.459	G	G
R2	111.9	146.8	0.578	0.815	G	A
R3	105.5	144.4	0.393	0.693	G	G
R4	106.1	144.7	0.531	0.817	G	A
R5	103.2	148.1	0.559	0.817	G	A
R6	105.5	151.2	0.550	0.797	G	R
R7	108.2	156.7	0.544	0.783	G	R
R8	93.9	125.4	0.470	0.656	G	G
R9	93.9	125.4	0.466	0.651	G	G
R10	103.9	137.3	0.374	0.657	G	G
R11	97.4	130.2	0.519	0.727	G	A
R12	100.3	132.7	0.540	0.753	G	A
R13	103.2	136.1	0.562	0.787	G	A
R14	106.2	139.4	0.546	0.809	G	A
R15	113.5	150.5	0.555	0.940	G	R
R16	121.7	153.8	0.423	0.878	G	R

Figure 5: The Rescue Sheet ZONE Colouring of the Geometry with aVEV for Each Room.

For the base case, the Egress Time and VEV for both devices are lower in rooms nearer exits, which is to be expected. In addition, larger rooms tend to have a lower VEV than smaller rooms with a similar Egress Time. This is due to the larger Spaciousness and Isovist values. When hazards were introduced, the mRSET and aVEV of both devices increased for rooms that were both near the hazard and where the hazard was between the room and the nearest exit. Hence, the model predictions for this simple example are in line with informed expectations.

DISCUSSION AND RECOMMENDATIONS

This simple test case demonstrates that HEPTAD can determine the most appropriate regions to accommodate patients with specific mobility requirements in order to safely evacuate them in the event of an emergency. The test case also demonstrates that different devices, such as an Evacuation Chair and Rescue Sheet, can have significantly different VEVs for the same room. This is due to the different spatial and kinematic constraints of the devices that influence their egress time and viable egress routes. Generally speaking, a device that is less spatially and kinematically constrained will perform better in an evacuation.

As a result of this research the following recommendations can be made for various stake holders involved in evacuation management:

- For Hospital Emergency Coordinators (HECs): To improve evacuation efficiency, careful consideration should be given to the allocation of patients to rooms. This must take into consideration the patients' mobility requirements to ensure that an evacuation using the appropriate assistance device is feasible from their location. In addition, both primary evacuation routes and alternative routes must be determined for each patient using the appropriate device.
- For assistance device manufacturers: Design goals should be to maximise the manoeuvrability of the device by ensuring there is no minimum turning radius (it can turn on the spot) and it is holonomic (the direction of movement does not depend of the direction it is facing) as well as to minimise the spatial constraints of the device by reducing the size as much as possible with no protrusions that may hinder its movement. In addition, more details about the performance of the device should be provided (such as in Table 2) by carrying out independent trials with different sets of people.
- For egress model developers: Incorporate the relevant spatial and kinematic constraints of assistance devices (and other objects) into simulation models as these influence the movement of the device and the movement of others who are also evacuating with the device.

Although HEPTAD has been designed primarily for use in hospitals, it can be applied to any building that utilises assistance devices. In addition, any movable object whose properties have been empirically established (as in Table 2), such as vehicles, luggage, and moveable furniture, can be represented using the methods presented here. It is hoped that the methods used here will enable egress model developers to extend the capabilities of their models to include any movable object that may be applicable in different scenarios and geometries.

CONCLUSIONS AND FUTURE WORK

The spatial and kinematic constraints of assistance devices may adversely impact the viability of certain egress routes, potentially limiting evacuation options and, as a result, increase egress times associated with the device. Despite this, current egress models are unable to represent many of these constraints and therefore produce unrealistic qualitative and quantitative results. The HEPTAD software represents a step forward in the development of egress models by demonstrating how these constraints can be incorporated utilising methods from fields of study outside of fire safety engineering (primarily autonomous robotics). As well as demonstrating the functionality of the theoretical models, HEPTAD has applications in and of itself. The software can quickly identify viable egress routes for assistance devices throughout an arbitrarily complex building layout and, through this, aid in patient distribution, evacuation planning, staff training and live route-finding during a real evacuation. Future work will include representing the interactions between assistance devices and other occupants in the building and the way in which devices move and interact in stairways.

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