# Simulating Hospital Evacuation

Aoife Hunt, Ph.D.

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# Introduction






- **1800 fires** in UK hospitals each year.
- Large, vulnerable populations requiring **continuing care**.
- **Mobility impairments** and associated mobility equipment.



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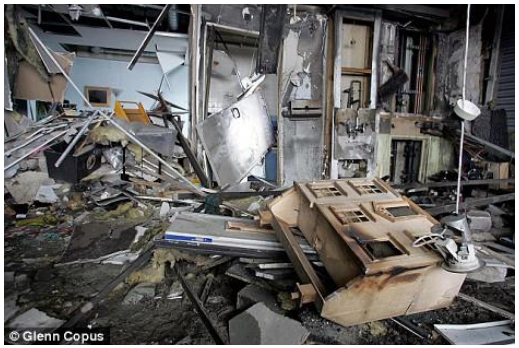
# Introduction

- Highly **complex spaces**.
- Dependency on **staff procedures** for evacuation.
- High staff turnover and challenges with **training**.
- **Live drills are impractical**, costly, and arguably unethical.
- Upcoming **demographic shift** will mean more elderly patients and more people with reduced mobility (**PRM**).

# Introduction





- **Hospital management are responsible** for evacuation planning.
- Progressive **horizontal evacuation** is typically prescribed.
- Post-incident analyses have highlighted the **need to revise** current procedures.
- **Movement assistance is vital** in an emergency.
- Availability and training in **movement devices** has not been consistent, or sufficient.

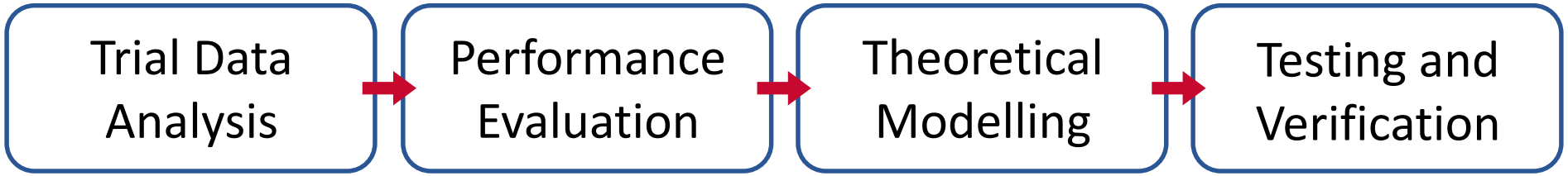
# Simulation

## What's missing?

- The **time required** for procedures and the **physical impact** of repeated patient collection is not well understood.
- Simulation models can provide insight, but currently **do not effectively represent** the assisted evacuation of PRM.
- Analysis is needed to **substantiate the current ideas** that the evacuation sequence should either begin or end with the most critical patients.
- There is a need to model assisted evacuation, not only for hospitals, but **for all buildings with PRM**.

# Our objectives

- What **influences the outcome** of hospital evacuation?
- What **data** and **modelling developments** are required?
- How do movement assist devices perform in the **horizontal and vertical evacuation of PRM**?
- How can these data be used to **compare the performance** of movement devices in evacuation?
- How can movement devices be **explicitly modelled**?



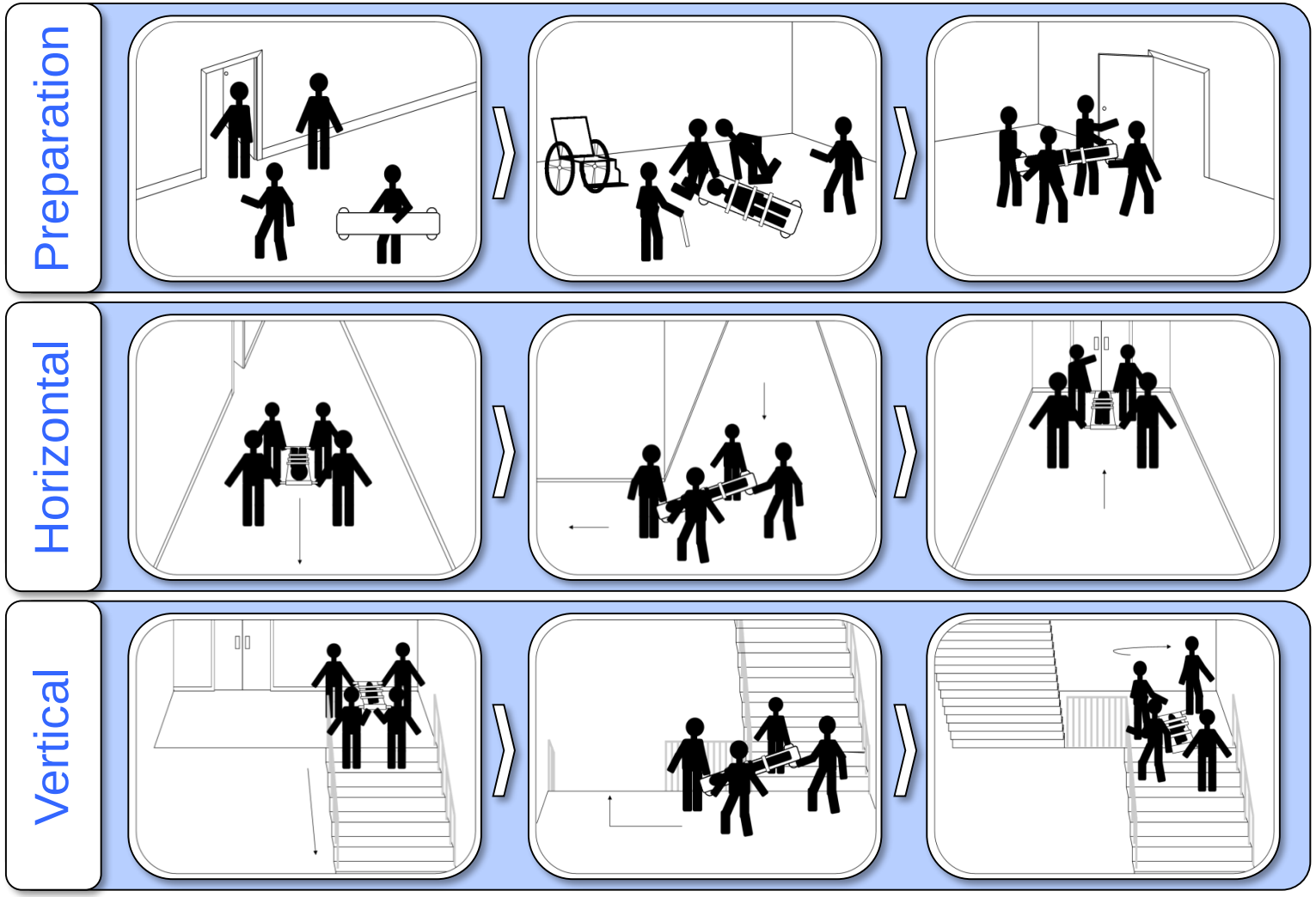
# Data collection




# Data collection

- Investigated the **time required** for hospital evacuation procedures and impact of repeated patient collection.
- 32 trials testing **four devices** over two days, through an **11 storey** hospital.
- Device operators were **expert manual handlers**.
- Two actor "**PRMs**".
- Four teams of University Ghent participants: two teams with **male operators** and two teams with **female operators**.

# Data collection



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# Data collection




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# Data collection





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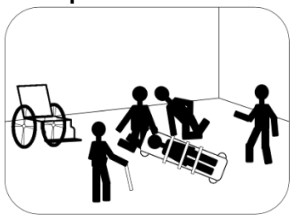
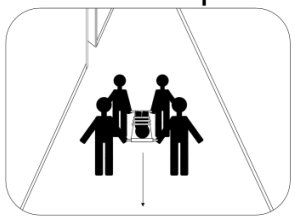
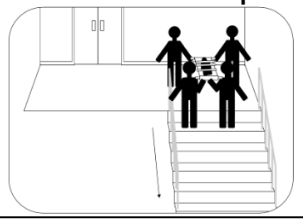
# Data collection

**1.09 m/s** ← (average)
**(0.99-1.23)** ← (range)

← **minimum number physically required**

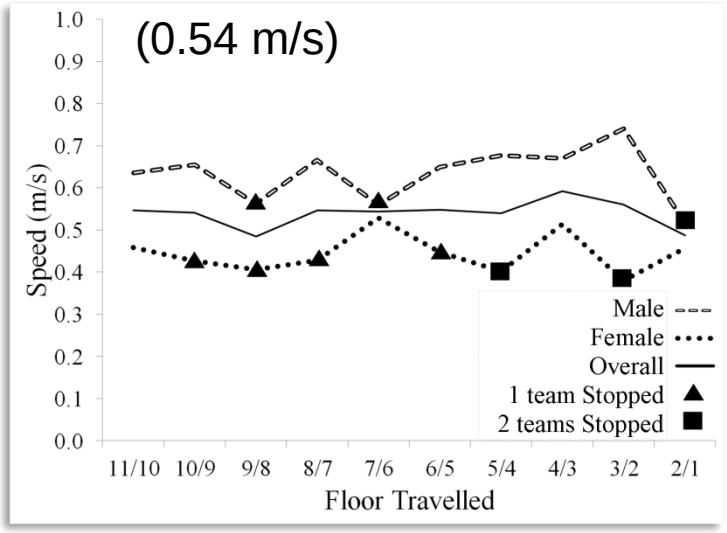




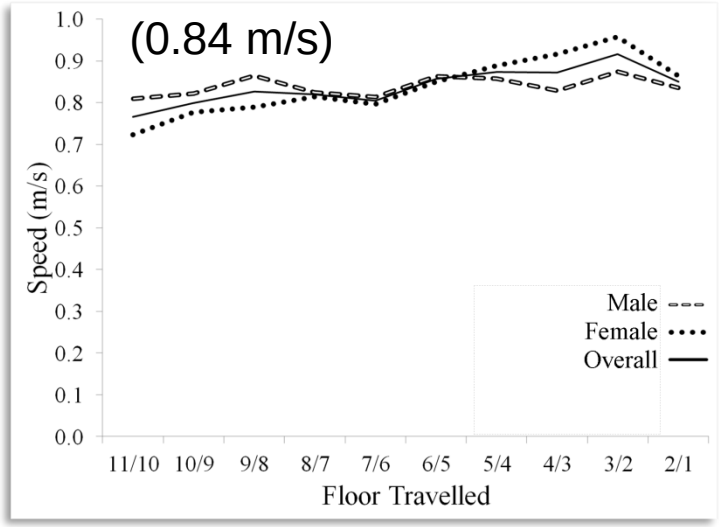
| | Stretcher | Evac Chair | Carry Chair | Rescue Sheet |
|---|---|---|---|---|
| Preparation Time  | **68 secs** (63-74) | **29 secs** (24-32) | **35 secs** (32-40) | **53 secs** (46-60) |
| | **88 secs** (61-120) | **36 secs** (30-42) | **48 secs** (41-52) | **78 secs** (67-86) |
| Horizontal Speed  | **1.09 m/s** (0.99-1.23) | **1.55 m/s** (1.51-1.65) | **1.54 m/s** (1.44-1.75) | **1.16 m/s** (1.08-1.23) |
| | **0.99 m/s** (0.91-1.09) | **1.39 m/s** (1.34-1.44) | **1.46 m/s** (1.41-1.51) | **0.72 m/s** (0.52-0.97) |
| Stair Descent Speed  | **0.63 m/s** (0.59-0.66) | **0.83 m/s** (0.78-0.88) | **0.50 m/s** (0.40-0.61) | **0.82 m/s** (0.78-0.85) |
| | **0.44 m/s** (0.40-0.48) | **0.82 m/s** (0.79-0.85) | **0.66 m/s** (0.58-0.74) | **0.52 m/s** (0.50-0.55) |

# Data collection

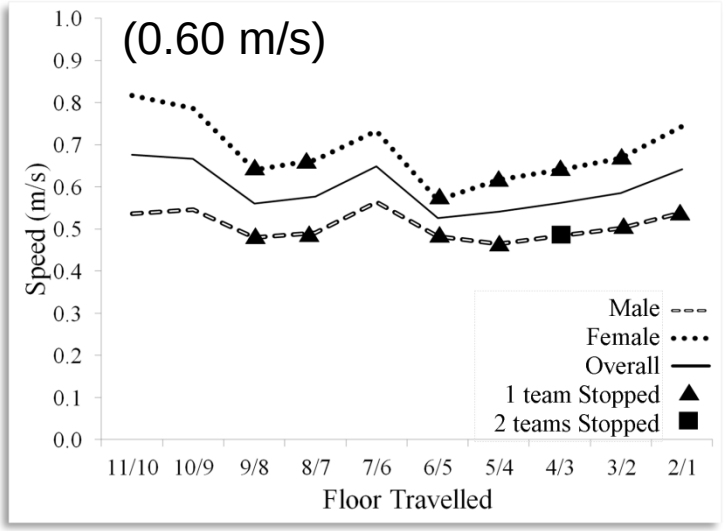
Stretcher



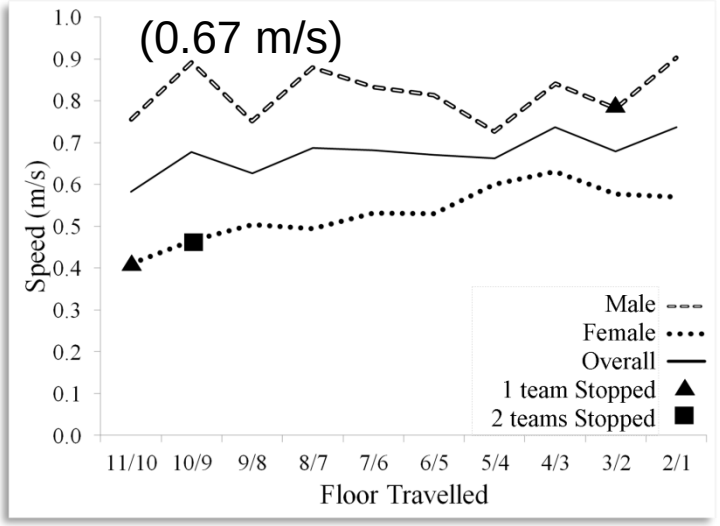

Evacuation Chair




Carry Chair




Rescue Sheet



# Data collection

| Average Corridor Speed (m/s) | Stretcher | | Evac Chair | | Carry Chair | | Rescue Sheet | |
|---|---|---|---|---|---|---|---|---|
| |  | F |  |  | M | F | M |  |
| Straight-Line Portion | 1.24 | 1.19 | 1.54 | 1.42 | 1.44 | 1.33 | 1.38 | 0.87 |

| Average Corridor Speed (m/s) | Stretcher | | Evac Chair | | Carry Chair | | Rescue Sheet | |
|---|---|---|---|---|---|---|---|---|
| | M | F | M | F |  |  |  |  |
| 90 Degree Corner Turn | 1.12 | 1.09 | 1.40 | 1.14 | 1.43 | 1.35 | 1.07 | 0.86 |

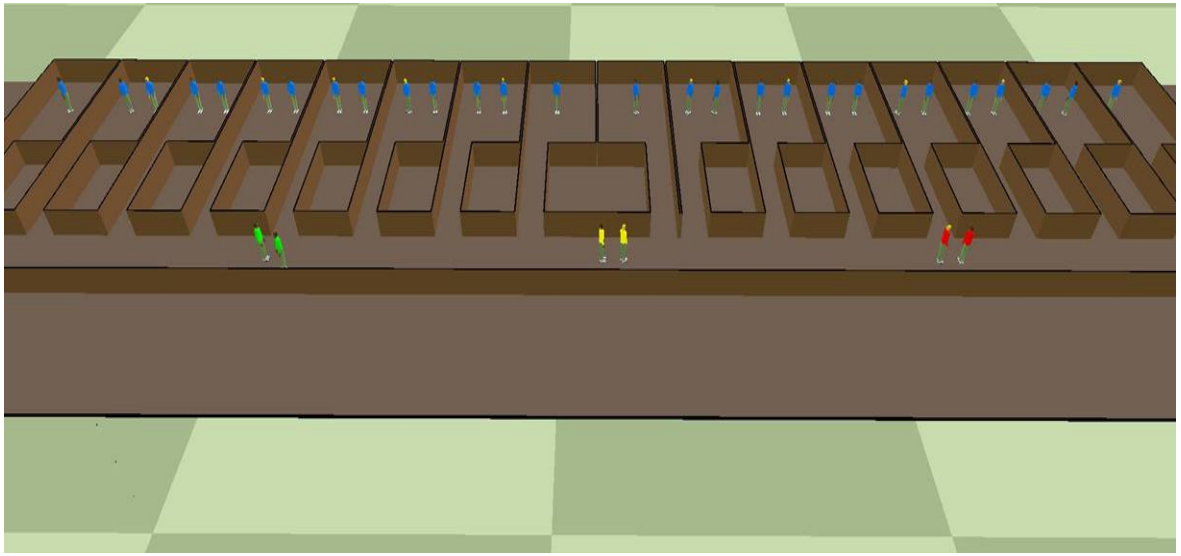
| Overtaking Potential | Stretcher | | Evac Chair | | Carry Chair | | Rescue Sheet | |
|---|---|---|---|---|---|---|---|---|
| |  |  |  |  |  |  | M | F |
| No. Stair Lanes Occupied | 2 | 2 | 1 | 1 | 1 | 2 | 1.5 | 1.5 |

# Performance Comparison

- Movement device performance comparison matrix, see:

Hunt, A., Galea, E. R., & Lawrence, P. J. (2015). An analysis and numerical simulation of the performance of trained hospital staff using movement assist devices to evacuate people with reduced mobility. *Fire and Materials*,*39*(4), 407-429.

- Implicit modelling in buildingEXODUS:





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# Theoretical model development

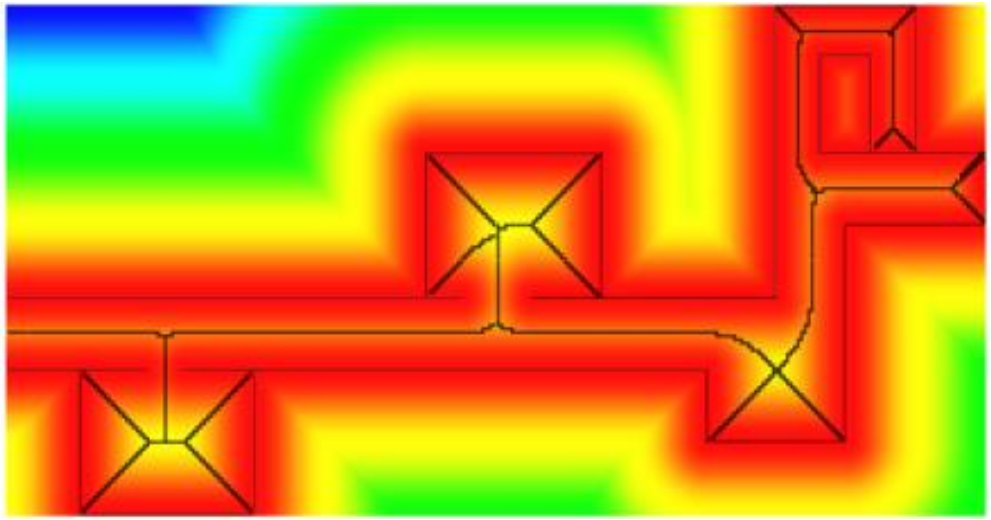
- Existing evacuation models were examined to determine their **suitability for use** in simulating hospital evacuations.
- Most models were unsuitable given **innate limitations** in the approach adopted (e.g. unable to represent individual behaviours).
- Others were able to simulate **reductions in agent speed**, but were incapable of effectively representing the physical presence of the device or the associated staffing procedures.
- **Incorporating large objects into evacuation models** (i.e. bigger than one agent) is vital and challenging.

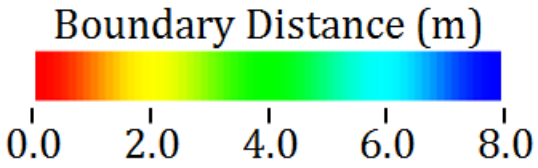
## Geometric decomposition

- It is required that objects interact with models on a continuous plane and on a **nodal system** (i.e. by occupying more than one node at a time).
- To assess space for object routes, it can be decomposed into a **Generalized Voronoi Diagram** (GVD):
    - *The set of points that are exactly the furthest distance away from two or more indices on the map, i.e. all of the points in the map whose distance to a boundary is not greater than their distance to any other boundary.*
- This method is typically used to divide regions into cells, but in this case can be used to **structure routes**.

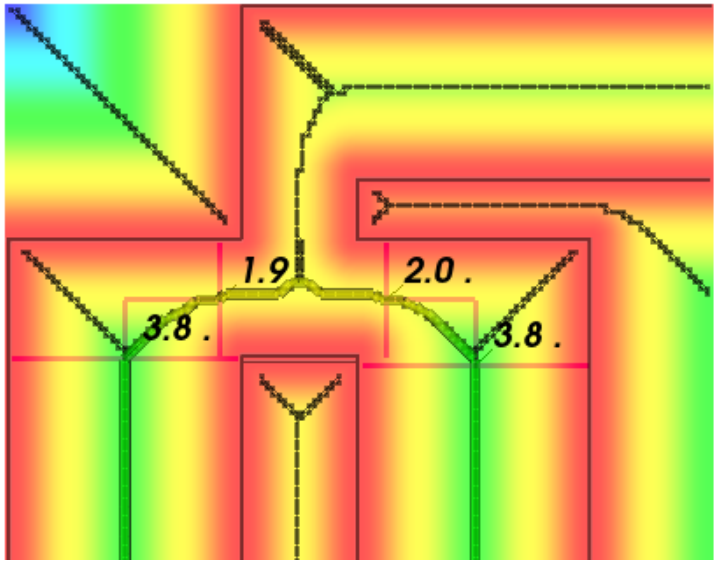
# Geometric decomposition

Locus of consecutive maxima:






Automated corner identification:



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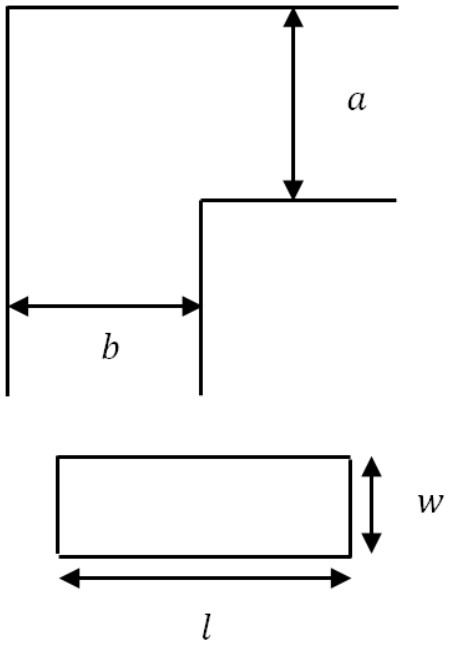
# Route analysis

- Two corridor dimensions define a 90° turn: $a$ and $b$ where $a \leq b$,
- The viability of the route can be tested for any rectangular object of width $w$ and length $l$, where $w \leq l$.



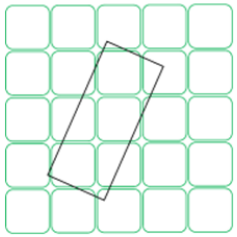

$$maxL = \sqrt{\left((1+\frac{1}{x^2})(a+xb-w\sqrt{x^2+1}\,)^2\right)}$$

Where $x$ is a real root of equation (2) in the interval $\left(0, \sqrt[3]{\frac{a}{b}}\right)$

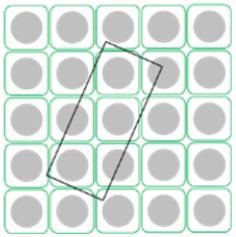
$$(bx^3-a)^2 - w^2(x^2-1)^2(x^2+1) = 0$$

# Movement algorithms

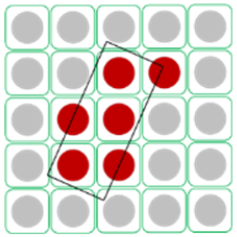
- Devices navigate according to the localised potential maps based on their target location (e.g. a door, a refuge, or an exit), by:
  - Deciding position on the relative utility of the surrounding potential values.
  - Identifying and turning towards the path of least resistance (i.e. recognising boundaries and considering other agents).
  - Occupying nodes based on intersection with a radial function:



(i) A device imposed on a nodal grid



(ii) The radial function from the centre of each node;



(iii) The nodes in which the device boundary intersects with the radial function.

# Movement algorithms

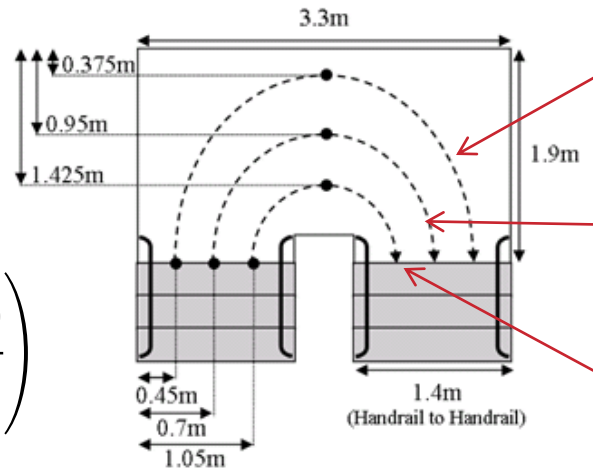
- In order to ensure overtaking where possible, stairway models prescribe positioning of devices in lanes on the stairs and landings.

Entrance position ($E$), landing position ($L_P$), landing width ($L_W$), and landing depth ($L_D$).

$$x = \left(\frac{L_W}{2} - E\right)(\cos(\pi - \tau) + 1)$$
$$y = (L_D - L_P)\sin(\pi - \tau)$$
$$0 \leq \tau \leq \pi$$

Turning motion $A$ (in radians):

$$A = tan^{-1}\left(\frac{-(L_D - L_P)^2\left(x - \frac{L_W}{2} + E\right)}{\left(\frac{L_W}{2} - E\right)^2 y}\right)$$



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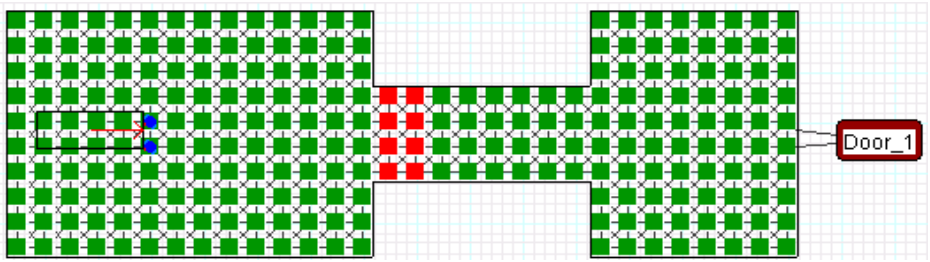
# Movement algorithms

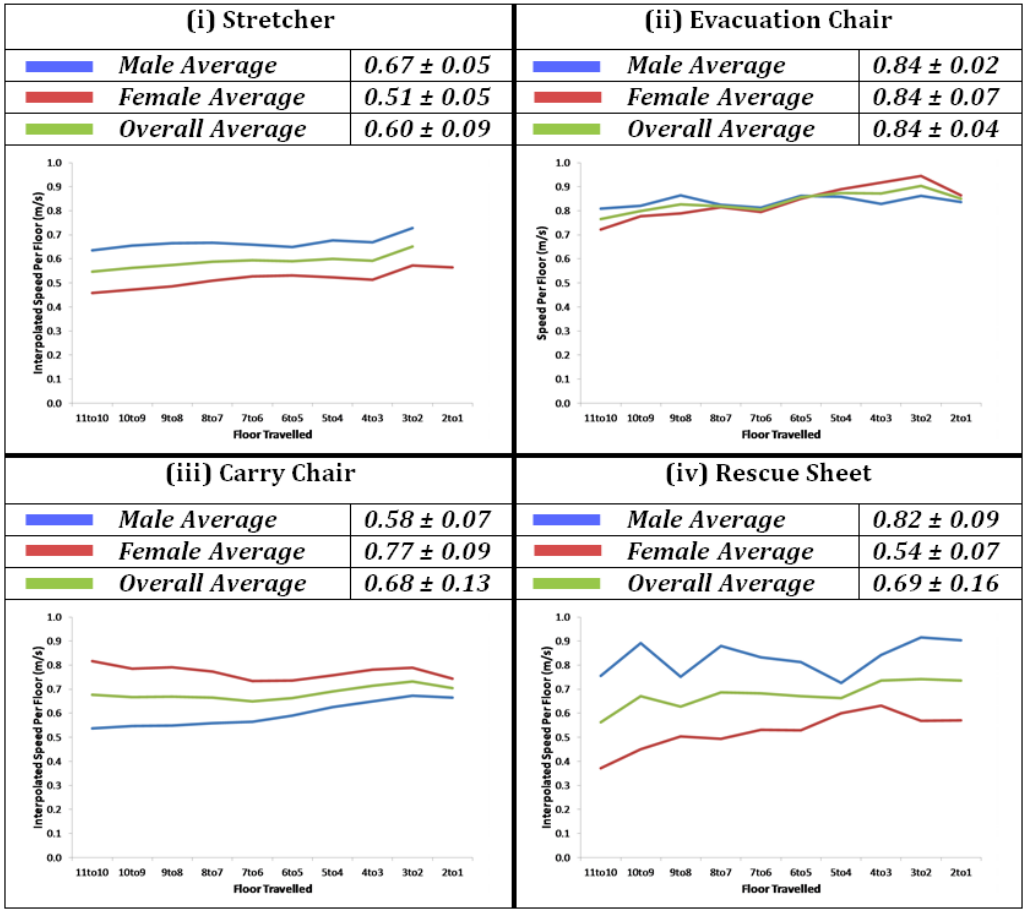
- Agent are allocated “attachment points” on devices, and delay/speed parameters to represent the collection, preparation, movement, and drop-off of PRM.
- A door transition algorithm calculates speed reductions based on the data and length of device.



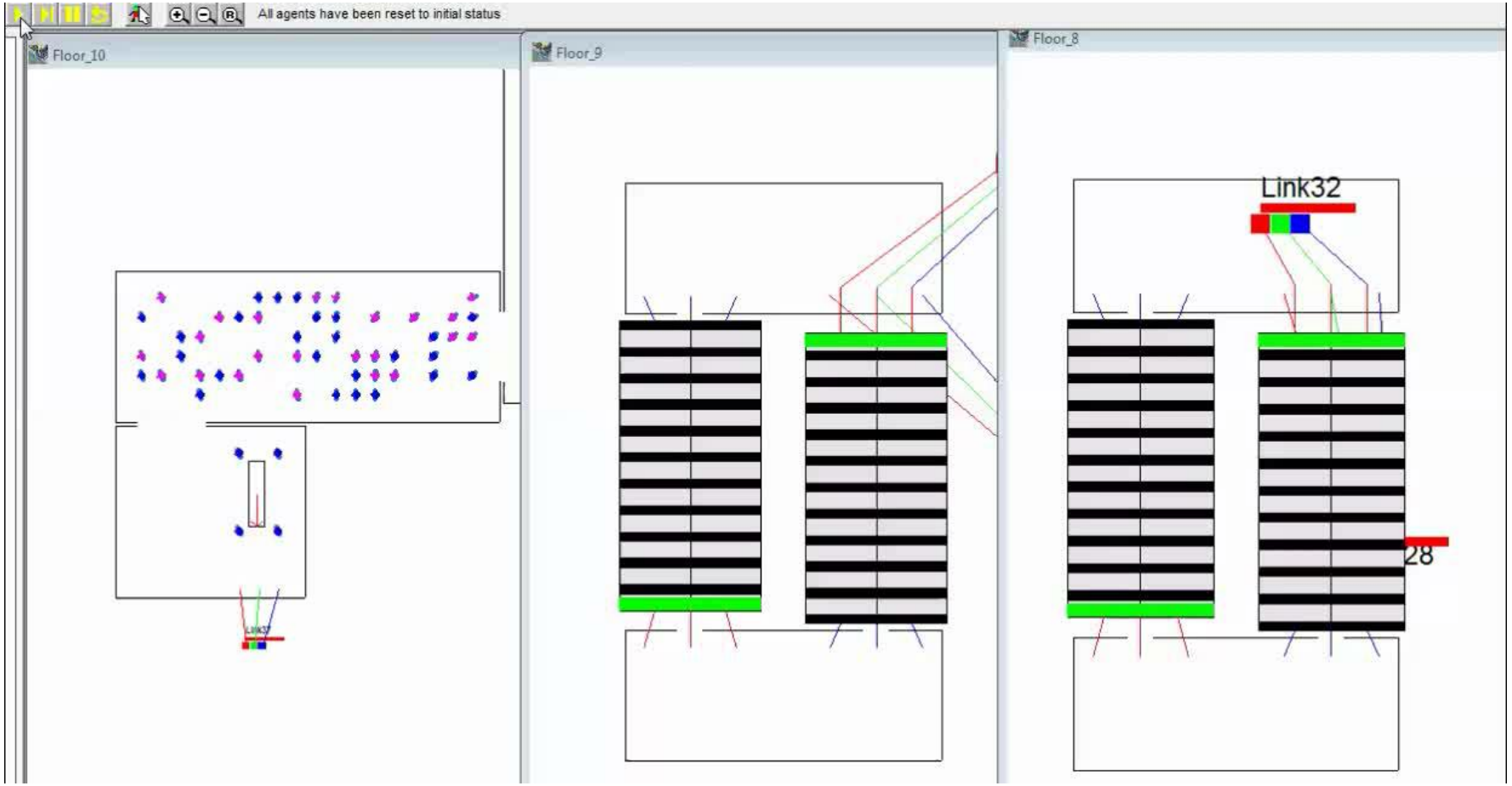

For door type $i$, speed: $D_{Speed} = \frac{\boldsymbol{m_l}}{\boldsymbol{d_{di}}}$ (m/s) for $\boldsymbol{d_{di}}$seconds.

# Movement algorithms

- Interpolated vertical speeds to remove the affect of stoppages, alongside a stopping function based on parameters:
  - Metres travelled in a staircase ($\boldsymbol{m_t}$),
  - Devices stopping distance ($\boldsymbol{m_s}$),
  - Modelled density in the stairwell behind the device ($\boldsymbol{d_f}$), and
  - Density tolerance ($\boldsymbol{d_t}$).



# Prototype: stair blocking



# Testing

- A **battery of component tests** were conducted for all sub-algorithms.
  - Route identification and analysis.
  - Device representation and movement algorithms.
  - Agent interaction (i.e. preparation, horizontal movement, vertical movement, and stopping).
  - Stair speeds, lane usage, stoppage, and blocking.

Functional verification confirmed that the **explicit representation was an improvement** on the implicit representation.

| | Numerical Simulation Results | | | | bEX Simulation Results | | | |
|---|---|---|---|---|---|---|---|---|
| | Male Teams | | Female Teams | | Male Teams | | Female Teams | |
| | Day (Hrs) | Night (Hrs) | Day (Hrs) | Night (Hrs) | Day (Hrs) | Night (Hrs) | Day (Hrs) | Night (Hrs) |
| Stretcher | 3.3 | 3.8 | 3.9 | 4.7 | 3.3 | 3.8 | 4.0 | 4.5 |
| Evacuation Chair | 0.5 | 0.9 | 0.6 | 1.1 | 0.5 | 0.9 | 0.6 | 1.0 |
| Carry Chair | 1.6 | 3.1 | 3.2 | 3.5 | 1.7 | 3.3 | 3.2 | 3.5 |
| Rescue Sheet | 1.1 | 1.6 | 1.5 | 2.1 | 1.2 | 1.5 | 1.6 | 2.0 |

# Impact

- Demonstration cases revealed new **forecasting ability**.
- This enhancement now allows practitioners to test the use of evacuation devices as part of hospital evacuation procedures and **quantify their impact** (positive or negative) on overall performance.
- In forecasting, this capacity enables **insight to be gained** prior to the implementation of a new procedure, a new building design or the use of new devices.
- The model enhances planning and diagnostic capabilities, so that new designs are better informed and that **risk assessments** and **evidence-based analyses** are better supported in the future.

## Our capability

- We can create **bespoke models** based on individual hospital plans.
- We can represent **normal operation and emergency situations** to test procedures and investigate safety factors.
- We can forecast the **time taken to fulfil procedures**; e.g. patient triage and registration, preparing patients for evacuation, and movement times for evacuation.
- We can **compare** progressive horizontal evacuation procedures with the full-building (i.e. vertical) evacuation procedures.

## Our capability

- We can model the **role of staff members** in order to test procedures, and to **aid in training** by providing a real-time simulation of staff members' various roles during an emergency event.

- We can aid with the design of **personal emergency evacuation plans and refuge areas** for patients and investigate the use of evacuation devices.

- We can create **bespoke assessments** in response to client needs, such as analysis of pedestrian movement in normal operations: **queuing management** for outpatients and A&E, **patient transfer** systems, and pedestrian **areas for visitors** and retail outlets, etc.

## Key advantages

- Enhancing **planning and diagnostic** capabilities within hospital and other healthcare facilities.
- Forecasting capacity **enables insight** to be gained prior to the implementation of new procedures, new building designs or the use of new devices.
- Risk assessments and evidence-based **analyses are better supported** in healthcare environments.

## The Future

- **More data** are required, for example to investigate:
  - Handler fatigue
  - Different medical and preparation requirements.
  - Physical performance (i.e. mixed-gender teams)
  - Impact of training
- The model **development is continuing** to make the representation of devices generic and user-friendly.
- The capability will be **extended to other objects**:
  - Prams, trolleys and luggage
  - Vehicles

# Thank You

aoife.hunt@aecom.com

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