Topic: Building Evacuation Modeling

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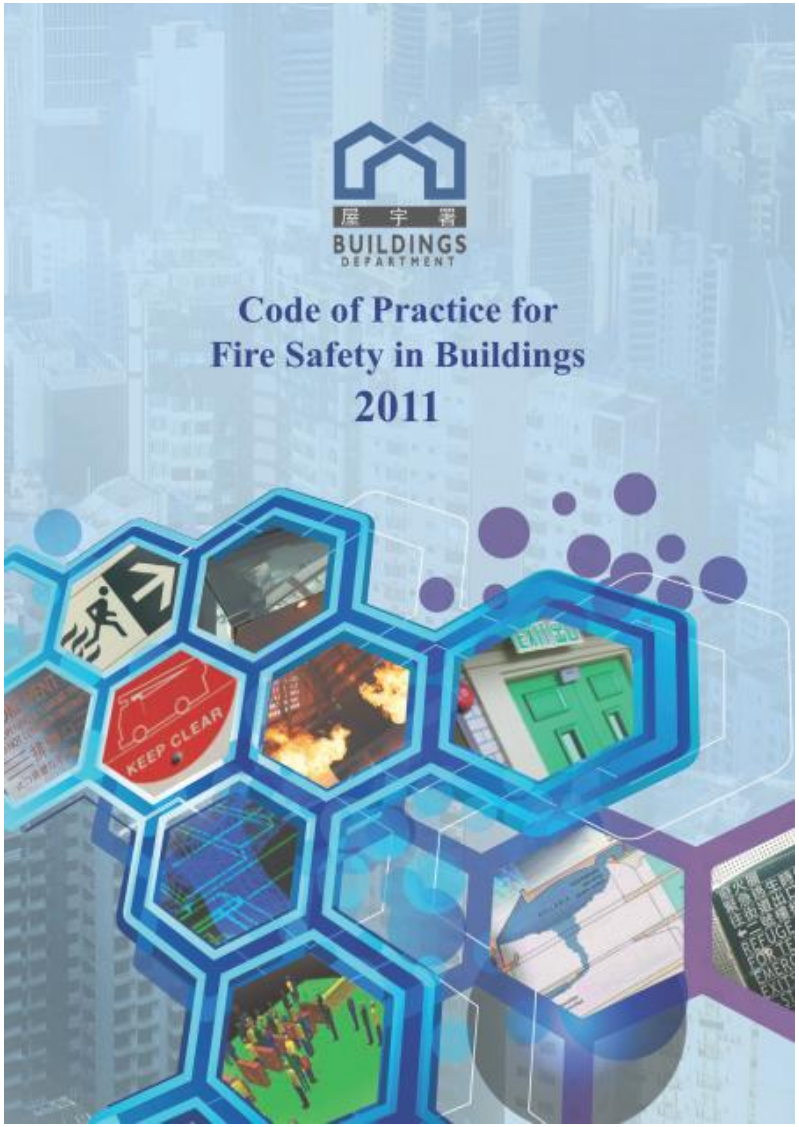
Contents

1. Introduction of human behaviour and concept
2. Interaction between fire and people
3. Evacuation modeling and technique
4. Case studies of evacuation performance assessment

Introduction

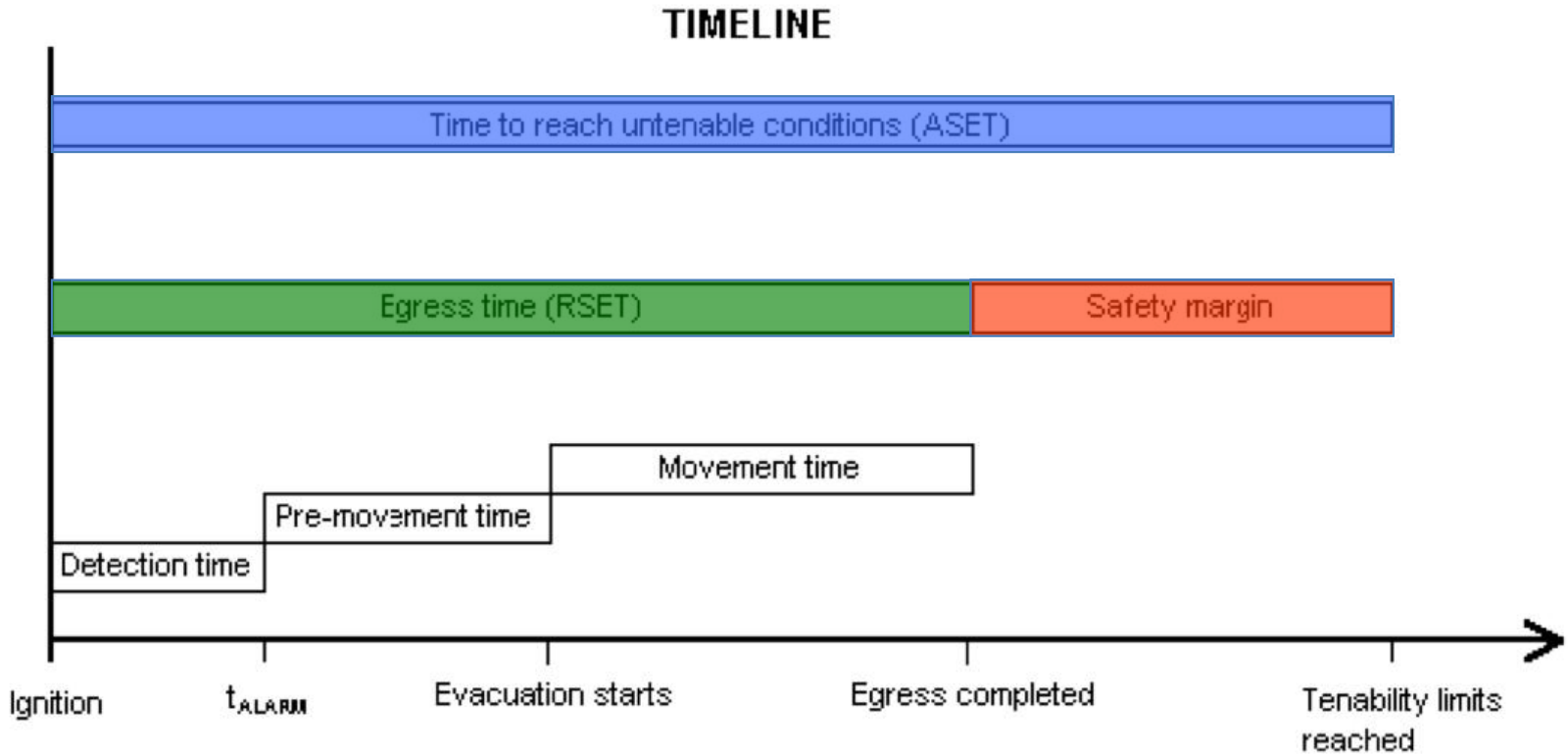


- Clause G6.4 Assessment Approaches:

  "The basic of many life safety assessments for a fire engineering approach is the utilisation of the "time-line" method where the "required time" for egress is compared with the "available time" for egress. This approach is the "RSET versus ASET" approach, where RSET is the Required Safe Egress Time and ASET is the Available Safe Egress Time."

Timeline Assessment

Diagram G1: Graphical Representation of a Timeline Assessment

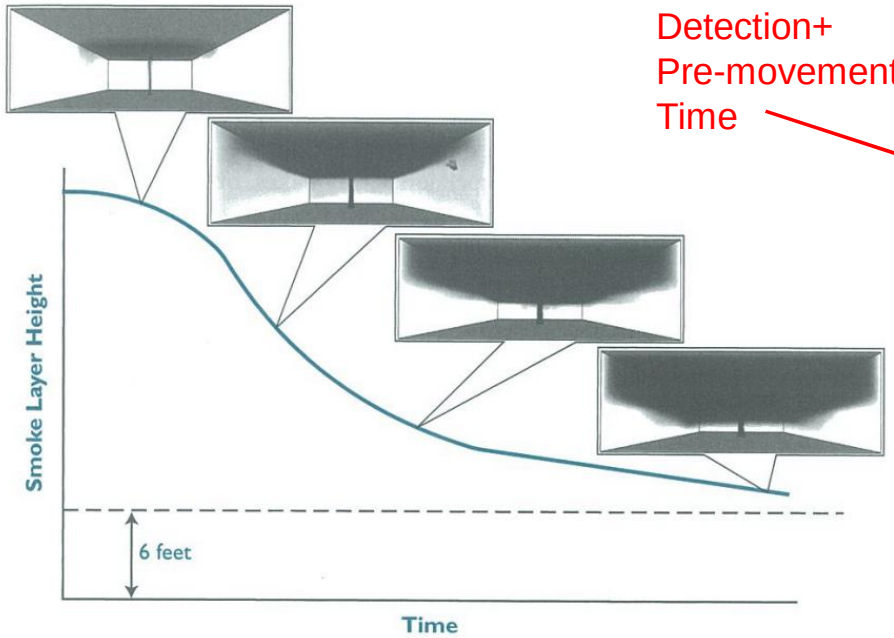


*** Extracted from Code of Practice for Fire Safety in Buildings 2011, Buildings Department, HKSAR*

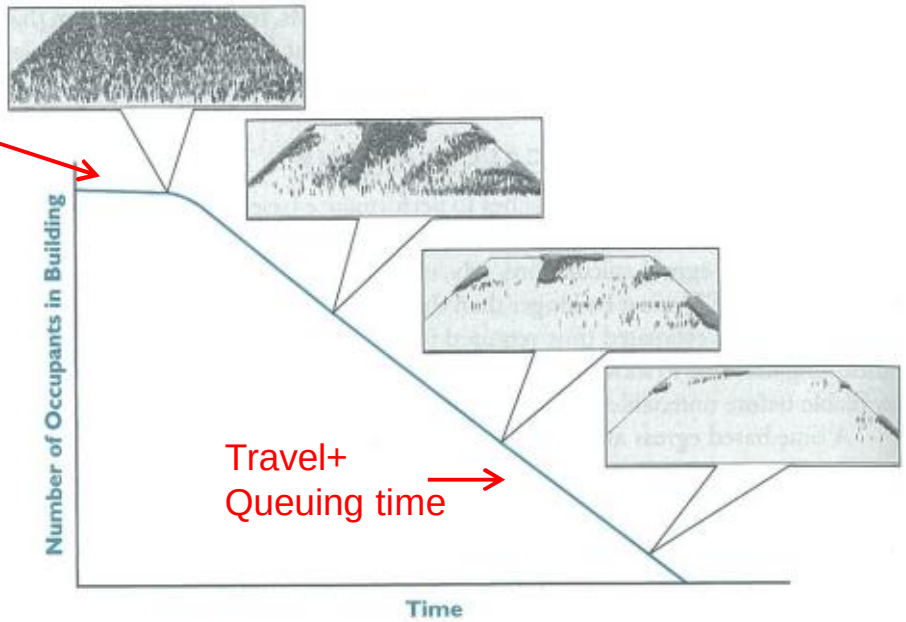
ASET & RSET

- ASET: calculated time available between ignition of a fire and the time at which tenability criteria are exceeded in a specified space in a building

- RSET: calculated time available between ignition of a fire and the time at which occupants in a specified space in a building are able to reach a place of safety



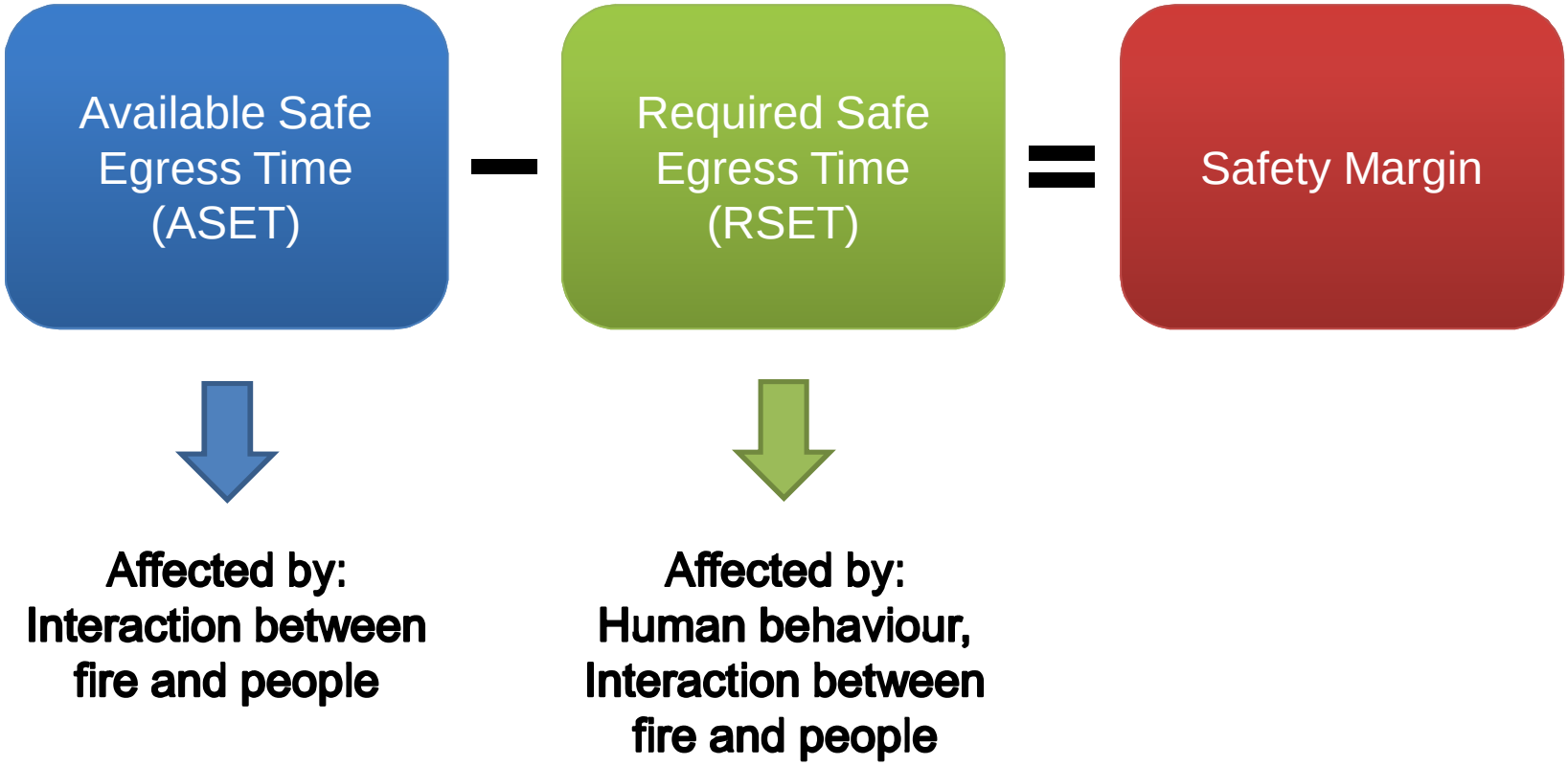
Detection+
Pre-movement
Time



*** Extracted from Egress design solutions – A guide to evacuation and crowd management planning, Wiley*

Performance-based Building Design

- Basic principle of a performance-based building design:

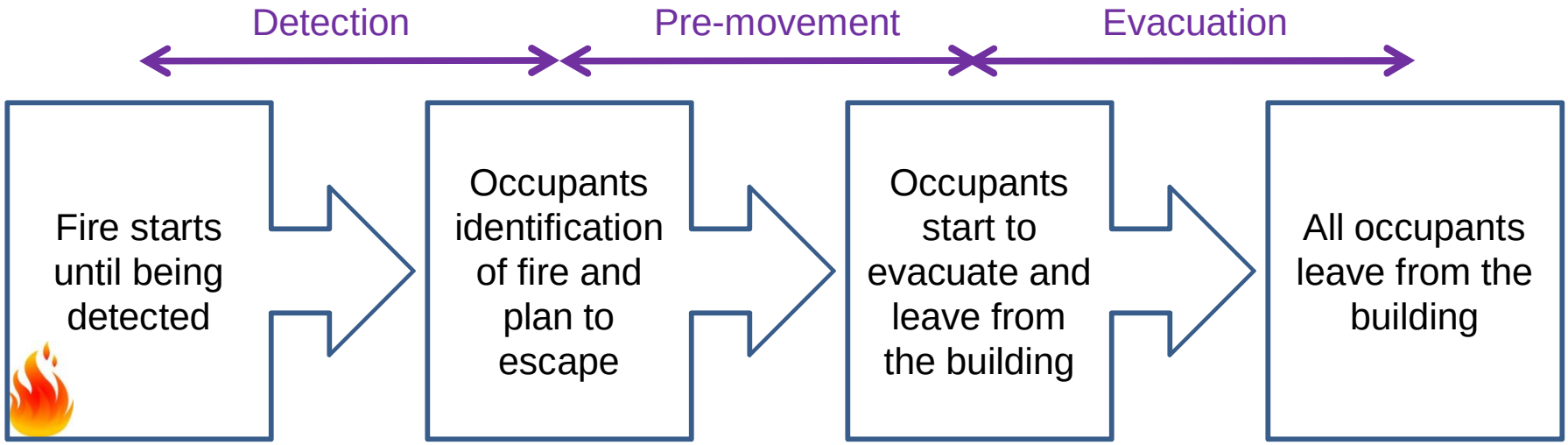


RSET: Human Behaviour and Concept

- A major consideration in any fire safety design is human behaviour
- Failure to consider human behaviour could lead to a failure in the design
- Designers and engineers should understand the likely actions people will take in a fire scenario to ensure their safety

Required Safety Egress Time (RSET)

- Three distinct phases



Detection Time

- Time from ignition to detection by an automatic system or first occupant to detect fire cues
- The actuation time or time lag required for actuation of smoke detector can be calculated in accordance with SFPE handbook:

$$t_{timelag\ of\ detector} = t_{transport} + t_{verify} + t_{system}$$

where

$t_{transport}$ - smoke transport time → By hand calculation / By CFD

t_{verify} - verification time

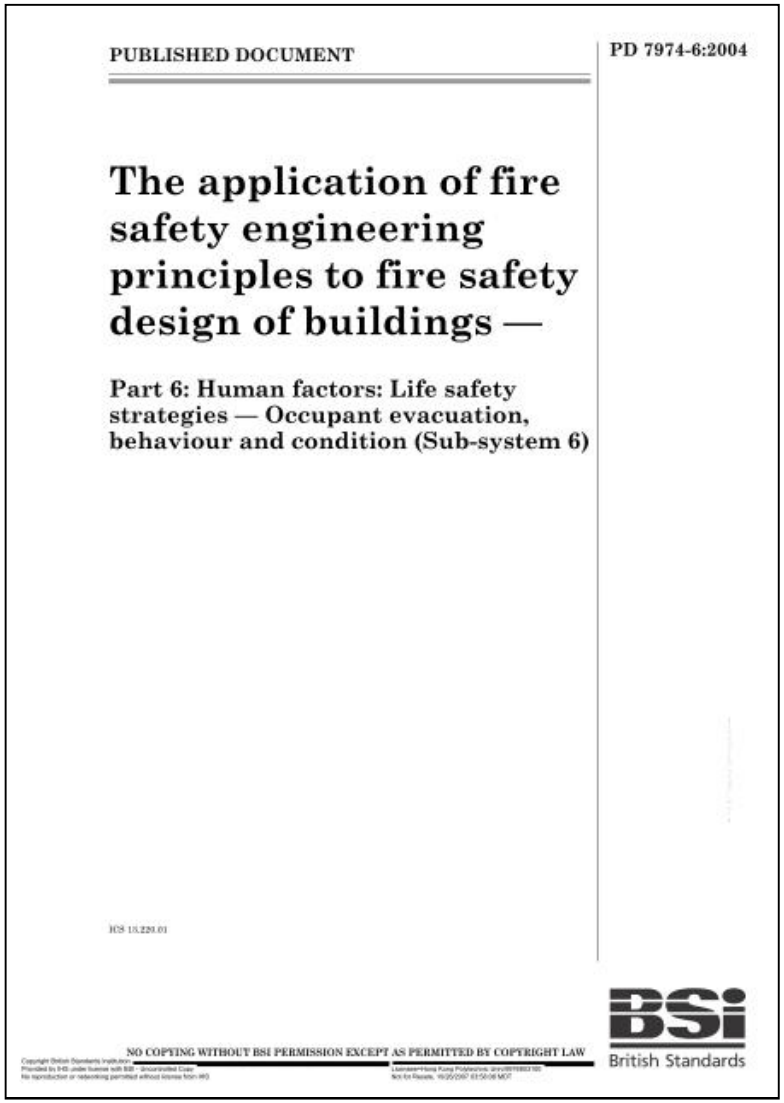
t_{system} - detection system response time

Pre-movement Time

- Time interval between a warning of fire is received and the first occupant move towards an exit

- According to PD 7974-6:2004: “The quantification of pre-movement time is highly influenced by aspects of human behaviour”

PD 7974-6:2004



PUBLISHED DOCUMENT

PD 7974-6:2004

The application of fire safety engineering principles to fire safety design of buildings —

Part 6: Human factors: Life safety strategies — Occupant evacuation, behaviour and condition (Sub-system 6)

ICS 13.220.01

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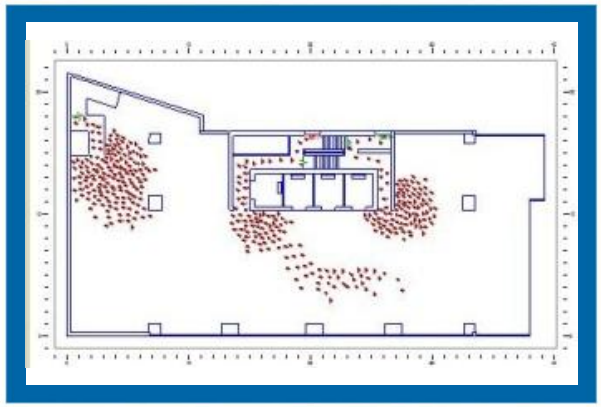
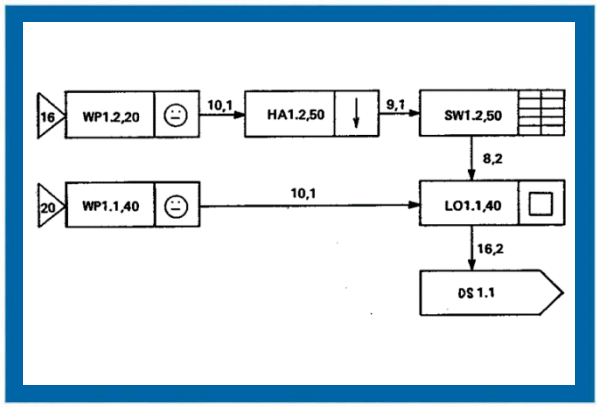
British Standards

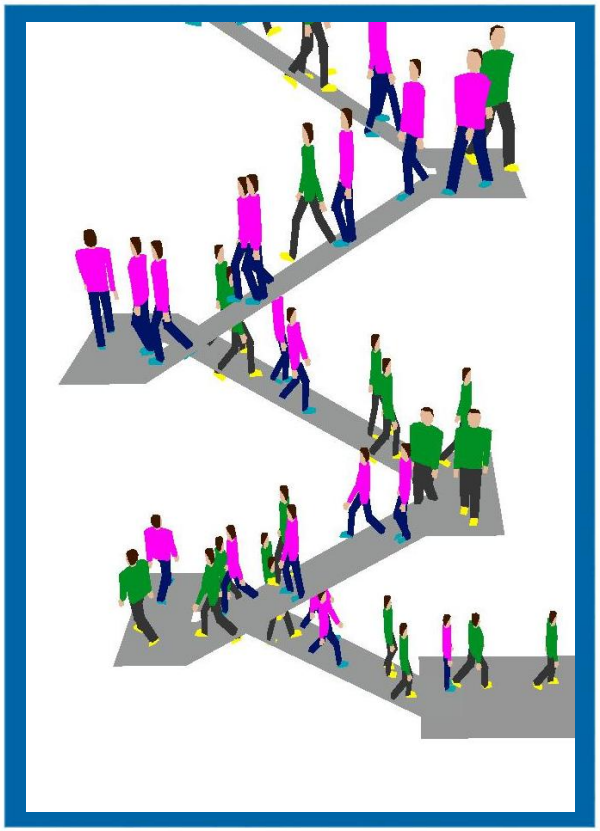
- Occupant behaviours in escape depend on:
  1. Building characteristics
  2. Occupant characteristics

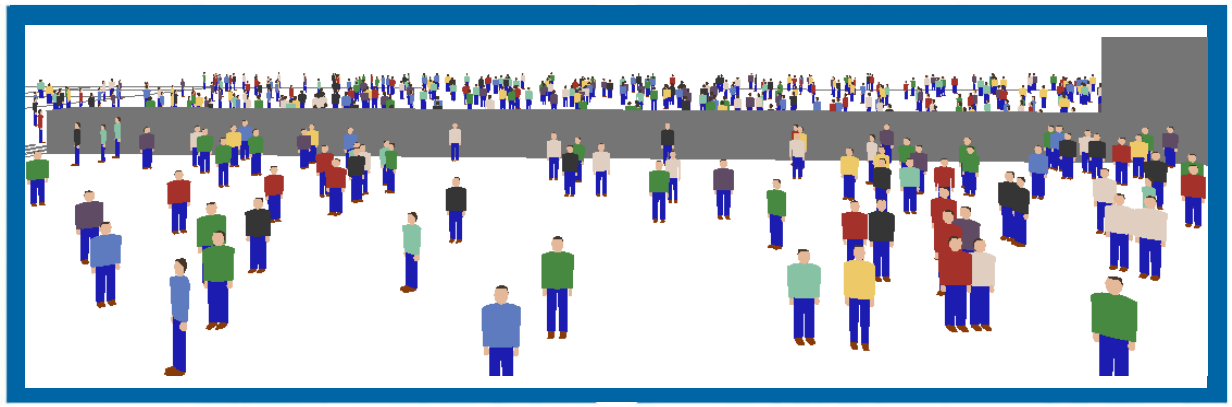
Occupant Behaviours

- Depend on a range of factors:
  - Occupant characteristics
    - Occupant profile
    - Awareness
    - Familiarity with the building
  - Building characteristics
    - Occupancy type
    - Building layout
    - Occupant density









Occupant Characteristics

Occupant Characteristics: Occupant Profile

- Physical ability of occupants are affected by:
  - Gender
    - Male, female
  - Age
    - Adult, child, elderly
  - Mobility
    - Normal, disabled

Affect walking speed

- Average walking speed

Male	Female	Child	Elderly	Disabled
1.2m/s	1m/s	0.9m/s	0.8m/s	0.6m/s
100%	83%	75%	67%	50%

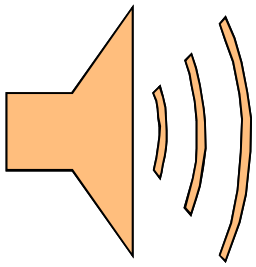
Occupant Characteristics: Awareness

- Refers to the occupant's state of alertness
- Depends on the occupant's ability to perceive danger signals:
  - Ability to see
  - Ability to hear
  - Ability to smell
  - Ability to feel

Occupant Characteristics: Awareness

- In the initial moments of fire, upon hearing the fire alarm, it is often observed that occupants do not react, and deny or ignore the situation

- Bryan (1995) studied that occupants do not respond well to non-voice alarms, such as alarm bells and sounders



Occupant Characteristics: Awareness

- Occupants are uncertain about what the signal indicates
  - Some occupants might fail to recognize it as an alarm bell
  - Some occupants might decide that the alarm is merely a system test
  - Especially true in public buildings where occupants do not want to overreact to a false alarm or a situation that is already under control
- Extend the pre-movement time for a building

Occupant Characteristics: Awareness

- Pre-movement time has been studied in two ways:
  - During fire drills
  - From fire victim interviews

- Perfect fire drill study should be conducted if the drill is non-announced
  - Represent exactly the situation that occupants would face if the fire was located on another floor of the building and the sudden sound of the fire alarm signal

Literature Reviews on Fire Drills

Occupancy type	Residential Building	Office Building	Retail Store	Underground Transport System
Researchers	Proulx and Fahy	Proulx and Pineau	Shields, Boyce and Silcock	Proulx and Sime
Year	1997	1996	1998	1991
No. of occupants under drills	Over 500	Over 1000	Not mention	Not mention
Average pre-movement time	Around 4 minutes	50s	25s	15s (after receiving the voice communication message
Spent time on pre-movement of occupants before leaving	• Getting dressed • Gathering children and/or pets • Taking purse, wallet and keys	• Finished phone calls • Saved data on computers • Secured files • Gathered belongings	• N/A	• Kept waiting for their train • Reading • Standing and never made a move

Occupant Characteristics: Familiarity with the Building

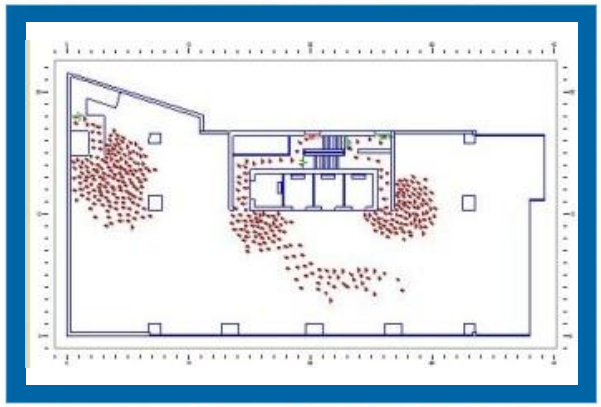
- Familiarity with a building will have a major impact on occupants' choice of evacuation route
- Non-familiar occupants are more likely to attempt to exit by the way they entered the building even though an emergency exit might be closer to their location
  - Occupants are unlikely to try a new unknown route during an emergency
- An open exit attracts more occupants than a closed exit
  - Occupants would be more likely to use the fire exit if they are able to see that it leads to the outside

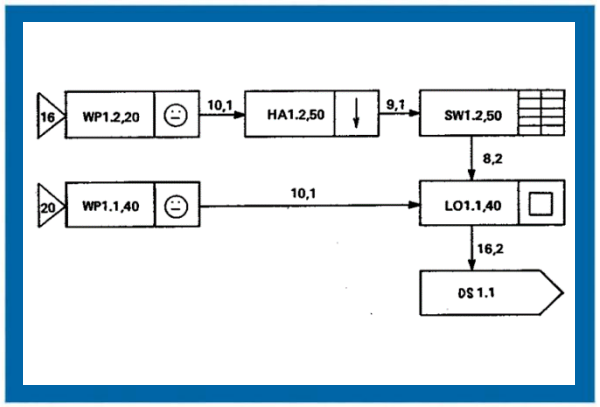
Behavioural Issues Associated With Building Use

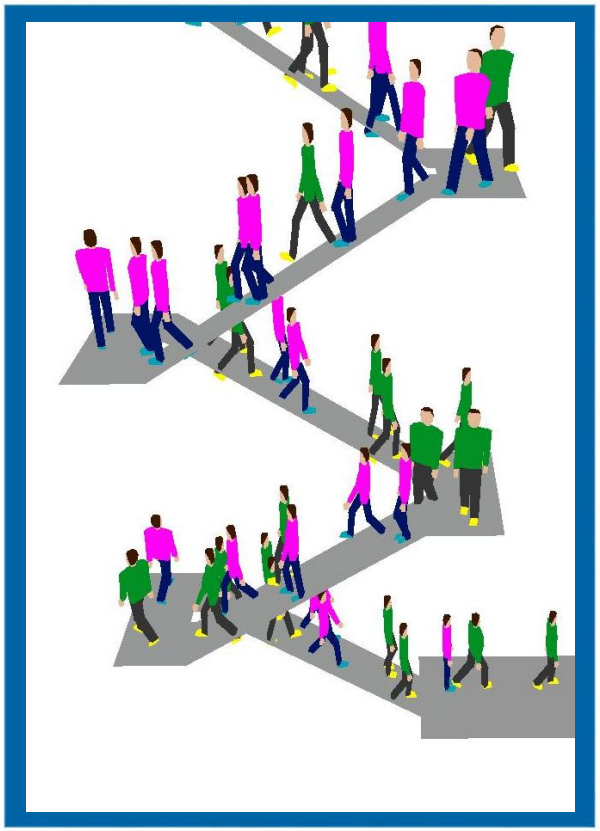
	Office	Residential	Health Care Facilities
Nature of occupants	• Better prepared to evacuate the building • Typically trained thro' evacuation drills • Dressed, alert and mainly responsible for themselves • More familiar with egress routes	• Maybe asleep, not ready to evacuate • Not dressed, long delay in start of evacuation • Longer pre-movement times than other buildings • Potential re-entry behaviour	• Involve people with temporary or permanent disabilities and mobility impairments

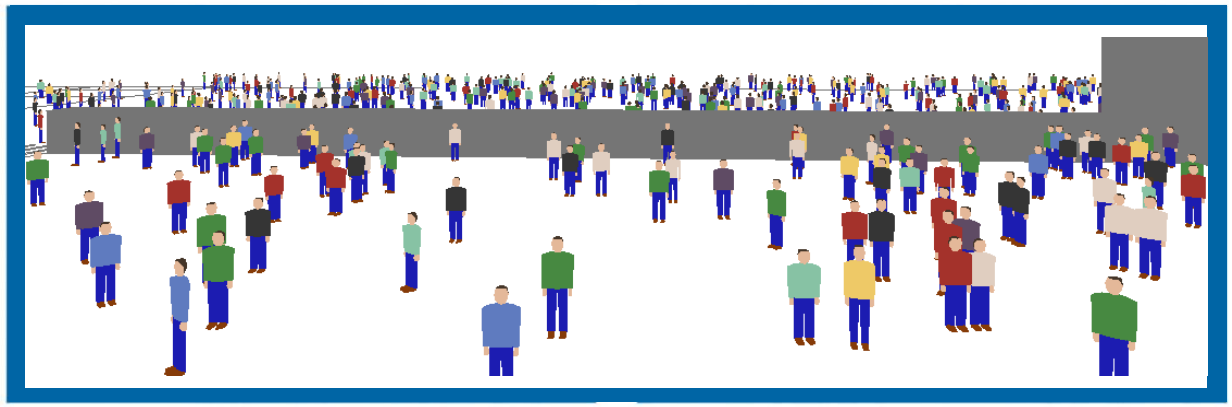
Behavioural Issues Associated With Building Use

	Office	Residential	Health Care Facilities
Specific issues	• Fire systems generally well maintained • May include recorded voice messages and fire alarms • Trained staff to facilitate evacuation	• Information spread is slower due to compartment ation	• Staff to assist evacuation but ratios may depend upon the time of the day • Many problems need to be addressed such as issues concerning fatigue, way-finding, use of vertical egress components (e.g. stairs, lifts)









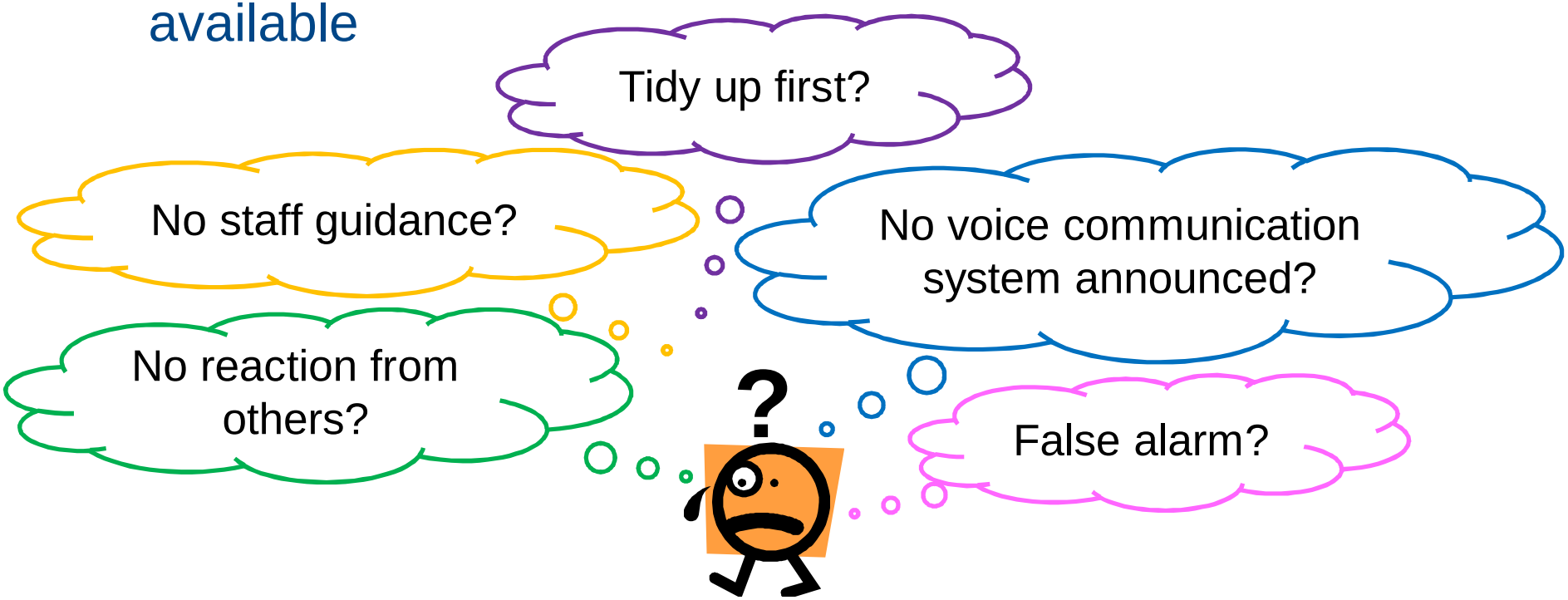
Building Characteristics

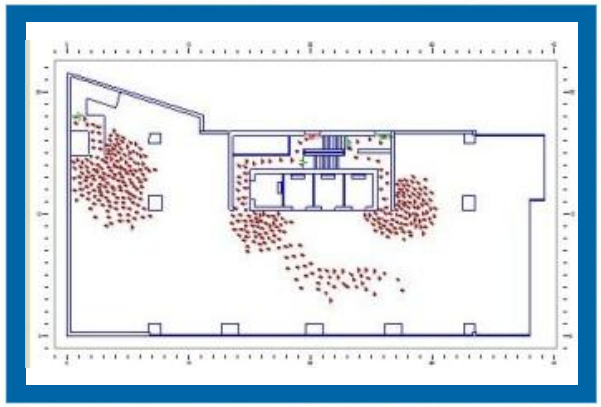
Building Characteristics

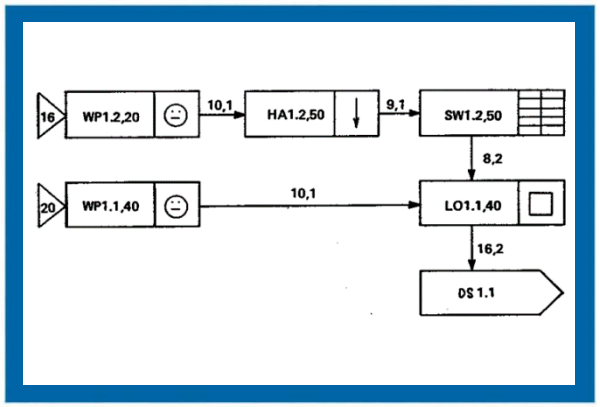
- Building layout such as single or multiple enclosures and spatial complexity affects the movement of occupants
- Warning system
- Fire safety management and staff/occupant training

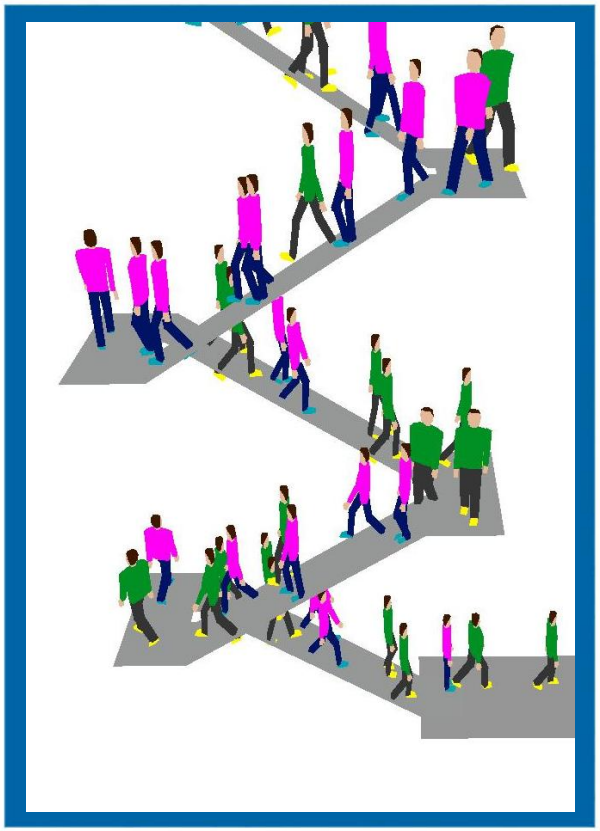
Pre-movement Time

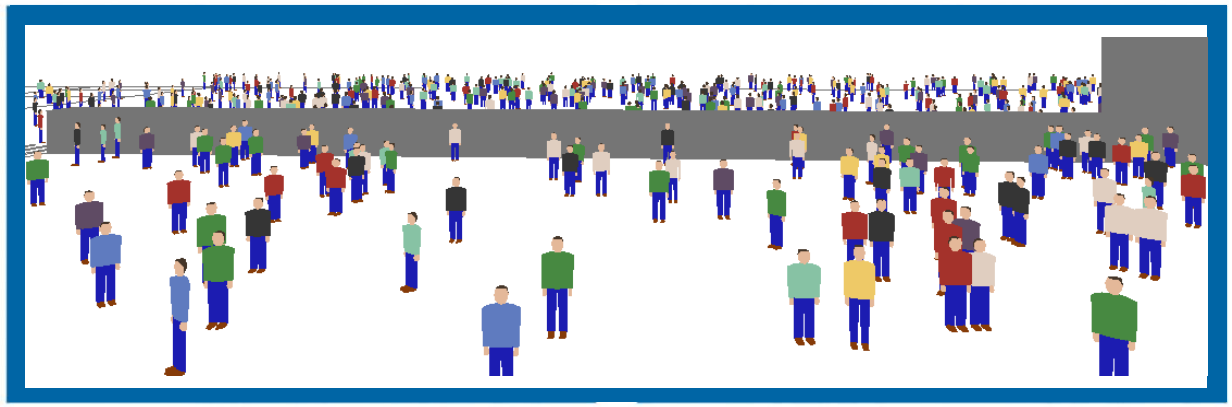
- Pre-movement time depends on the type of warning obtained and varies according to the information available











How to Quantify Pre-movement Time?

PD 7974–6:2004
Design Behavioural Scenarios and Occupancy Type

Table 1 — Design behavioural scenarios and occupancy types

Category	Occupant alertness	Occupant familiarity	Occupant density	Enclosures/ complexity	Examples of Occupancy types
A	Awake	Familiar	Low	One or many	Office or industrial
B1	Awake	Unfamiliar	High	One or few	Shop, restaurant, circulation space
B2	Awake	Unfamiliar	High	One with focal point	Cinema, theatre
Ci	Asleep Long term: individual occupancy.	Familiar	Low	Few	Dwelling Without 24 h on site management.
Cii	Managed occupancy:				Serviced flats, halls of residence, etc.
Ciii	Asleep	Unfamiliar	Low	Many	Hotel, hostel
D	Medical care	Unfamiliar	Low	Many	Residential (institutional)
E	Transportation	Unfamiliar	High	Many	Railway station/Airport

*** Extracted from PD 7974-6, The application of fire safety engineering principles to fire safety design of buildings – Part 6: Human factors: Life safety strategies – Occupant evacuation, behaviour and condition (Sub-system 6), British Standards Institution, London, 2004*

PD 7974–6:2004

- According to PD7974-6, pre-movement time distributions are further dependent upon a range of variables
  - Quality of the alarm system
  - Complexity of the building
  - Quality of the fire safety management

PD 7974–6:2004 Quality of the Alarm System

Alarm system level	Automatic detection	Activation of alarm
A1	Yes (Throughout building)	Immediate general alarm
A2	Yes (2 state alarm with pre-alarm to management or security)	Manual activation of general alarm / general alarm after a fixed delay
A3	No (Local automatic detection and alarm only)	Manual activation of general alarm

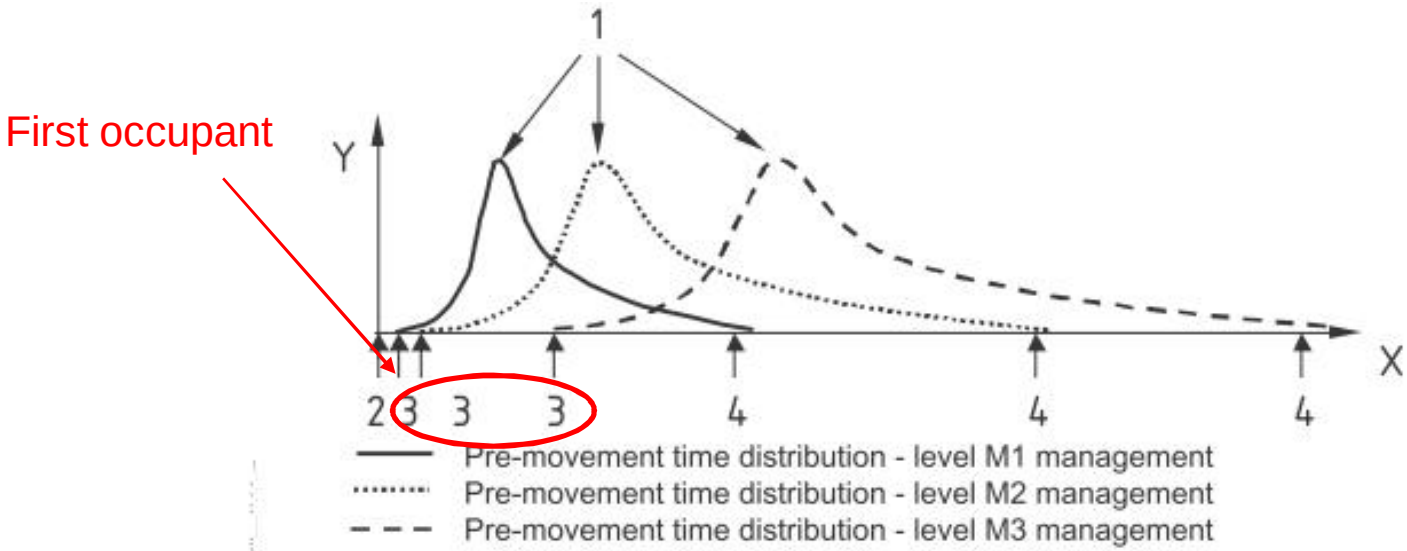
PD 7974–6:2004 Complexity of the Building

Building level	Configuration	Examples
B1	• Simple rectangle single storey building • One or few enclosures and simple layout with good visual access • Good level of exit provision	Simple supermarket
B2	• Simple multi-enclosure (multi-storey) building • Simple internal layouts	Simple multi-storey office block
B3	• Large complex building • Large building complexes with a number of existing buildings on the same site	Leisure centers, shopping centers, airports

PD 7974–6:2004 Quality of the Fire Safety Management

Management level	Provisions	Staff ratio
M1	• Normal occupants (staff or residents) should be trained to a high level of fire safety management with good fire prevention and maintenance practice, a well-developed emergency plan and regular drills • A voice alarm system should be provided in public	High
M2	• Similar to M1	Low
M3	• Basic minimum fire safety management • Not suitable for a fire-engineered design	Minimal

PD 7974–6:2004 Quality of the Fire Safety Management



Key

X Time

Y Persons/s

1 $\Delta t_{pre\ (occupant\ distribution)}$

2 Alarm

3 $\Delta t_{pre\ (first\ occupants)}$

4 99th percentile

NOTE Pre-movement of first occupants to move and subsequent pre-movement time distribution is lengthened by progressively lower levels of fire safety management.

Figure C.1 — Representation of pre-movement time distributions and effects of different levels of fire safety management

*** Extracted from PD 7974 -6, The application of fire safety engineering principles to fire safety design of buildings – Part 6: Human factors: Life safety strategies – Occupant evacuation, behaviour and condition (Sub-system 6), British Standards Institution, London, 2004*

PD 7974–6:2004 Pre-movement Time

Table C.1 — Suggested pre-times for different design behavioural scenario categories

Scenario category and modifier	First occupants $\Delta t_{pre\ (1st\ percentile)}$	Occupant distribution $\Delta t_{pre\ (90th\ percentile)}$[a]
A: awake and familiar		
M1 B1 – B2 A1 – A2	0.5	1.0
M2 B1 – B2 A1 – A2	1	2
M3 B1 – B2 A1 – A3	*>15*	*>15*
For B3, add 0.5 for wayfinding		
M1 would normally require voice alarm/PA if unfamiliar visitors likely to be present		
B: awake and unfamiliar		
M1 B1 A1 – A2	0.5	2
M2 B1 A1 – A2	1.0	3
M3 B1 A1 – A3	*>15*	*>15*
For B2 add 0.5 for wayfinding		
For B3 add 1.0 for wayfinding		
M1 would normally require voice alarm/PA		
Ci: sleeping and familiar		
(e.g. dwellings – individual occupancy)		
M2 B1 A1	*5*	*5*
M3 B1 A3	*10*	*>20*
For other units in a block assume one hour		
Cii: managed occupancy		
(e.g. serviced apartments, hall of residence)		
M1 B2 A1 – A2	*10*	*20*
M2 B2 A1 – A2	*15*	*25*
M3 B2 A1 – A3	*>20*	*>20*
Ciii sleeping and unfamiliar		
(e.g. hotel, boarding house)		
M1 B2 A1 – A2	*15*	*15*
M2 B2 A1 – A2	*20*	*20*
M3 B2 A1 – A3	*>20*	*>20*
For B3, add 1.0 for wayfinding		
M1 would normally require voice alarm/PA		
D: medical care		
Awake and unfamiliar (e.g. day centre, clinic, surgery, dentist)		
M1 B1 A1 – A2	0.5	2
M2 B1 A1 – A2	1.0	3
M3 B1 A1 – A3	*>15*	*>15*
For B2 add 0.5 for wayfinding		
For B3 add 1.0 for wayfinding		
M1 would normally require voice alarm/PA		
Sleeping and unfamiliar (e.g. hospital ward, nursing home, old peoples' home)		
M1 B2 A1 – A2	5[b]	10[b]
M2 B2 A1 – A2	10[b]	20[b]
M3 B2 A1 – A3	*>10*[b]	*>20*[b]
For B3 add 1.0 for wayfinding		
M1 would normally require voice alarm/PA		
E: transportation (e.g. railway, bus station or airport)		
Awake and unfamiliar		
M1 B3 A1 – A2	1.5	4
M2 B3 A1 – A2	2.0	5
M3 B3 A1 – A3	*>15*	*>15*
M1 and M2 would normally require voice alarm/PA		

*** Extracted from PD 7974 -6, The application of fire safety engineering principles to fire safety design of buildings – Part 6: Human factors: Life safety strategies – Occupant evacuation, behaviour and condition (Sub-system 6), British Standards Institution, London, 2004*

PD 7974–6:2004 Pre-movement Time

Category

Building level

Alarm level

Management level

Table C.1 — Suggested pre-times for different design behavioural scenario categories

Scenario category and modifier	First occupants $\Delta t_{pre\ (1st\ percentile)}$	Occupant distribution $\Delta t_{pre\ (99th\ percentile)}$[a]
A: awake and familiar		
M1 B1 – B2 A1 – A2	0.5	1.0
M2 B1 – B2 A1 – A2	1	2
M3 B1 – B2 A1 – A3	*>15*	*>15*
For B3, add 0.5 for wayfinding		
M1 would normally require voice alarm/PA if unfamiliar visitors likely to be present		

$\Delta t_{pre\ (1st\ percentile)}$ – time from alarm to movement of first few occupants

$\Delta t_{pre\ (99th\ percentile)}$ – time from alarm to movement of last few occupants

Code of Practice for Fire Safety in Buildings 2011

Table G2 – Summary of Pre-movement Times

Pre-movement time	PD7974[1]		SFPE[2]	NZ Framework[3]		CIBSE Guide E[4]
	T1[a]	T2[b]		Origin	Remote	
Occupants are awake and familiar with the building (office, industrial)						
Voice alarm signal/ trained staff	0.5[c]	1[c]	< 1	0.5	1	1
Standard alarm signal throughout the building	1[c]	2[c]	3			
Local/ Standard Alarm Signal & non-trained staff	> 15[c]	> 15[c]	> 4			
Occupants are awake and unfamiliar with the building (Retail, restaurant, cinema, theatre)						
Voice alarm signal/ trained staff	0.5[d,e]	2[d,e]	< 2	0.5	1	3
Standard alarm signal throughout the building	1[d,e]	3[d,e]	3	1	2	
Local/ Standard Alarm Signal & non-trained staff	> 15[d,e]	> 15[d,e]	> 6			
Occupants are sleeping and familiar with the building (Dwelling – individual occupancy)						
Voice alarm signal/ trained staff	-	-	< 2	1	5	5
Standard alarm signal throughout the building	5	5	4			
Local/ Standard Alarm Signal & non-trained staff	10	> 20	> 5			
Occupants are sleeping and familiar with the building (Serviced flats, hall of residence)						
Voice alarm signal/ trained staff	10	20	< 2	1	5	5
Standard alarm signal throughout the building	15	25	4			
Local/ Standard Alarm Signal & non-trained staff	> 20	> 20	> 5			
Occupants are sleeping and unfamiliar with the building (Hotel, boarding house)						
Voice alarm signal/ trained staff	15	15	< 2	1	5	20
Standard alarm signal throughout the building	20	20	4		10	
Local/ Standard Alarm Signal & non-trained staff	> 20	> 20	> 6			
Occupants are awake and require assistance (Day care, clinic, dentist)						
Voice alarm signal/ trained staff	0.5[f]	2[f]	< 3	1	2	2
Standard alarm signal throughout the building	1[f]	3[f]	5			
Local/ Standard Alarm Signal & non-trained staff	> 15[f]	> 15[f]	> 8			
Occupants are sleeping and require assistance (Hospital, nursing home)						
Voice alarm signal/ trained staff	5	10	< 3	5	30	-
Standard alarm signal throughout the building	10	20	5			
Local/ Standard Alarm Signal & non-trained staff	> 10	> 20	> 8			

- Note a: Pre-movement time of the first few occupants
- Note b: Pre-movement time of the last few occupants
- Note c: For a large complex building, add 0.5min
- Note d: For a simple multi-storey building, add 0.5min
- Note e: For a large complex building, add 1.0min
- Note f: These times depend upon the presence of staff

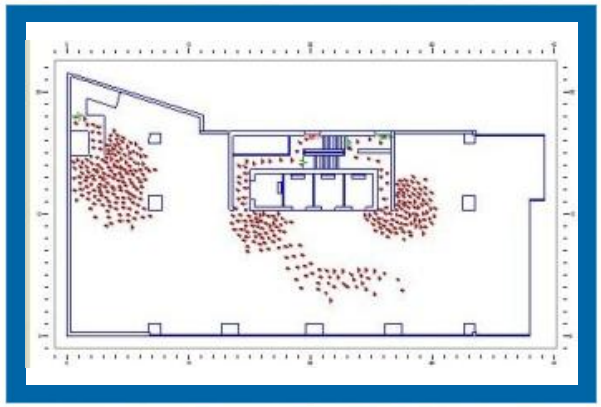
References used:

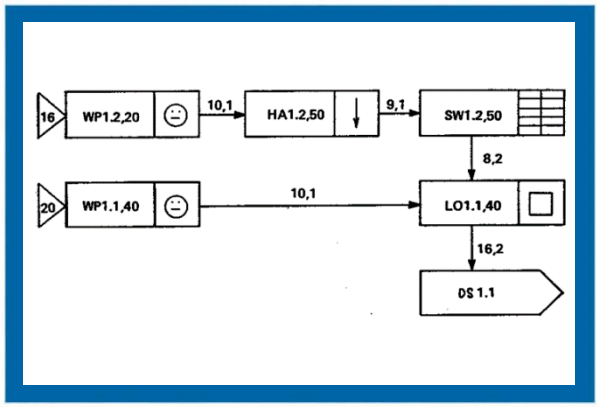
[1] PD 7974-6, The *Application of Fire Safety Engineering Principles to the Design of Buildings – Part 6: Human Factors: Life Safety Strategies – Occupant Evacuation Behaviour and Conditions (Sub-System 6)*, British Standards Institution, London, 2004.

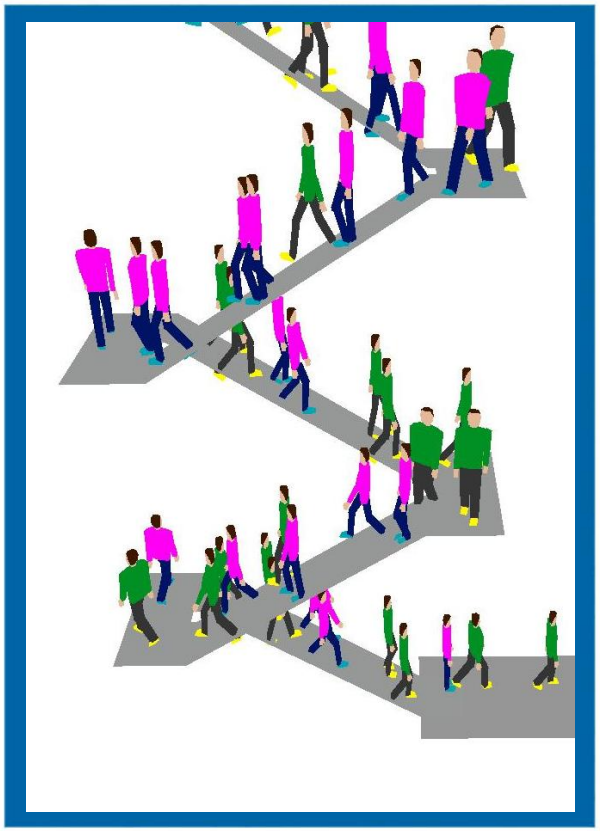
[2] Proulx, G., "Movement of People," in SFPE Handbook of Fire Protection Engineering, 3rd ed., Section 3, Chapter 13, P.J. DiNenno et al. (Eds.), National Fire Protection Association, Quincy, MA, 2002.

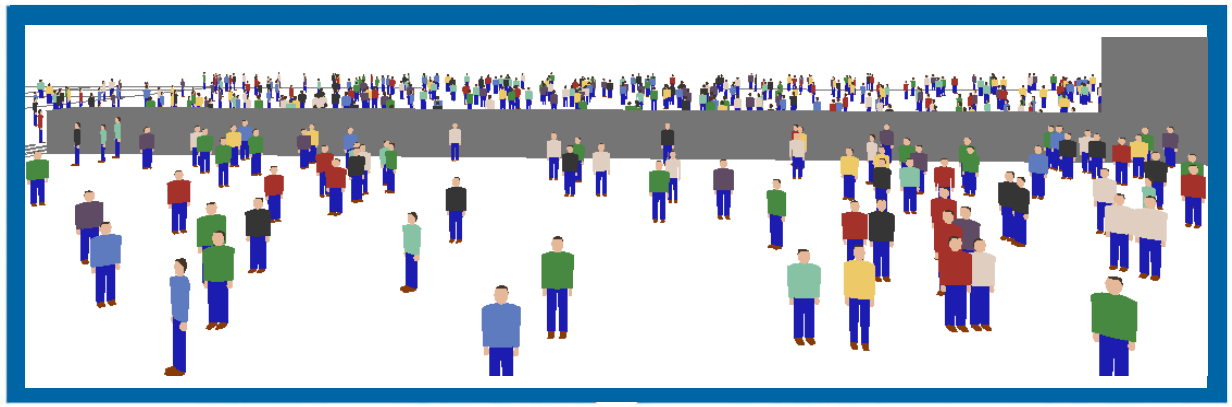
[3] Beever, P, et al., "A New Framework for Performance Based Fire Engineering Design in New Zealand," *8th International Conference on Performance-Based Codes and Safety Design Methods*, Sweden, 2010.

[4] CIBSE Guide E Fire Safety Engineering, Chartered Institution of Building Services Engineers, London, 3rd Edition, 2010.









Evacuation Time

Evacuation Time

Egress Components	Egress Strategies
Stairs	Total evacuation
Evacuation Elevators	Phased evacuation
Sky-bridges	Defend-in-Place
Refuge Floors	Delayed evacuation

Stairs

- Traditional method to evacuate a building
- Designed in accordance with Building Code requirements

Table B2

Table B2: Minimum number and width of exit doors and exit routes from a room, fire compartment or storey

Occupant Capacity of room, fire compartment or storey (No. of persons)	Minimum No. of exit doors or exit routes	Minimum total width (in mm)		Minimum Width (in mm) of each	
		Exit doors	Exit routes	Exit door	Exit route
4- 30	1			750	1050
31-200	2	1750	2100	850	1050
201-300	2	2500	2500	1050	1050
301-500	2	3000	3000	1050	1050
501-750	3	4500	4500	1200	1200
751-1000	4	6000	6000	1200	1200
1001-1250	5	7500	7500	1350	1350
1251-1500	6	9000	9000	1350	1350
1501-1750	7	10500	10500	1500	1500
1751-2000	8	12000	12000	1500	1500
2001-2250	9	13500	13500	1500	1500
2251-2500	10	15000	15000	1500	1500
2501-2750	11	16500	16500	1500	1500
2751-3000	12	18000	18000	1500	1500
>3000 persons - the number of exit doors, exit routes and their width to be determined by the Building Authority					

Stairs

Commentary

Floors containing more than 3000 people may be designed by fire engineering. This is particularly relevant for large floor area buildings such as exhibition spaces, conference halls, sports facilities.

Stairs

- Fatigue during stair evacuations in high-rise buildings (Children, Elderly etc.)
- Stair evacuation present significant issues regarding people with disabilities
- Counter flows – presence of fire-fighters during the stair evacuation

Evacuation elevators

- Traditional concept that elevators should not be used during an emergency
- Could be a faster and effective methods to evacute tall buildings
- Associated with the evacuation of people with disabilities using stairs

Problems concerning use of elevators

- Limited space in elevators may create crush of the people, restricted spaces and high density conditions
- Flame, heat and smoke may invade the elevator shaft, particularly, while elevators move, negative pressure will suck in smoke inside the elevator – *piston effect*
- Emergency power supply and water protection
- Pick-up locations – in a floor that can be occupied by large crowds and be linked to the

  area of refuge
- Willingness to use elevators
- Evacuation of mobility impaired

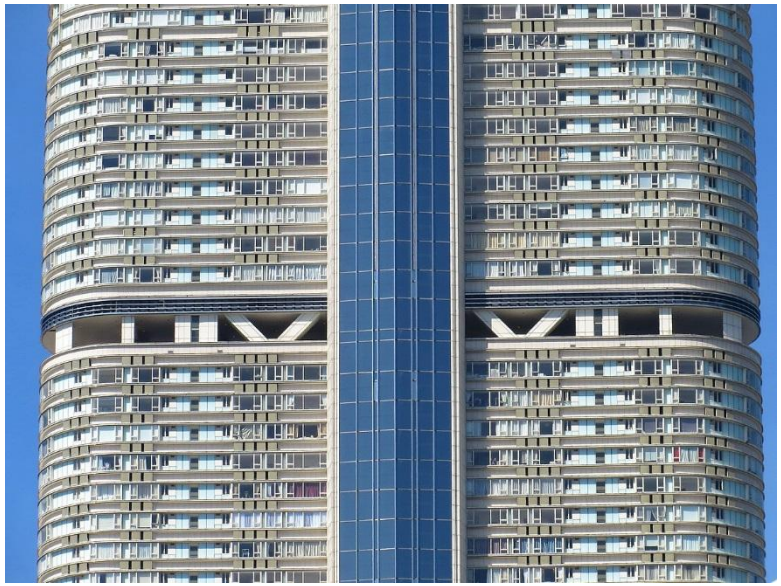
Sky-bridges

- Horizontal evacuation means at height – the use of sky-bridges link towers. E.g Petronas Towers in Malaysia
- Reduce vertical travel distance and the increase in the options available for the evacuation
- A sky-bridge should be placed at a level where there is the lift zoning changeover and in a position between higher and lower floors
- Effectiveness of sky-bridges

  are yet to be further studied

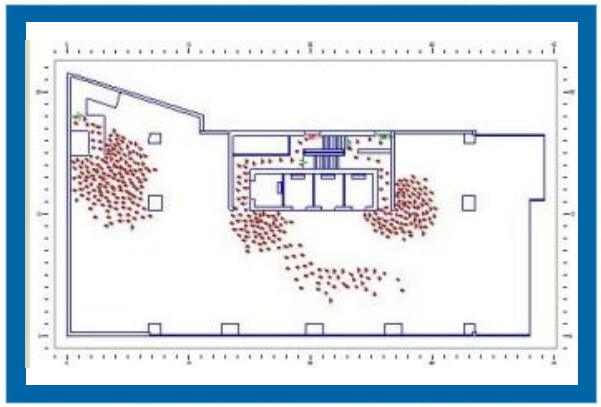
Refuge Floors

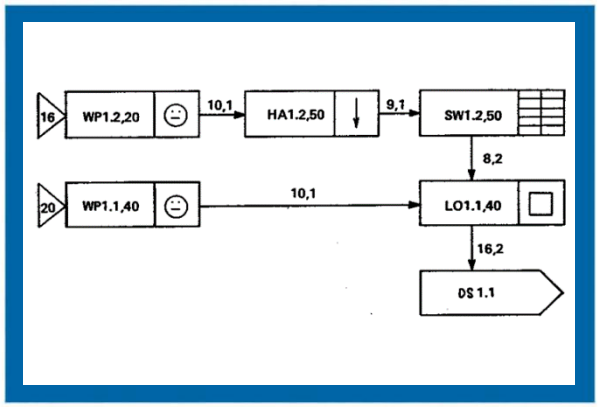
- Refuge floors are floors designated for holding occupants in a building
- From an evacuation perspective, advantages of refuge floors are:
  - A place of rest for the evacuees
  - Possibility of stairs or lift shafts filled with smoke is reduced
  - To protect people with disabilities and/or injured evacuees
  - Used as a command point for rescue teams to assist evacuation
  - Serve as a fire-fighting base
  - May serve as pick-up floors for lift evacuation

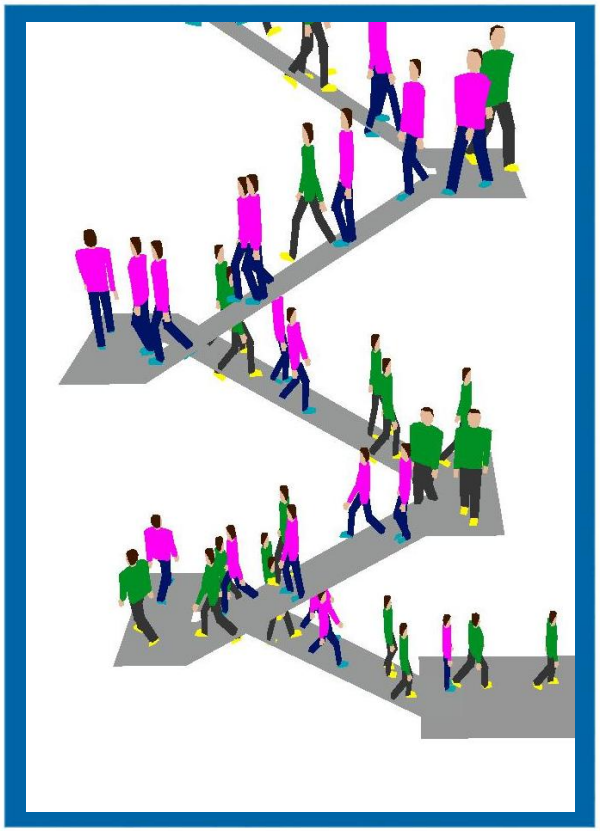


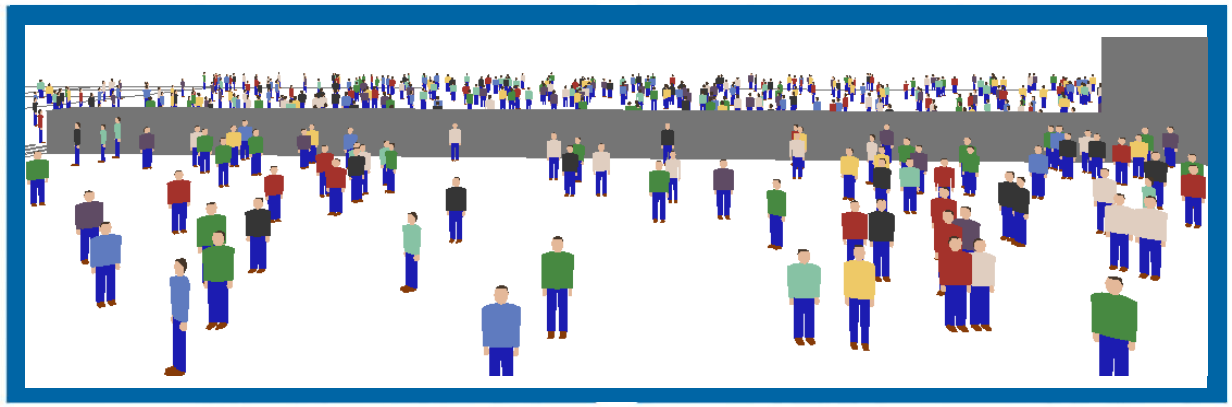
Egress Strategies

Total evacuation	Phased evacuation	Defend-in-place	Delayed evacuation
• Evacuate all building occupants at once • Large population involved in a high-rise building may cause significant high densities in the MoE	• Occupants in the most critical floors such as the fire floor and floors nearby will be prioritized for evacuation • Reduce people densities in the MoE • Compartmentation plays a key role • Effectiveness relies on type of FSI, staff training, adequate means of communication	• Occupants to shut the door and wait for rescue • Disabilities/mobility impairments • Suitable for: (1) Above 6 storeys (2) Residential with compartmentation (3) Building to be of non-combustible construction (4) An alarm system (5) Voice communication system • Lack of information is one of the main failure of this strategy	• Evacuees temporary wait at dedicated areas of refuge and assisted by rescuers • For injured occupants or disabilities such as health care facilities • Space available for evacuation is a main factor









ASET: Interaction Between Fire and People

Available Safe Egress Time (ASET)

- According to PD 7974-6:2004, the psychological and physiological effects of exposure to toxic smoke and heat in fires combine to cause varying effects on escape capability, which can lead to physical incapacitation and permanent injury or death

Available Safe Egress Time (ASET)

- ASET - tenability criteria:
  - Smoke layer height
  - Radiated heat transfer
  - Toxicity
  - Visibility
  - Smoke temperature

Available Safe Egress Time (ASET)

- Behaviour modifying or incapacitating effects includes:

	Smoke / flame	Optical smoke density	Inhalation of irritant smoke	Inhalation of toxic gas	Heat
Effects	• Fear of approaching smoke or heat-logged areas or escape routes	• Impaired vision	• Respiratory tract pain / breathing difficulties	• Asphyxiation • Confusion and loss of consciousness	• Pain to exposed skin and hyperthermia • Prevention of escape and leading to collapse
Criteria	• Smoke temperature • Smoke layer height	• Visibility	• Smoke layer height	• Toxicity	• Radiated heat transfer • Smoke temperature
FS Code 2011	• < 60ºC • > 2m	• > 10m	• > 2m	• CO < 1000ppm (>30min)	• < 2.5kW/m^2 • < 60ºC

Criteria for Temperature: SFPE handbook

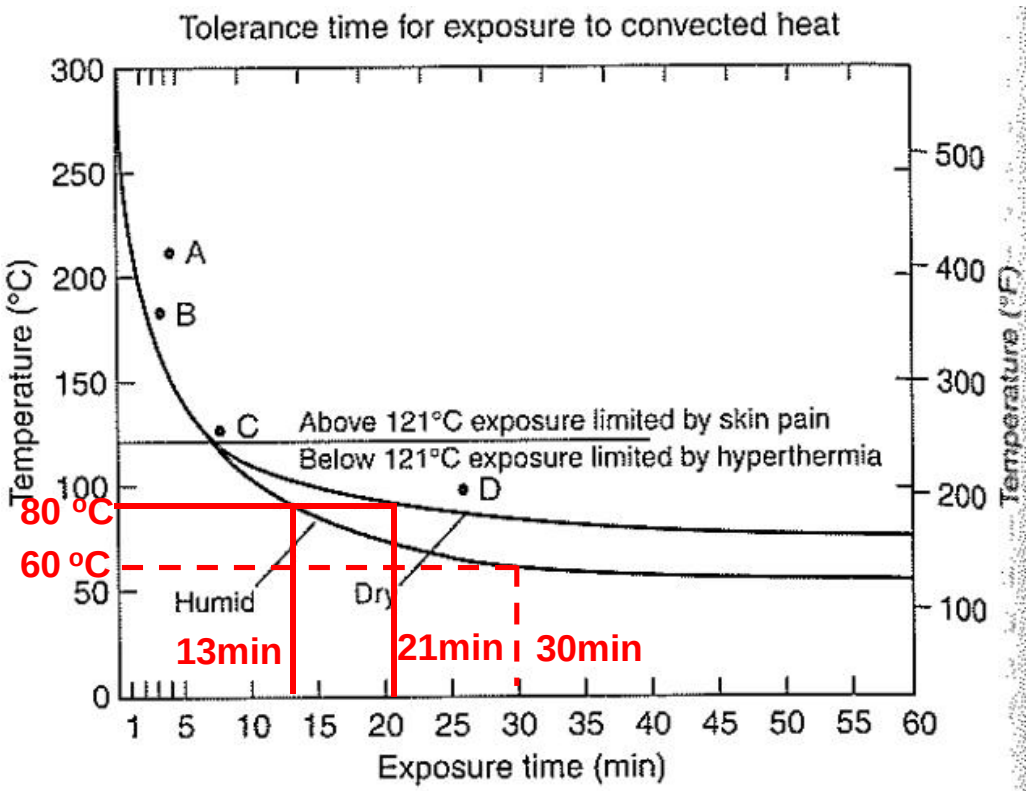


Figure 2-6.27. ***Thermal tolerance for humans at rest, naked skin exposed, with low air movement (less than 30 m/min). Adapted from Blockley.[117] See text and Table 2-6.17 for discussion of data points A to D.[116,119,120]***

*** Extracted from The SFPE handbook of fire protection engineering, 4th edition*

Criteria for Temperature: CIBSE Guide E

Table 6.6 Critical temperature for different exposure conditions

Type and period of exposure	Effect	Temperature / °C
Radiation	Severe skin pain	185*
Conduction (metal) (1 second)	Skin burns	60
Convection (30 minutes)	Hyperthermia	100
Convection (< 5 minutes)	Skin/lungs burns by hot gases	120
Convection (< 1 minute)	Skin/lungs burns by hot gases	190

* Black-body: 2.5 $kW \cdot m^{-2}$

Criteria for Temperature: NFPA 130 (2016 Edition)

- For unclothed or lightly clothed subjects, it might be more appropriate to use Equation B.2.1.1c:

$$t_{Iconv} = \left(5\times10^{7}\right)\ T^{-3.4} \qquad \textbf{(B.2.1.1c)}$$

where:

t_{Iconv} = time in minutes

T = temperature (°C)

Therefore, with

T = 120°C, t_{conv} = 4.2 minutes

T = 100°C, t_{conv} = 7.9 minutes

T = 80°C, t_{conv} = 16.9 minutes

T = 60°C, t_{conv} = 45.0 minutes

Criteria for Temperature: PD 7974-6:2004

Table G.3 — Tenability limits for radiative and convective heat

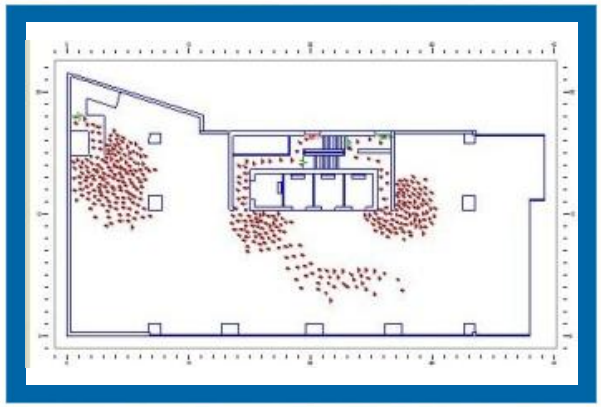
Mode of heat transfer	Intensity	Tolerance time
Radiation	<2.5 $kW \cdot m^{-2}$	>5 min
	2.5 $kW \cdot m^{-2}$	30 s
	10 $kW \cdot m^{-2}$	4 s
Convection	<60 °C 100 % saturated	>30 min
	100 °C < 10 % H_2O[a]	8 min
	110 °C < 10 % H_2O	6 min
	120 °C < 10 % H_2O	4 min
	130 °C < 10 % H_2O	3 min
	150 °C < 10 % H_2O	2 min
	180 °C < 10 % H_2O	1 min

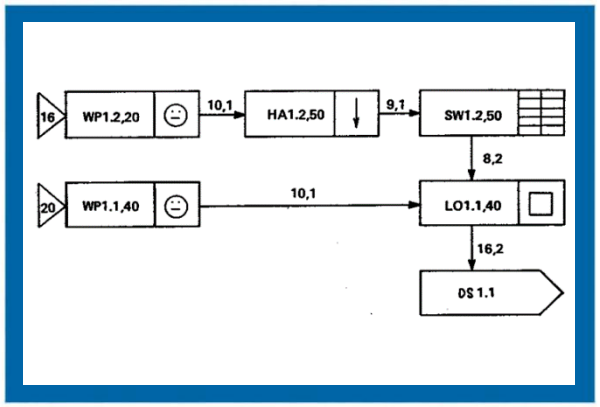
[a] v/v

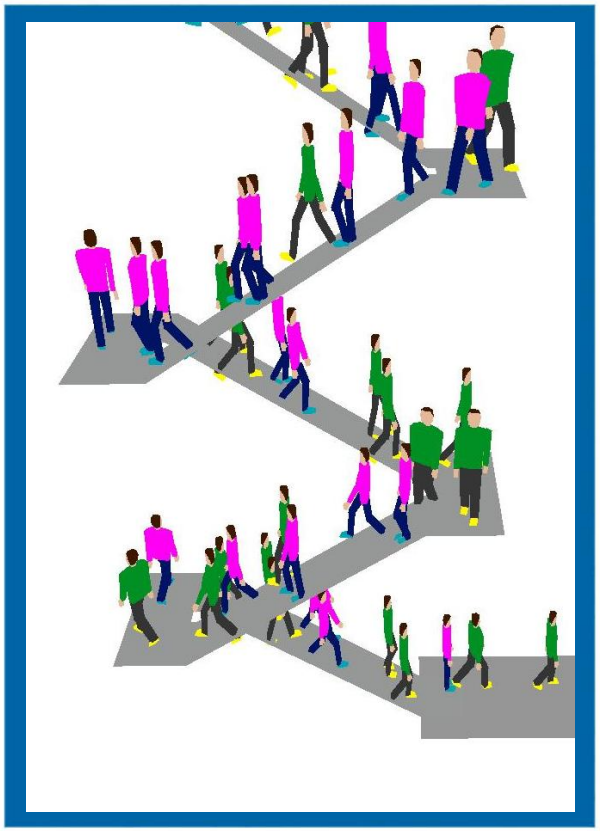
*** Extracted from PD 7974 -6, The application of fire safety engineering principles to fire safety design of buildings – Part 6: Human factors: Life safety strategies – Occupant evacuation, behaviour and condition (Sub-system 6), British Standards Institution, London, 2004*

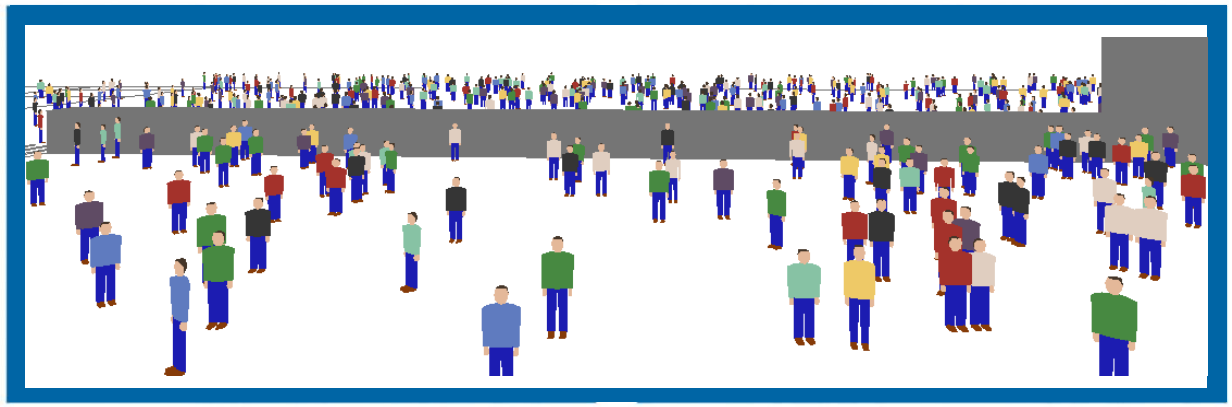
Criteria for Radiant Heat Flux

Standard	NFPA 130	BS7899-2 (COP-Assessment of Hazard to Life & Health from Fire)
Tenability limit for exposure of skin to radiant heat	2.5kW/m^2	2.5kW/m^2
Tolerance time below 2.5kW/m^2	30 minutes or longer	More than 5 minutes
Tolerance time above 2.5kW/m^2	Time to burning of skin due to radiant heat decreases rapidly $t_{frad} = 4q^{-1.35}$ where: t = time in minutes, q = radiant heat flux (kW/m^2)	Cause skin pain followed by burns within a few second









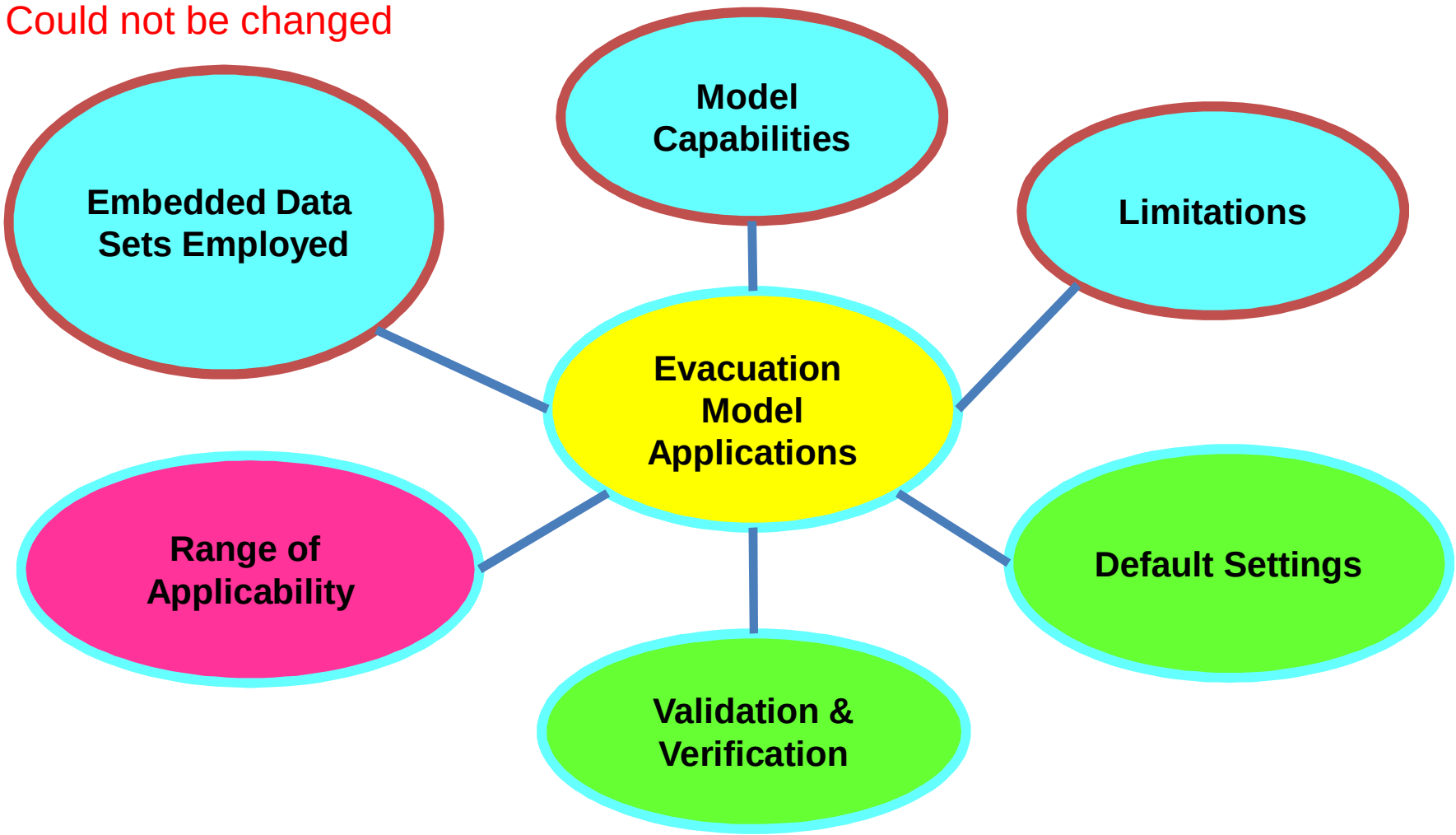
Evacuation Modeling and Technique

Evacuation Modeling and Technique

- Evacuation Model Review
- Special Feature
- Input Parameters

Evacuation Model Applications

Could not be changed



Evacuation Model Review

According to “A Review of Building Evacuation Models: 2nd Edition”, NIST 2010, model features are categorized as follows:

- Type of grid / structure of the method
- Movement of occupants
- Incorporation of fire effects
- The use of computer-aided design (CAD) drawings
- Visualization methods
- Model availability
- Modeling method
- Model purpose
- Model view of the occupants
- Occupants’ view of the building
- Behaviour of the occupants
- Validation methods

Type of Grid / Structure of the Model

To assign the method of occupant movement throughout the building model.

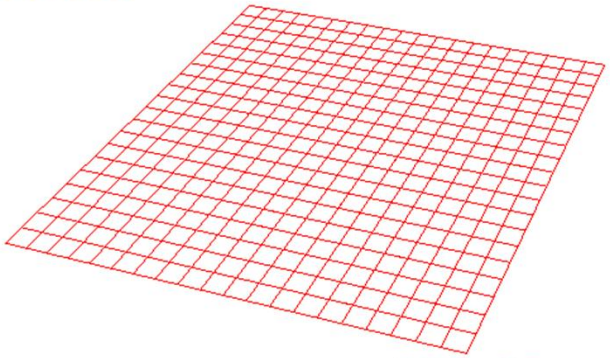
<u>Coarse Network Model</u>

- The space is represented as a network of nodes and arcs, representing different parts of the infrastructure (e.g. rooms, stairs etc.)
- The simplest method to simulate an evacuation scenario
- Advantages: fast computational time
- Limitations: simple representation of the evacuation which does not include many of the behaviours that occur in evacuation
- Example: EXIT89

Type of Grid / Structure of the Model

<u>Fine Network</u>

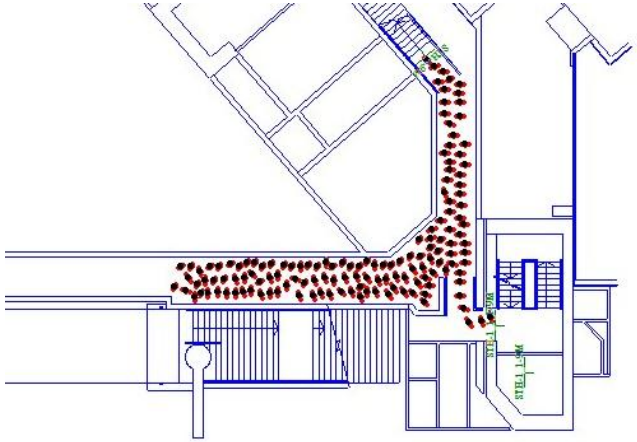
- This model divides a floor plan into a number of small grid cells (0.5m x 0.5m) that the occupants move to and from.
- Grid cells commonly allow for only one occupant at a time.
- Example: STEPS, Building Exodus, PedGo



Type of Grid / Structure of the Model

Continuous Network

- This model applies a 2-D continuous plan to the floor plans of structure, allowing the occupants to walk from one point in space to another throughout the building.
- The occupants are not tied to a specific cell, but there are often rules that limit the minimum distance between occupants.
- Example: Pathfinder, Simulex, Legion, Simwalk



Evacuation Model Review
- Movement of Occupants

Continuous Structure

- Occupant Density
- Inter-person Distance

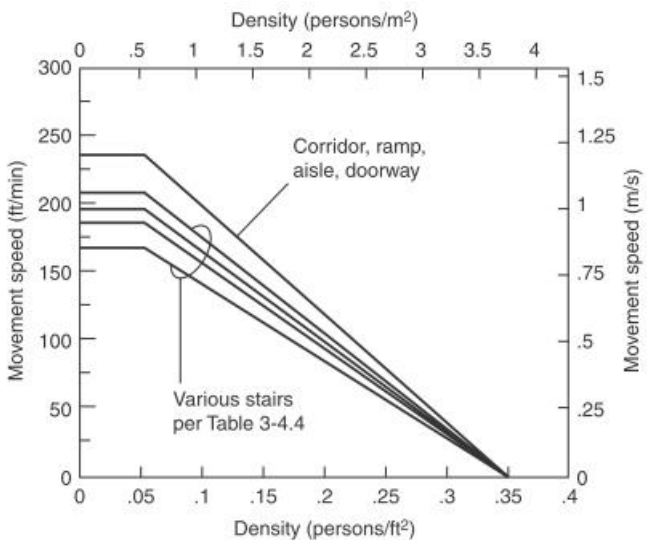
Fine Grid

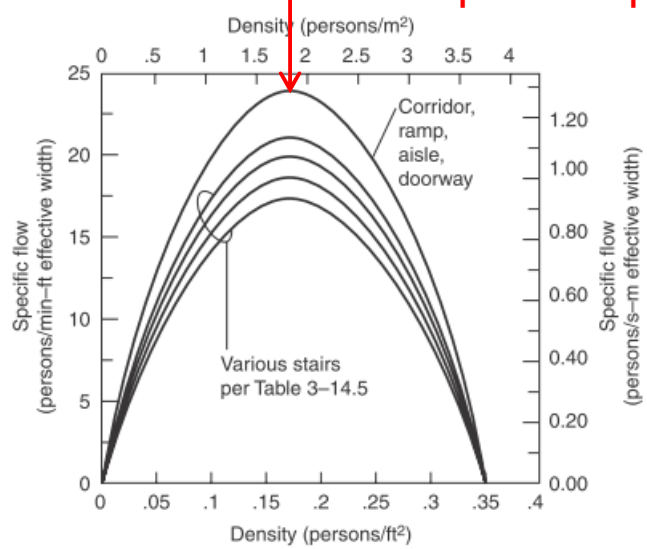
- Potential
- Decision Process

Evacuation Model Review
- Movement of Occupants - Occupant Density

- A very important factor in determining the occupant flow
- Can be varied greatly, depending on the function or use of the premises
- Assigns a speed and flow to individuals or populations based on the density of the space.

Optimum point





*** Extracted from SFPE Handbook*

Speed

Flow

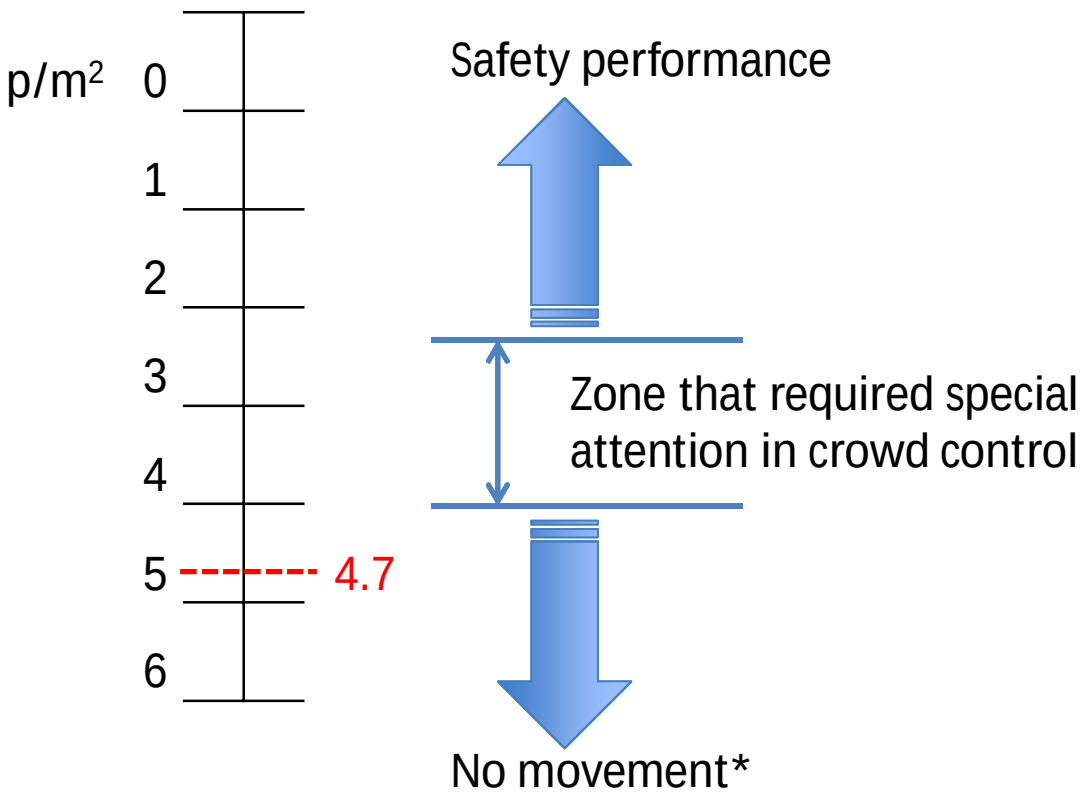
Evacuation Model Review
- Movement of Occupants - Occupant Density

- According to The Green Guide (1997), The Purple Guide (1999) and The Primrose Guide (1998), the safety limit for crowd density is defined as
  - 40 people in $10m^2$ for a moving crowd
  - 47 people in $10m^2$ for standing areas

Researcher	Field survey location	Restricted movement density
Ando et al. (1988)	Railway stations	$4p/m^2$
Still (2000)	Wembley stadium	$4.7p/m^2$

Evacuation Model Review
- Movement of Occupants - Occupant Density

- It is concluded that the occupant density not exceeding 4.7p/m^2 is acceptable for a safe condition for evacuation



** G.K. Still (2000). PhD Thesis. Crowd Dynamics, University of Warwick*

Evacuation Model Review
- Movement of Occupants - Occupant Density

- Still (2000) illustrated a figure of showing a packing to four people per square meter

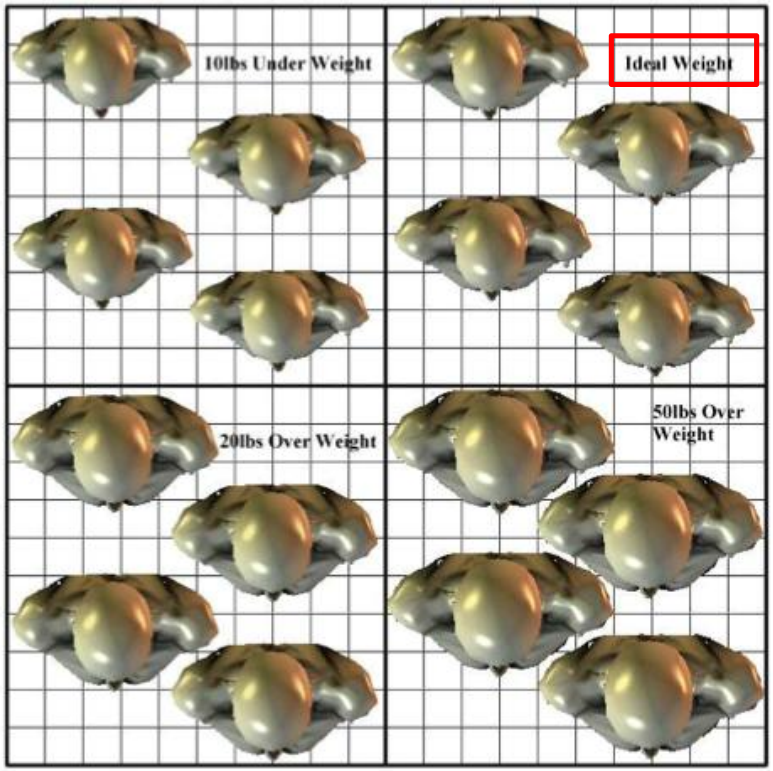


Figure 58 - Packing to four people per square metre

**Ideal weight is taken as an occupant of 500mm by 300mm profile

*** Extracted from G.K. Still (2000). PhD Thesis. Crowd Dynamics, University of Warwick*

Evacuation Model Review
- Movement of Occupants - Occupant Density

- A field survey at Wembley stadium is conducted by Still in 2000 found that a density of 4.7ppl/m^2 is still possible

Figure 9 - View from top of players tunnel - bidirectional crowd flow.

*** Extracted from G.K. Still (2000). PhD Thesis. Crowd Dynamics, University of Warwick*

Evacuation Model Review
- Movement of Occupants - Occupant Density

- Density of 4.7ppl/m^2
  - Still flows in a bi-directional manner
- Density > 4.7ppl/m^2
  - Very tightly packed
  - No clear sense of direction

Figure 10 - Zoom of Figure 9 showing the ***fingering*** patterns forming

Figure 22 - The heads and faces show no clear sense of direction in this crowd.

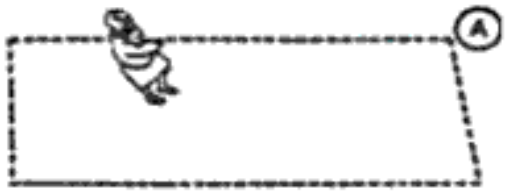
*** Extracted from G.K. Still (2000). PhD Thesis. Crowd Dynamics, University of Warwick*

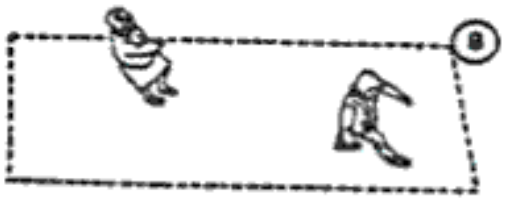
Evacuation Model Review
- Movement of Occupants - Occupant Density

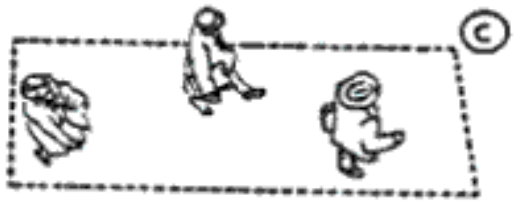
Fruin - Levels of Service (LoS)

- Criteria for safety standards in places of public assembly
- The level of service concept where the density and speed relationship are stated as guidelines for comfort and safety
- Measurements in a pedestrian street environment
- Pedestrian profile: 579mm by 330mm

Evacuation Model Review
- Movement of Occupants - Occupant Density



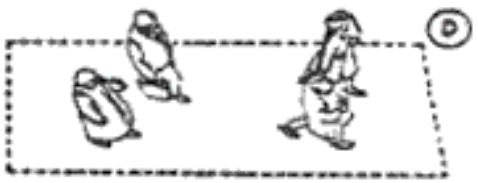




LoS	Density p/m²	Average speed m/s	Movement
A	< 0.31	> 1.3	Free flow
B	0.31 – 0.43	1.27	Minor conflicts
C	0.43 – 0.72	1.22	Some restrictions to speed

*** Extracted from Egress design solutions – A guide to evacuation and crowd management planning, Wiley*

Evacuation Model Review
- Movement of Occupants - Occupant Density

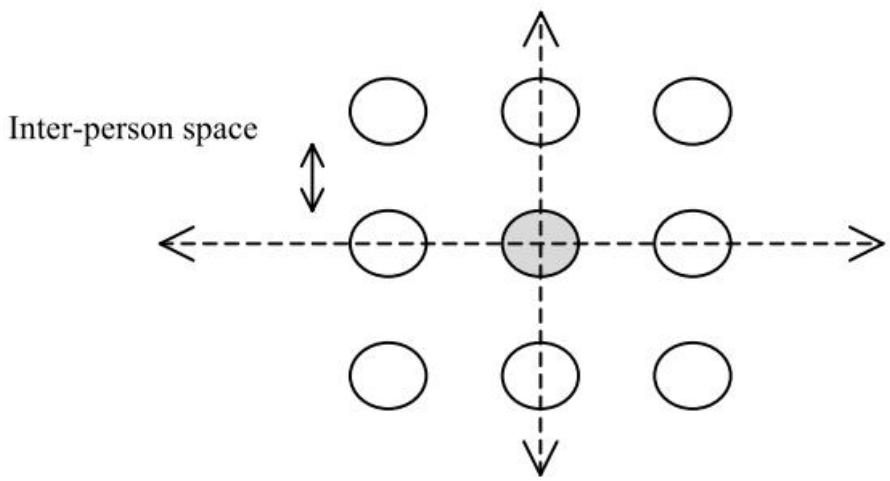


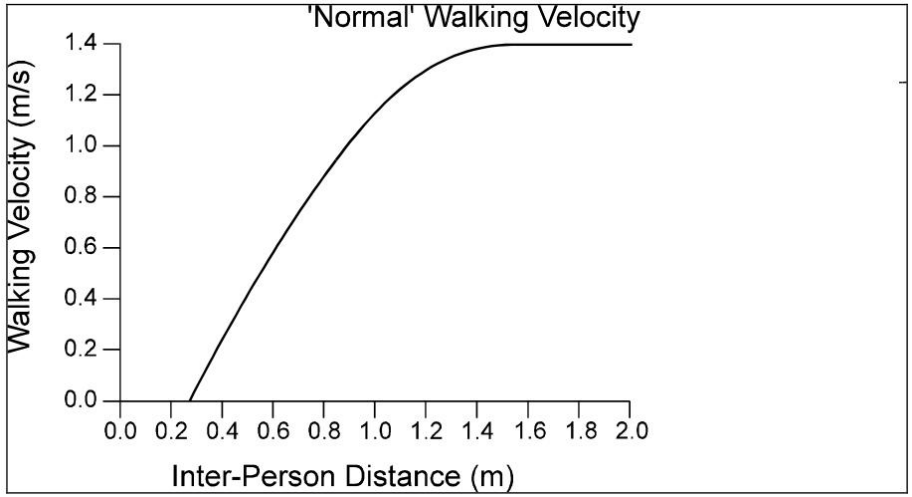
LoS	Density p/m²	Average speed m/s	Movement
D	0.72 – 1.08	1.14	Restricted movement for most
E	1.08 – 2.17	0.76	Restricted movement for all
F	> 2.17	0.76	Shuffling movement for all

*** Extracted from Egress design solutions – A guide to evacuation and crowd management planning, Wiley*

Evacuation Model Review
- Movement of Occupants - Inter-person distance

- Each individual is surrounded by a 360° “bubble” that requires them to have a certain minimum distance from other occupants, obstacles, and components of the building (walls, corners, handrails, etc.)





Evacuation Model Review
- Movement of Occupants - Potential

- Each grid cell in the space is given a certain number or potential value (e.g. STEPS or “distance map” in Simulex)
- This value is proportional to the distance from the exit
- Occupants follow a potential map and attempt to lower their potential with every step or grid cell to which they travel

Exit

5	4	3	2	1	0	1	2	3	4	5
7.5	5.6	3.9	2.4	1.4	1	1.4	2.4	3.9	5.6	7.5
10.7	7.6	5.2	3.5	2.4	2	2.4	3.5	5.2	7.6	10.7
15.0	10.6	7.3	5.2	3.9	3	3.9	5.2	7.3	10.6	15.0
21.2	15.0	10.6	7.6	5.6	4	5.6	7.6	10.6	15.0	21.2
30.0	21.2	15.0	10.7	7.5	5	7.5	10.7	15.0	21.2	30.0
42.2	29.7	20.8	14.4	9.6	6	9.6	14.4	20.8	29.7	42.2
58.7	40.8	27.9	18.6	11.9	7	11.9	18.6	27.9	40.8	58.7
80.2	54.7	36.5	23.5	14.3	8	14.3	23.5	36.5	54.7	80.2
107.7	71.8	46.6	28.9	16.9	9	16.9	28.9	46.6	71.8	107.7
142.0	92.5	58.2	35.0	19.6	10	19.6	35.0	58.2	92.5	142.0

Evacuation Model Review
- Movement of Occupants - Potential

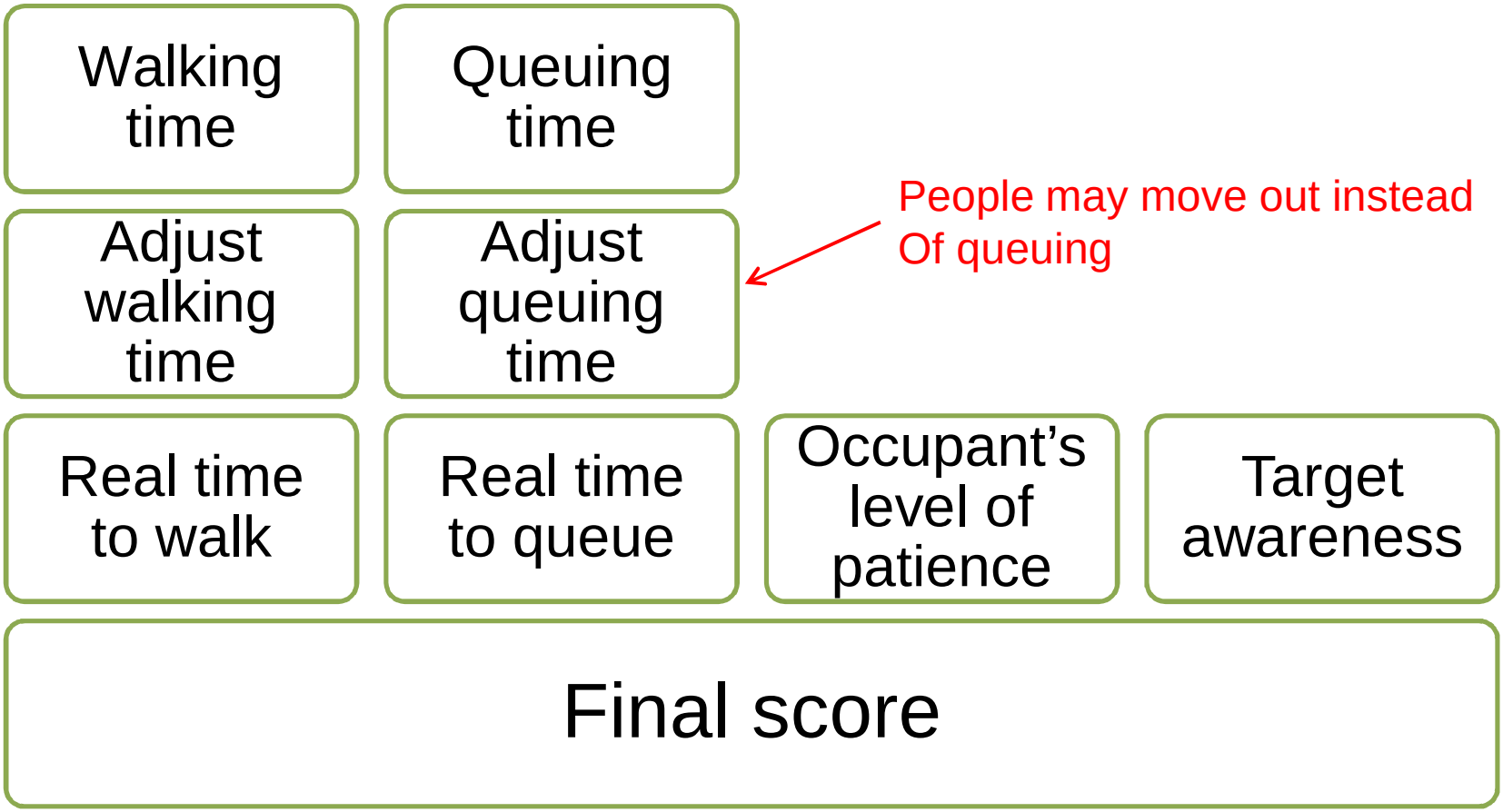
- The potential of the route can be altered by such variables as patience of the occupant, attractiveness of the exit, familiarity of the occupant with the building, etc.

Exit

5	4	3	2	1	0	1	2	3	4	5
7.5	5.6	3.9	2.4	1.4	1	1.4	2.4	3.9	5.6	7.5
10.7	7.6	5.2	3.5	2.4	2	2.4	3.5	5.2	7.6	10.7
15.0	10.6	7.3	5.2	3.9	3	3.9	5.2	7.3	10.6	15.0
21.2	15.0	10.6	7.6	5.6	4	5.6	7.6	10.6	15.0	21.2
30.0	21.2	15.0	10.7	7.5	5	7.5	10.7	15.0	21.2	30.0
42.2	29.7	20.8	14.4	9.6	6	9.6	14.4	20.8	29.7	42.2
58.7	40.8	27.9	18.6	11.9	7	11.9	18.6	27.9	40.8	58.7
80.2	54.7	36.5	23.5	14.3	8	14.3	23.5	36.5	54.7	80.2
107.7	71.8	46.6	28.9	16.9	9	16.9	28.9	46.6	71.8	107.7
142.0	92.5	58.2	35.0	19.6	10	19.6	35.0	58.2	92.5	142.0

Evacuation Model Review
- Movement of Occupants - Decision Process

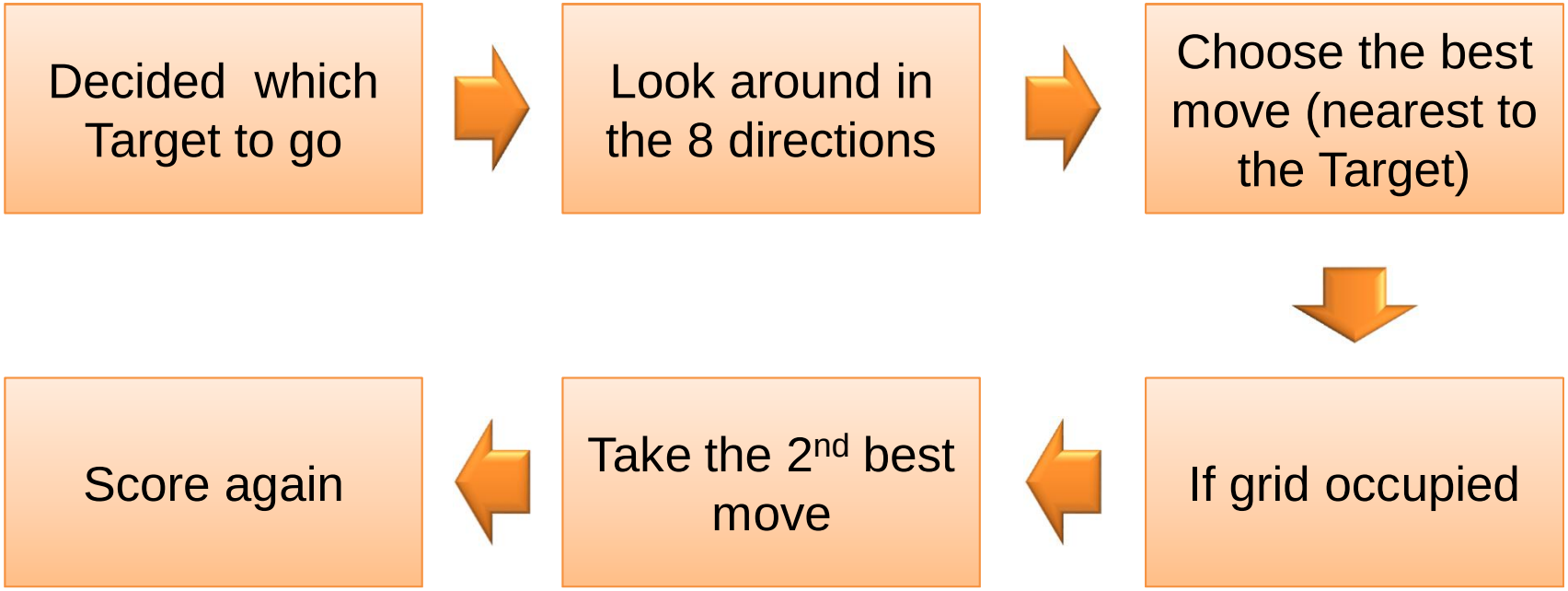
- Choosing the Target/Exit



Calculation procedures and decision process in STEPS

Evacuation Model Review
- Movement of Occupants - Decision Process

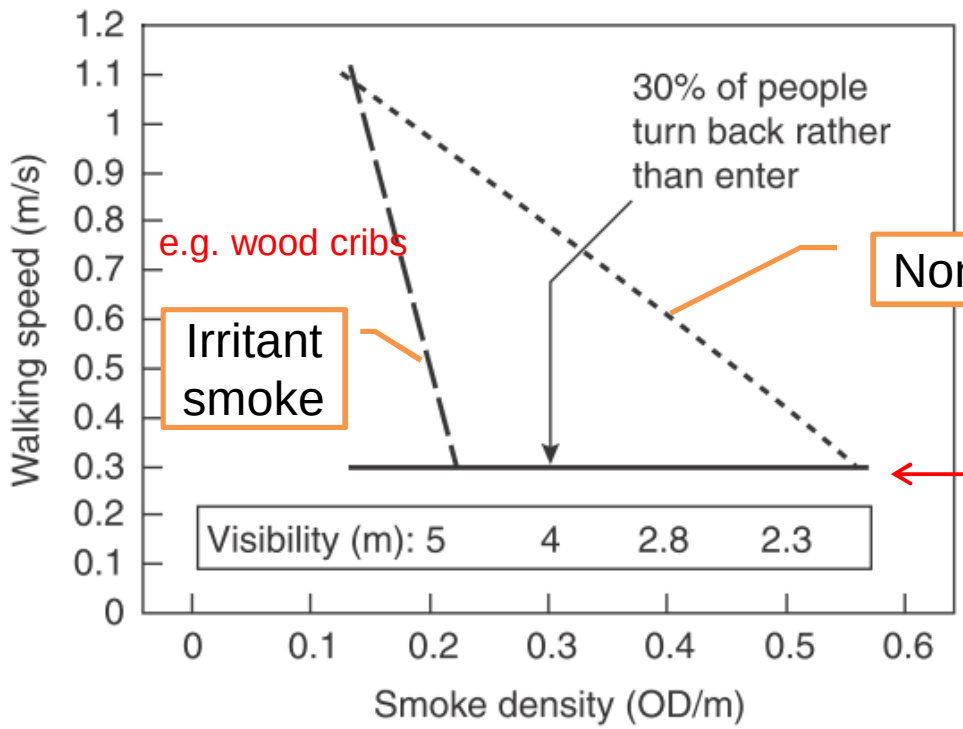
- Moving to the chosen Target/Exit



Calculation procedures and decision process in STEPS

Evacuation Model Review
- Incorporation of Fire Effects

- To assess the safety of the occupants who travel through degraded conditions and how it can alter their behavior.
- To slow occupant movement.



STEPS

e.g. kerosene

Minimum walking speed (as if in darkness)

- Physical ability to move thru' dense smoke
- Decision making whether continue or redirect

*** Extracted from "SFPE Handbook 4th Edition"*

Evacuation Model Review
- Incorporation of Fire Effects

- To access if occupant will turn back instead of move forward into the smoke-filled space.
- Calculate occupants time to incapacitation.
  - Fractional Effective Dose (FED) heat

$$\mathrm{FED} = \sum_{t_1}^{t_2} \left(\frac{1}{t_{I\mathrm{rad}}} + \frac{1}{t_{I\mathrm{conv}}} \right) \Delta t$$

  - FED toxicity

Hyperventilator factor induced by CO_2

$$\mathrm{FED}_{\mathrm{tot}} = \mathrm{FED}_{\mathrm{CO}} \times \mathrm{HV}_{\mathrm{CO}_2} + \mathrm{FED}_{\mathrm{O}_2}$$

Low oxygen - hypoxia

$$\mathrm{FED}_{\mathrm{CO}} = 4.607 \times 10^{-7} \left(C_{\mathrm{CO}}\right)^{1.036} t$$

$$\mathrm{FED}_{\mathrm{O}_2} = \frac{t}{60 \exp\left[8.13 - 0.54\left(20.9 - C_{\mathrm{O}_2}\right)\right]}$$

$$\mathrm{HV}_{\mathrm{CO}_2} = \frac{\exp\left(0.1930 C_{\mathrm{CO}_2} + 2.0004\right)}{7.1}$$

*** Extracted from "FDS User Manual"*

Evacuation Model Review
- Incorporation of Fire Effects

- FDS+EVAC: FED heat, FED toxicity
- STEPS: Visibility
- Building Exodus: FED heat, FED toxicity

Evacuation Model Review
- Visualization methods

3D

2D

Evacuation Model Review - Summary

Software	Developer	Grid / Structure	Movement	Import fire data	CAD	Visual	Elevator use
STEPS	Mott MacDonald	Fine	Potential, Emptiness of next grid cell	Yes	Yes	2D, 3D	Yes
Simulex	IES	Cont.	Inter-person distance	No	Yes	2D	No
FDS+Evac	VTT Technical Research Centre of Finland	Cont.	Inter-person distance	Yes	Yes (by 3rd party software)	2D, 3D	No
Pathfinder	Thunderhead Engineering	Cont.	Density correlation, Inter-person distance	No	Yes	2D, 3D	Yes
SimWalk	Savannah Simulations AG	Cont.	Potential	No	Yes	2D, 3D	Yes
Building Exodus	University of Greenwich	Fine	Potential, Emptiness of next grid cell	Yes	Yes	2D, 3D	Yes

Evacuation Modeling and Technique

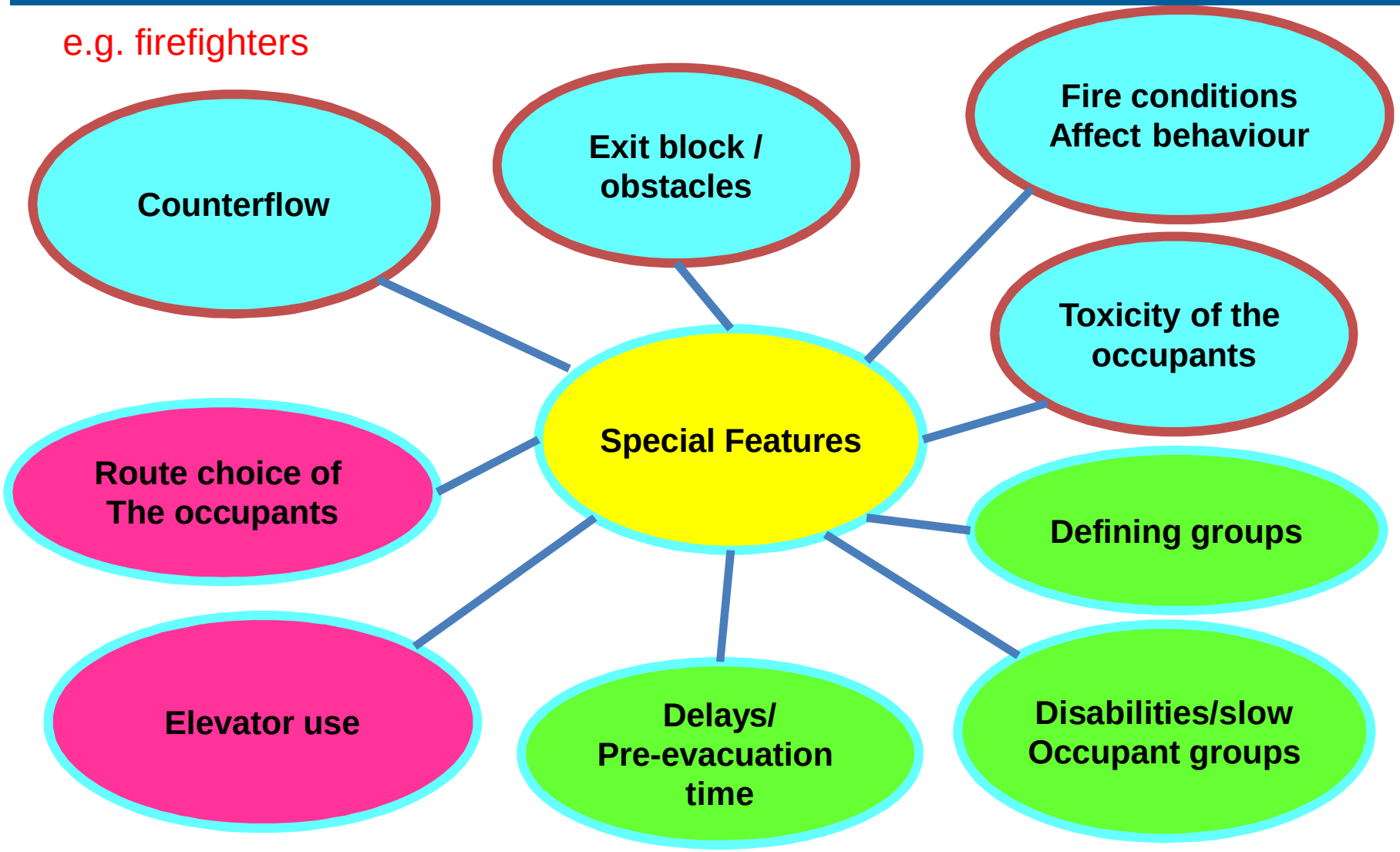
- Evacuation Model Review
- Special Feature
- Input Parameters

Special Features

Special Features

Special Features

e.g. firefighters



Special Features

	Counter-flow	Exit Block	Fire Conditions	Toxicity	Groups	Disabled / slower	Delays / pre-evacuation	Elevator use
STEPS	✓	✓	✓	✓	✓	✓	✓	✓
Simulex	✓	✓			✓	✓	✓	
FDS+Evac	✓	✓	✓	✓		✓	✓	
Pathfinder	✓	✓			✓	✓	✓	
SimWalk	✓				✓	✓	✓	✓
Building Exodus	✓	✓	✓	✓	✓	✓	✓	

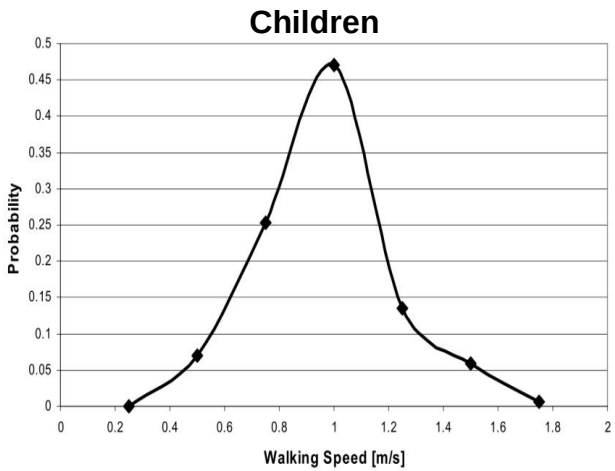
Evacuation Modeling and Technique

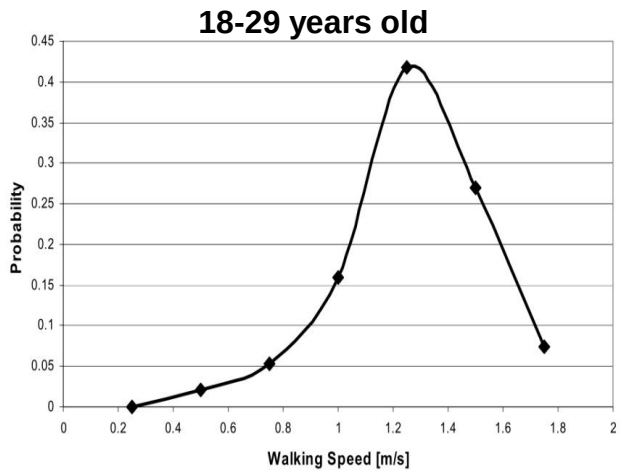
- Evacuation Model Review
- Special Feature
- Input Parameters

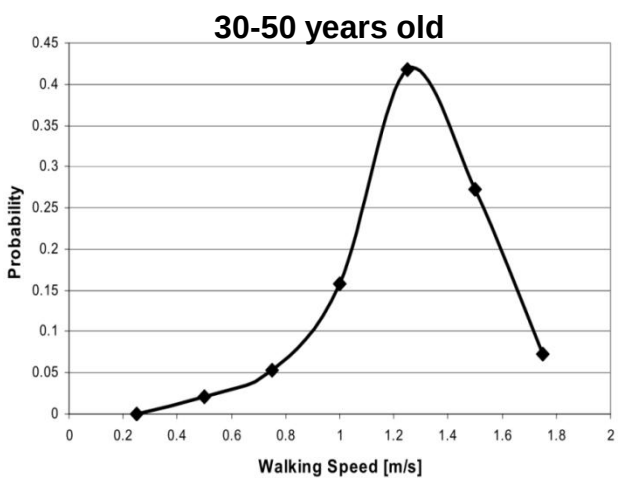
Input Parameters

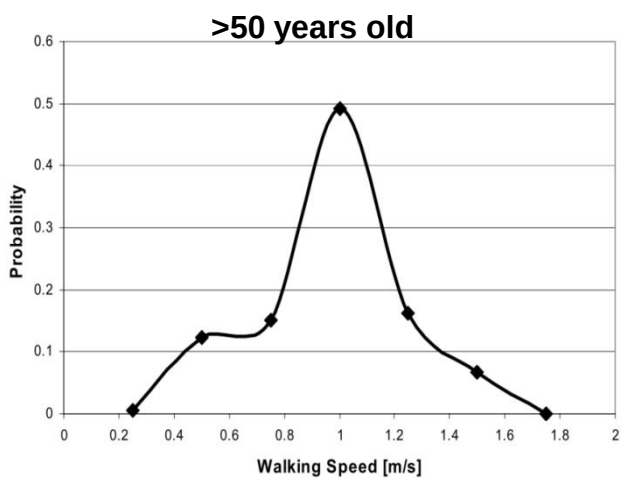
- Walking Speed
- Level of Patience
- Grouping / Family
- Staircase / Escalator
- Occupant Distribution
- Body Size

Input Parameters
- Walking Speed



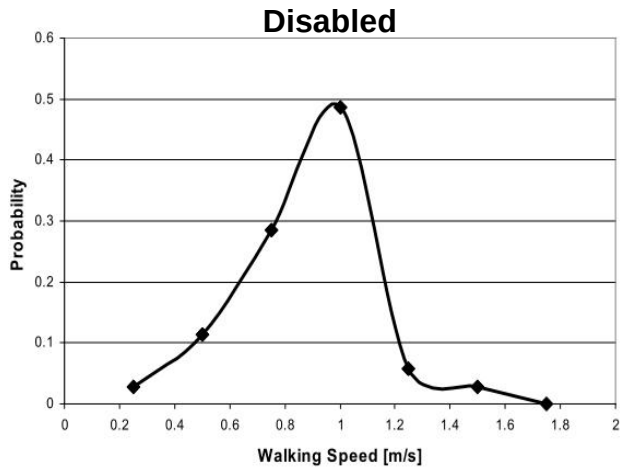






*** Extracted from "Guide for evaluating the predictive capabilities of computer egress models", NIST 2005*

Input Parameters
- Walking Speed

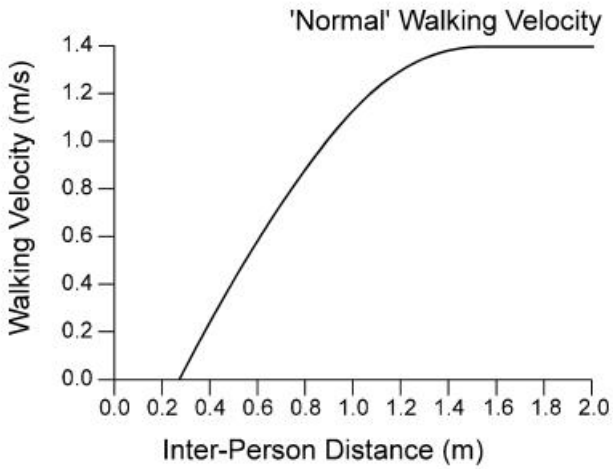


*** Extracted from "Guide for evaluating the predictive capabilities of computer egress models", NIST 2005*

Subject Group (number)	Mean (m/s)	Standard Deviation (m/s)	Range (m/s)	Interquartile Range (m/s)
All disabled (n = 107)	1.00	0.42	0.10–1.77	0.71–1.28
With locomotion disability (n = 101)	0.80	0.37	0.10–1.68	0.57–1.02
no aid (n = 52)	0.95	0.32	0.24–1.68	0.70–1.02
crutches (n = 6)	0.94	0.30	0.63–1.35	0.67–1.24
walking stick (n = 33)	0.81	0.38	0.26–1.60	0.49–1.08
walking frame or rollator (n = 10)	0.57	0.29	0.10–1.02	0.34–0.83
Without locomotion disability (n = 6)	1.25	0.32	0.82–1.77	1.05–1.34
Electric wheelchair (n = 2)	0.89	—	0.85–0.93	—
Manual wheelchair (n = 12)	0.69	0.35	0.13–1.35	0.38–0.94
Assisted manual wheelchair (n = 16)	1.30	0.34	0.84–1.98	1.02–1.59
Assisted ambulant (n = 18)	0.78	0.34	0.21–1.40	0.58–0.92

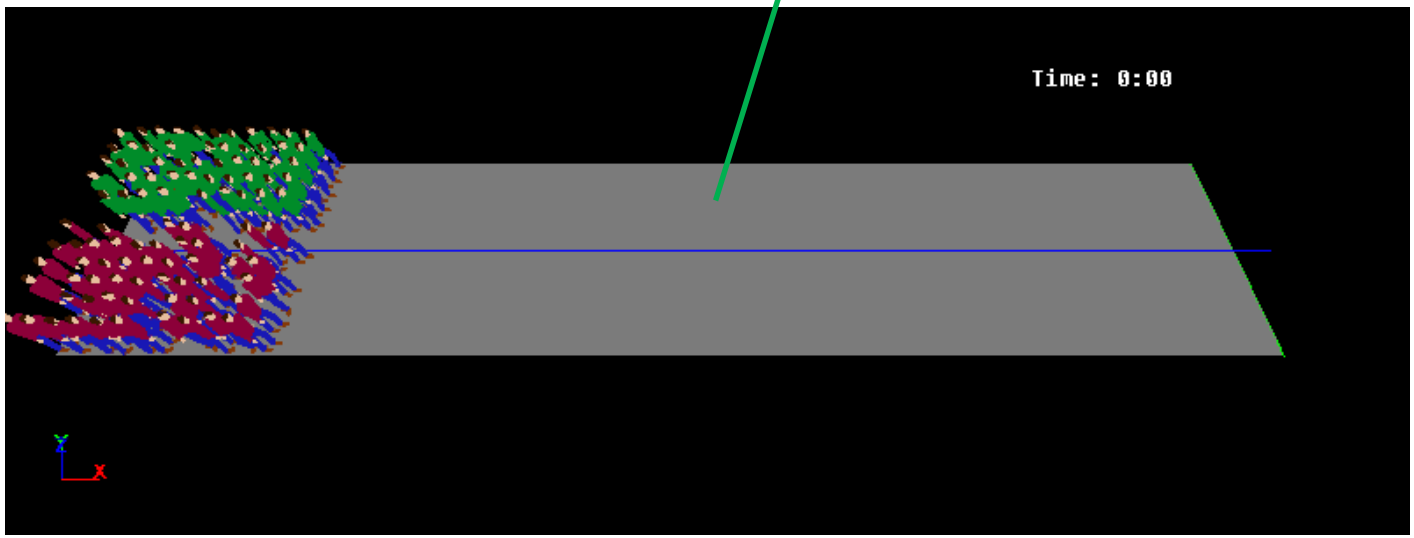
*** Extracted from "SFPE Handbook 4th Edition"*

Input Parameters
- Walking Speed



Thompson inter-person distance and walking speed relationship

Inter-person distance enabled



Input Parameters
- Impact of Smoke on Walking Speed

2 methods adopted within evacuation models

3 different behaviour hypothesis

Final speed in Smoke depends On individual Walking speed Then reduces With some Functions relating to Travel speed in smoke

A. Fractional Speed Reduction

Final speed in Smoke depends Only on smoke Conditions. Regardless of Initial walking speed

B. Absolute Speed Reduction

1. No minimum speed

Reduces speed In relation to Extinction coeff

2. Constant minimum speed

Same Minimum speeds For individuals

3. Variable minimum speed

Different Minimum speeds For individuals

*** Extracted from "Representation of the Impact of Smoke on Agent Walking Speeds in Evacuation Models", NIST 2012*

Input Parameters
- Impact of Smoke on Walking Speed

2 methods adopted within evacuation models

3 different behaviour hypothesis

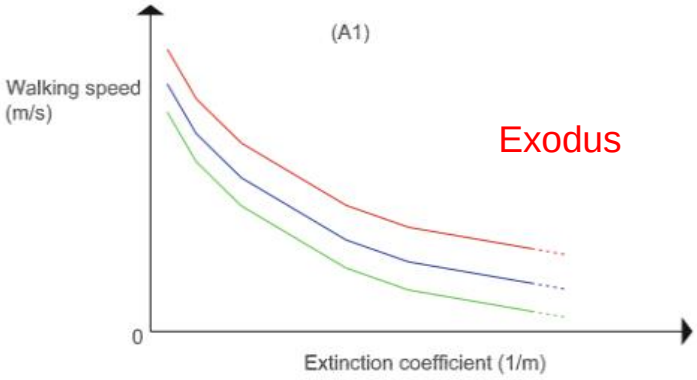
A. Fractional Speed Reduction

B. Absolute Speed Reduction

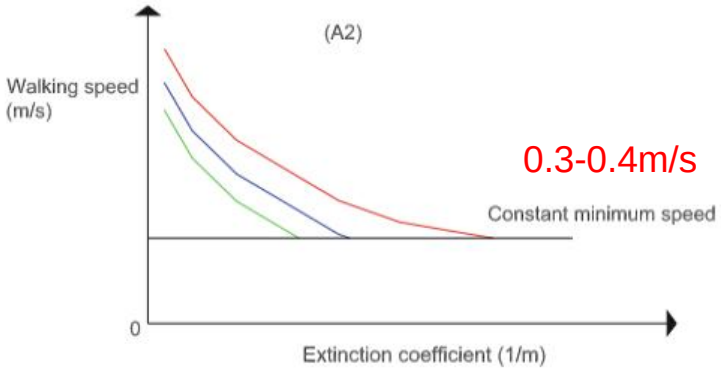
1. No minimum speed

2. Constant minimum speed

3. Variable minimum speed



Schematic representation of the fractional / no minimum speed interpretation **(A1)**



Schematic representation of the fractional / constant minimum speed interpretation **(A2)**

*** Extracted from "Representation of the Impact of Smoke on Agent Walking Speeds in Evacuation Models", NIST 2012*

Input Parameters
- Impact of Smoke on Walking Speed

2 methods adopted within evacuation models

3 different behaviour hypothesis

A. Fractional Speed Reduction

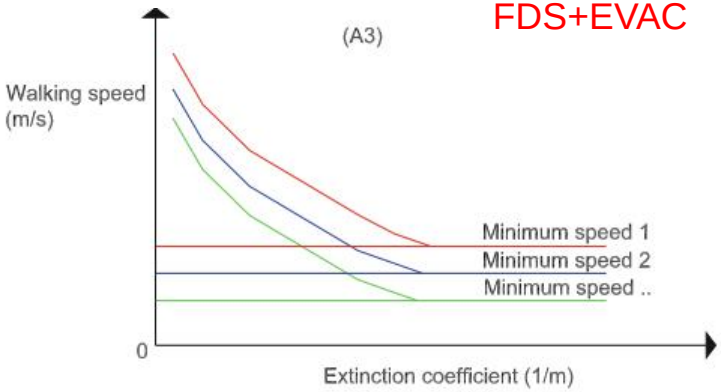
B. Absolute Speed Reduction

1. No minimum speed

2. Constant minimum speed

3. Variable minimum speed

FDS+EVAC



Schematic representation of the fractional / variable minimum speed interpretation **(A3)**

Different individuals will have Different minimum speeds

*** Extracted from "Representation of the Impact of Smoke on Agent Walking Speeds in Evacuation Models", NIST 2012*

Input Parameters
- Impact of Smoke on Walking Speed

2 methods adopted within evacuation models

A. Fractional Speed Reduction

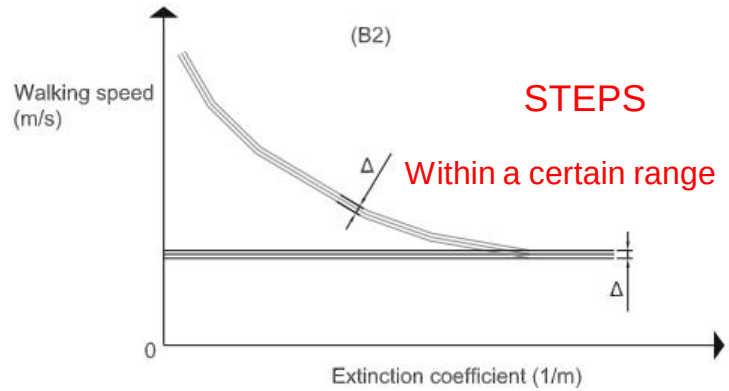
B. Absolute Speed Reduction

3 different behaviour hypothesis

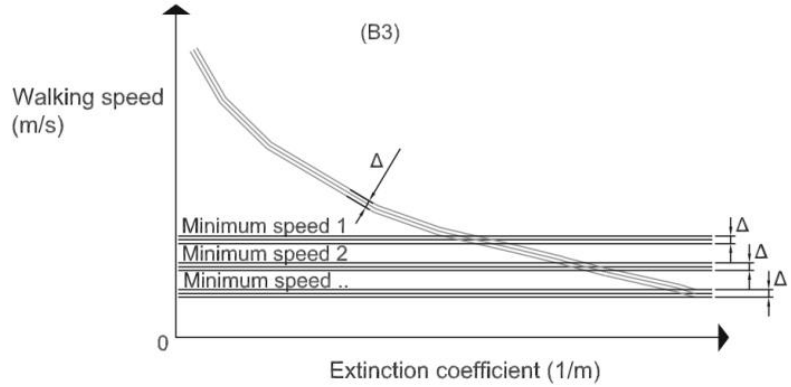
1. No minimum speed

2. Constant minimum speed

3. Variable minimum speed



Schematic representation of the absolute / constant minimum speed interpretation **(B2)**



Schematic representation of the absolute / variable minimum speed interpretation **(B3)**

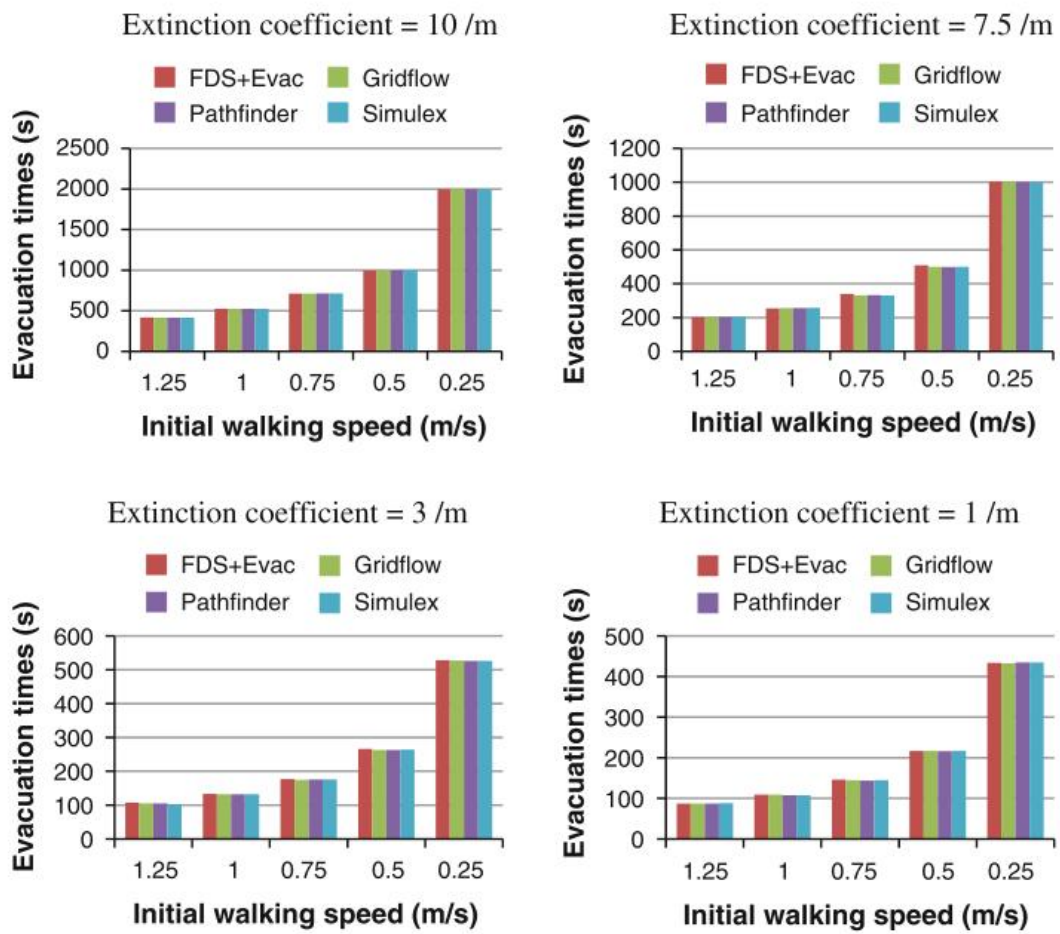
*** Extracted from "Representation of the Impact of Smoke on Agent Walking Speeds in Evacuation Models", NIST 2012*

Input Parameters
- Impact of Smoke on Walking Speed

A simple straight corridor (100 m of length and 3.5 m of width) with a single exit located at one end is modeled to test the impact of the different model assumptions on the results produced

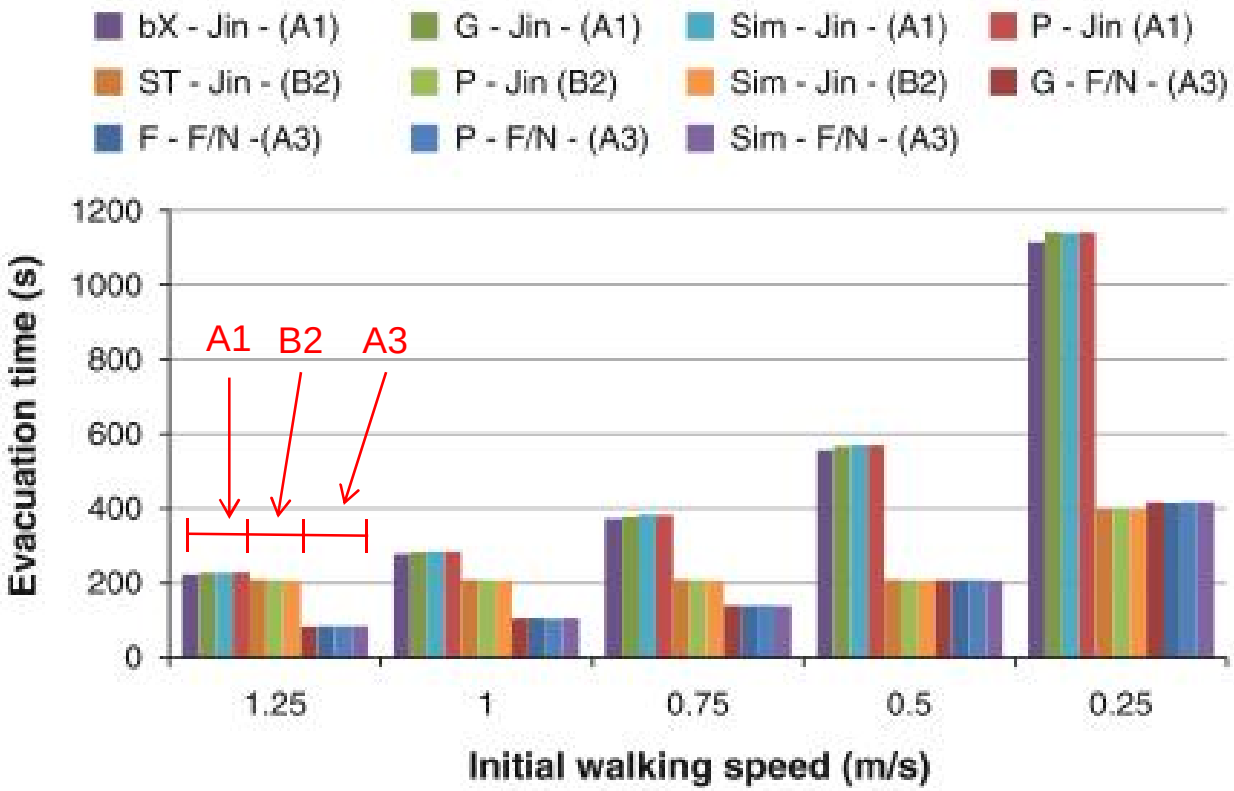
Same data set from Nilsson's (2003)

Fractional variable minimum speed (A3)



*** Extracted from "Representation of the Impact of Smoke on Agent Walking Speeds in Evacuation Models", NIST 2012*

Input Parameters
- Impact of Smoke on Walking Speed



Evacuation times for scenarios with extinction coefficient = 0.5/m and irritant smoke using six models. X-Y-(Z): X is the model employed: [FDS+Evac=F, Gridflow=G, buildingEXODUS=bX, STEPS=ST, Pathrinder=P, Simulex=Sim]; Y is the data-set employed: [F/N=Fractzich and Nilsoon is the data-set employed, Jin=Jin is the data-set employed]; (Z)=the type of interpretation of the smoke impact on speeds as described in Section 2.2.

*** Extracted from "Representation of the Impact of Smoke on Agent Walking Speeds in Evacuation Models", NIST 2012*

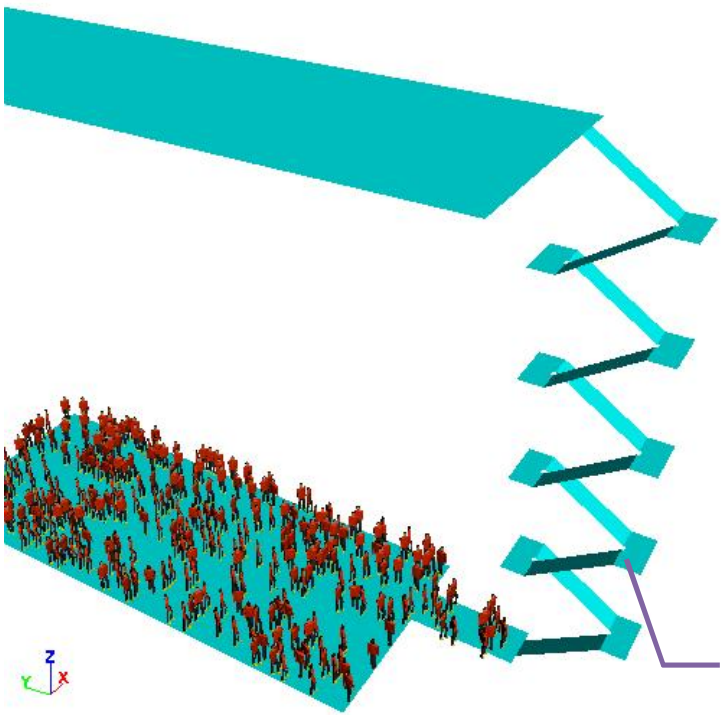
Input Parameters
- Impact of Smoke on Walking Speed

Conclusion:

1. Need to make appropriate judgement
2. May need to adopt the most conservative results

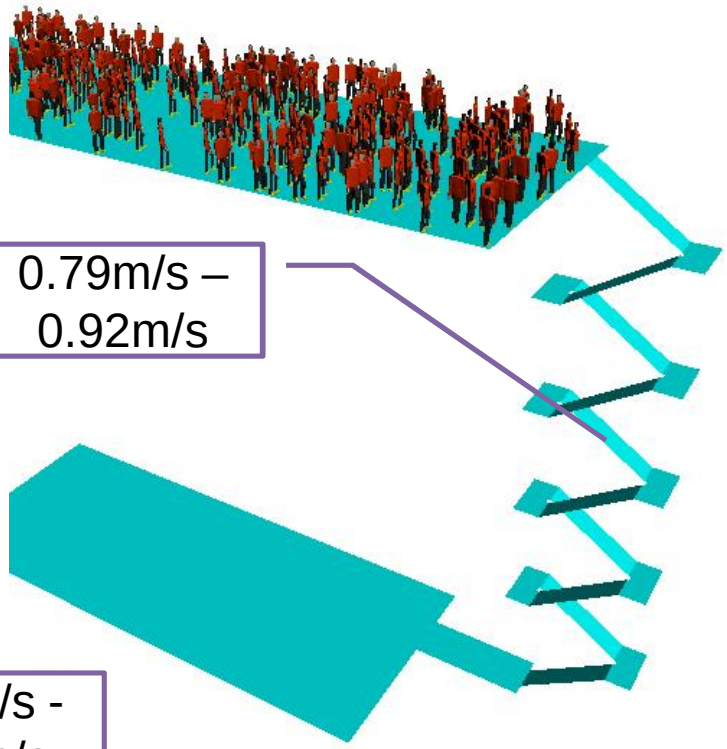
Input Parameters
- Impact of Travel Upwards / Downwards Stair

Stair upwards



0.74m/s - 0.83m/s

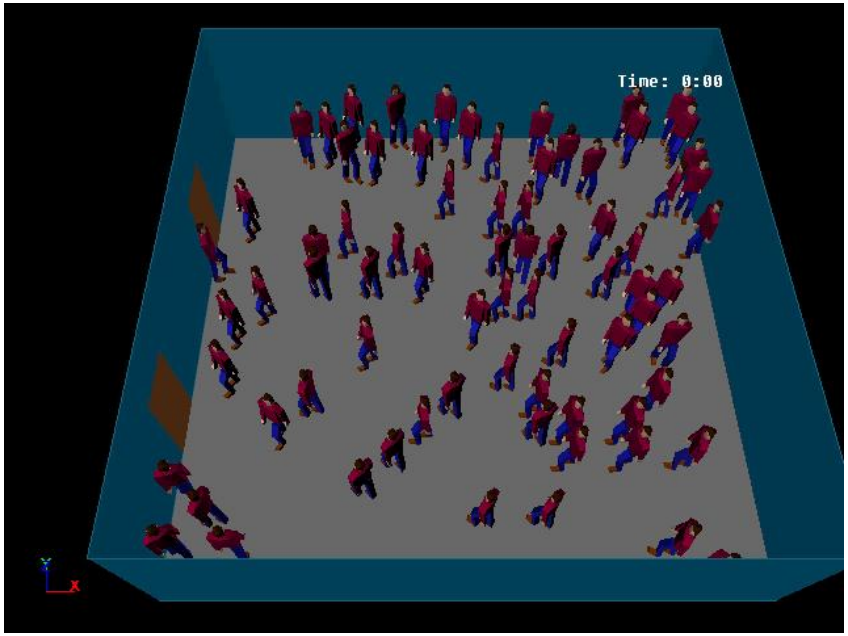
Stair downwards



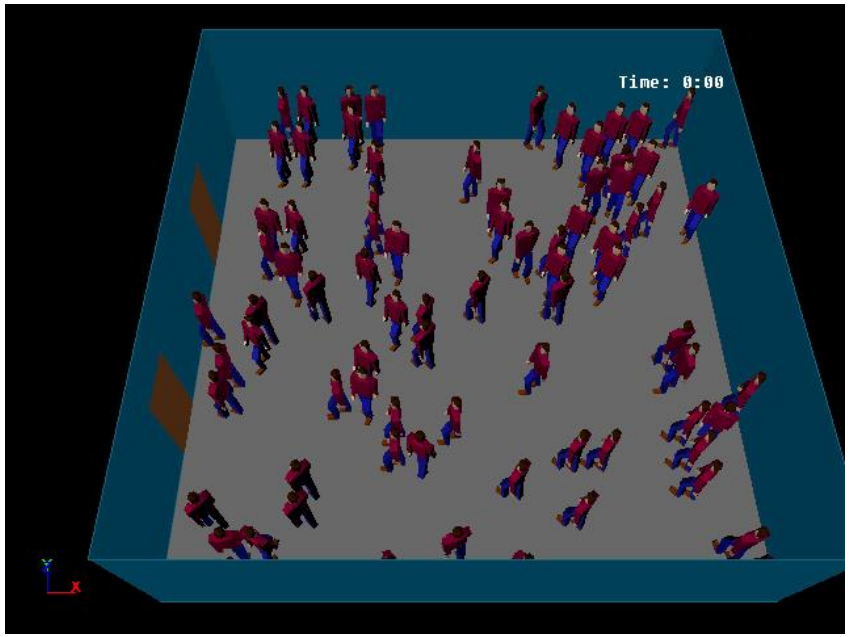
0.79m/s – 0.92m/s

Input Parameters
- Level of Patience

- Patient people

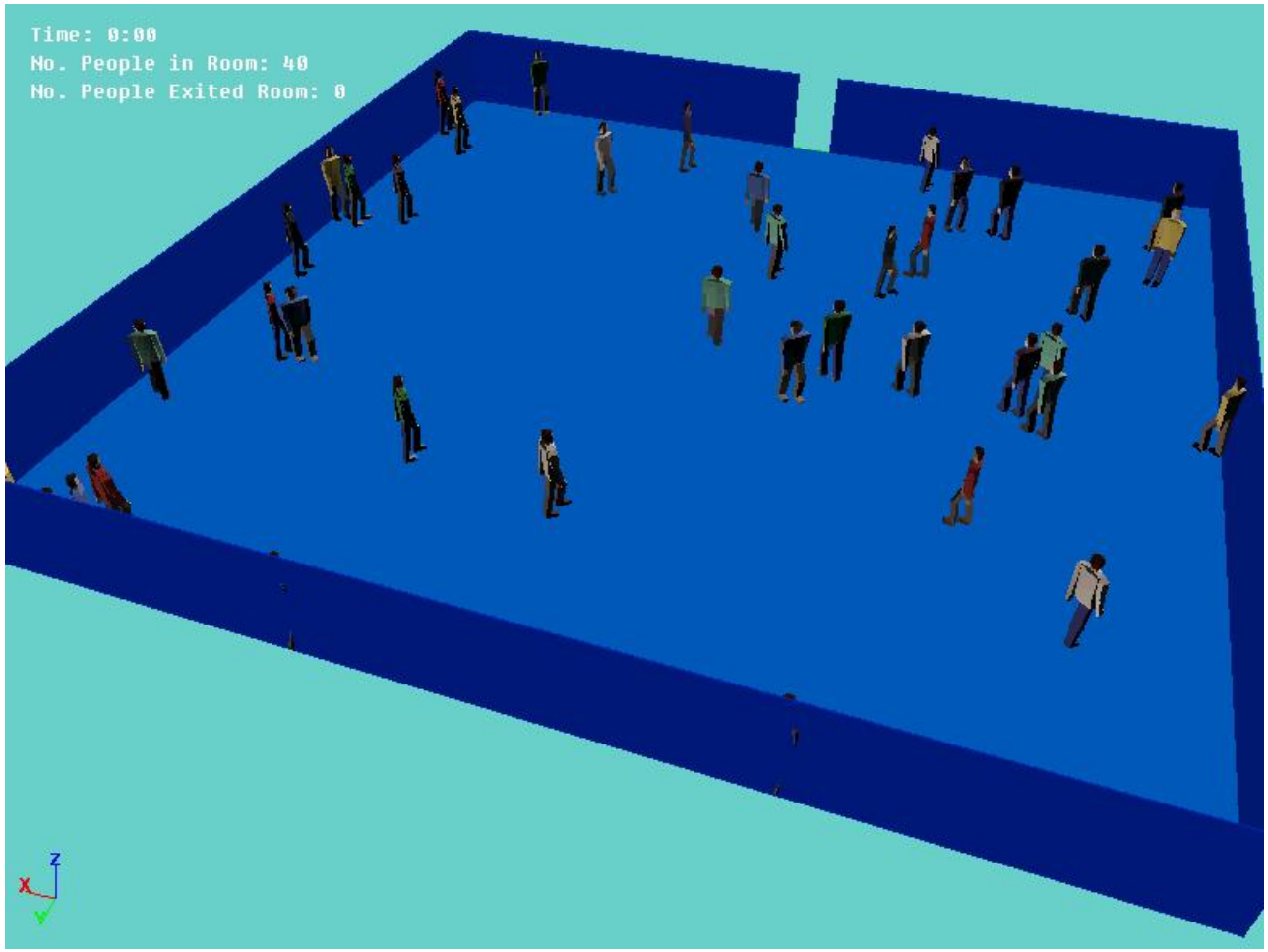


- Impatient people



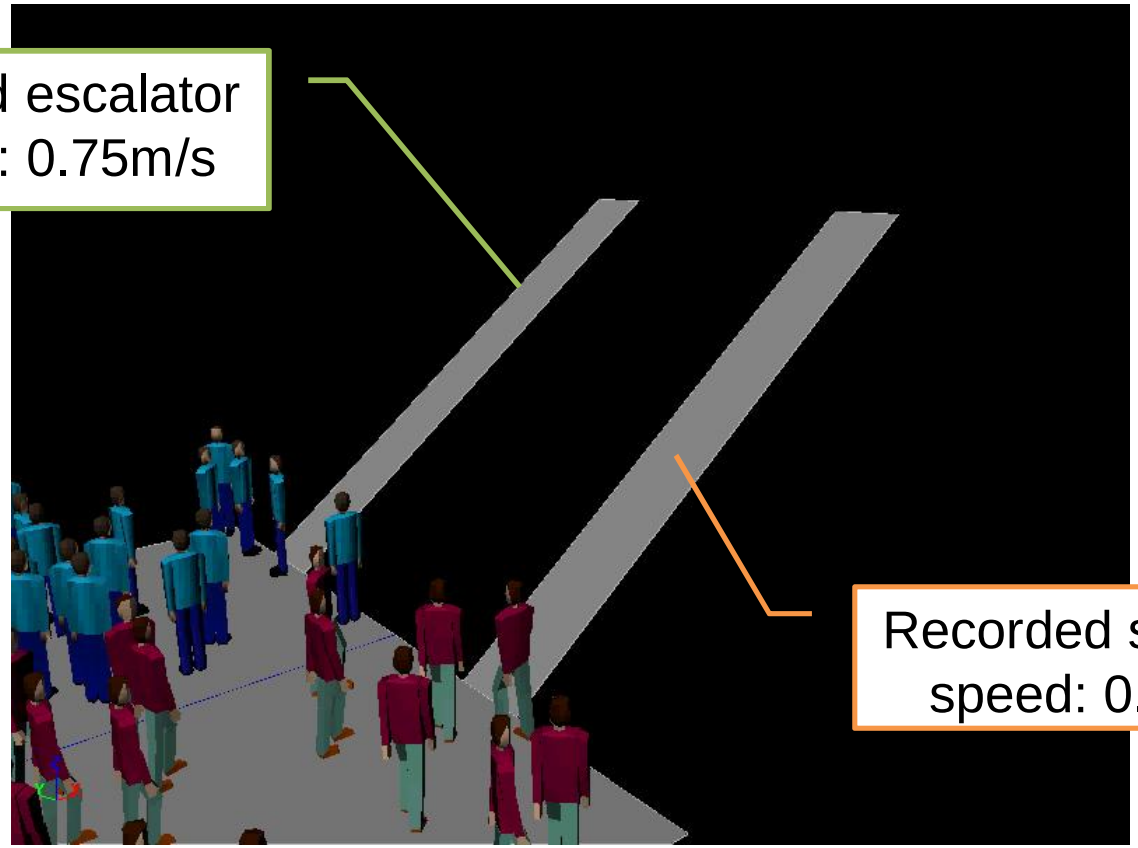
Patience Level	0 – 1
Neutral	0.5
Patient	>0.5
Impatient	<0.5

Input Parameters
- Grouping / Family



Input Parameters
- Staircase / Escalator

Horizontal walking speed: 1.5m/s

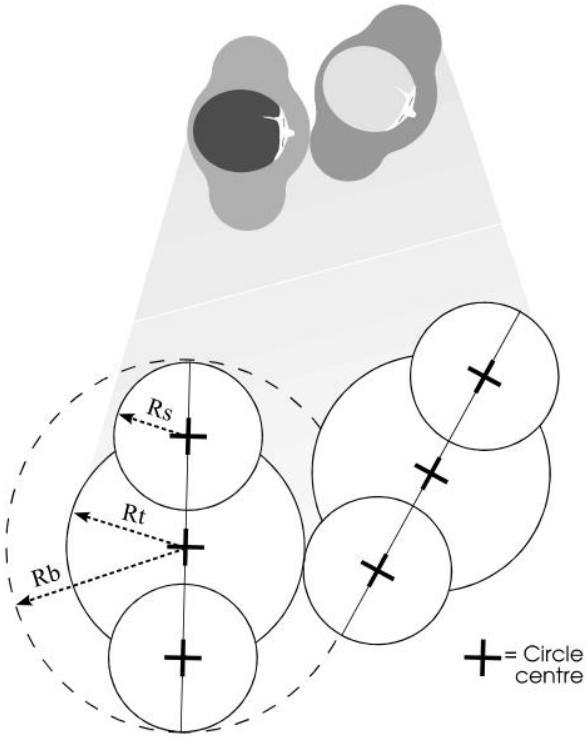


Input Parameters
- Occupant distribution

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

*** Extracted from "Simulex user guide"*

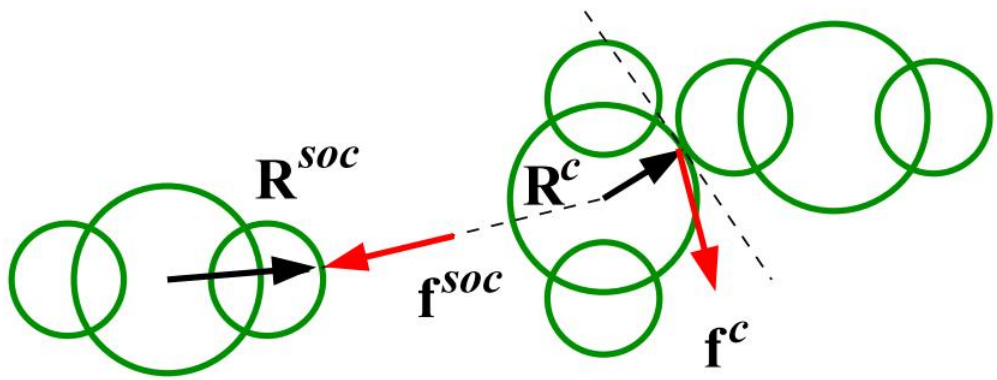
Input Parameters
- Body Size



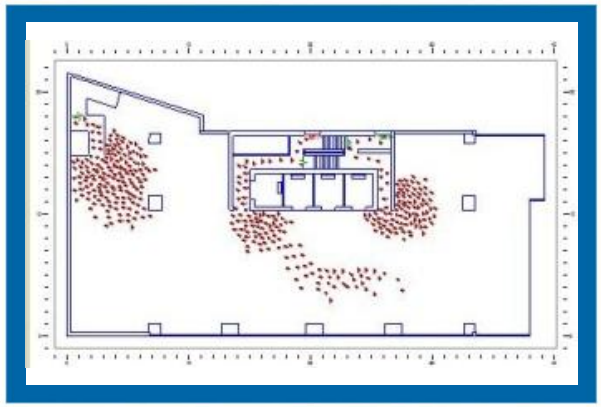
*** Extracted from "Simulex user guide"*

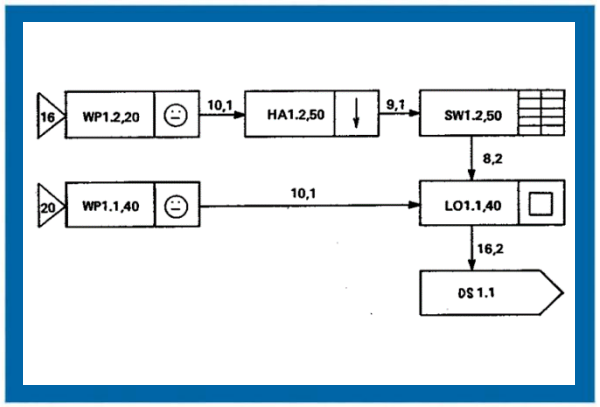
Body Type	Rb(m)	Rt(m)	Rs(m)
Median	0.25	0.15	0.10
Adult Male	0.27	0.16	0.10
Adult Female	0.24	0.14	0.09
Child	0.21	0.12	0.07
Elderly	0.25	0.15	0.09

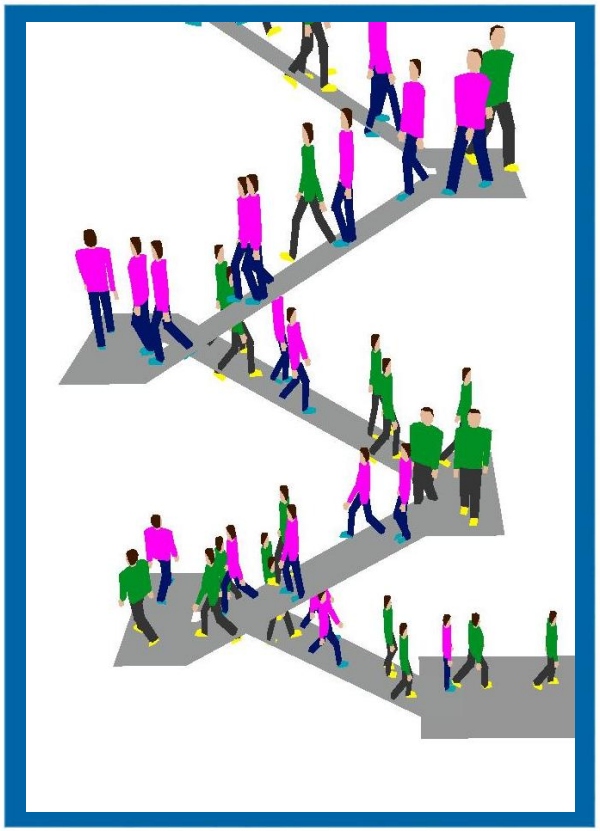
*** Extracted from "Simulex user guide"*

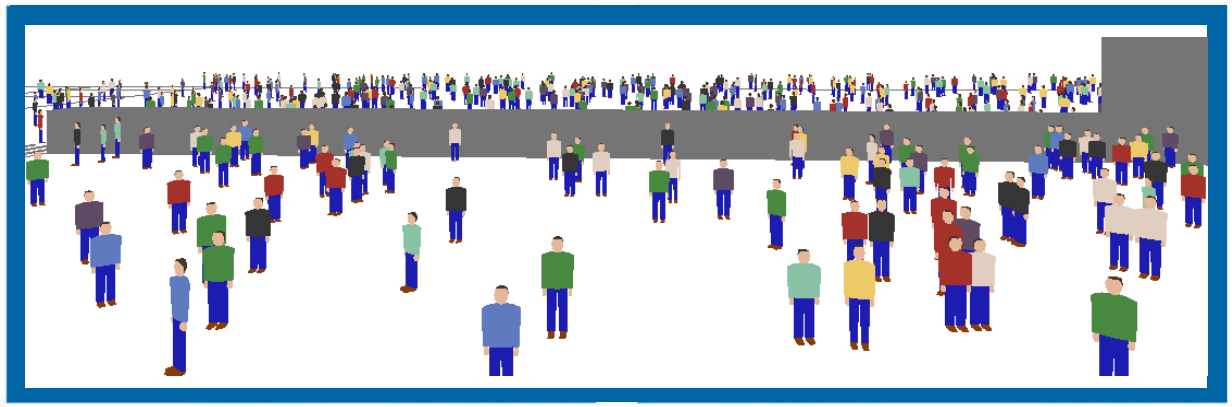


*** Extracted from "User guide for FDS+EVAC"*





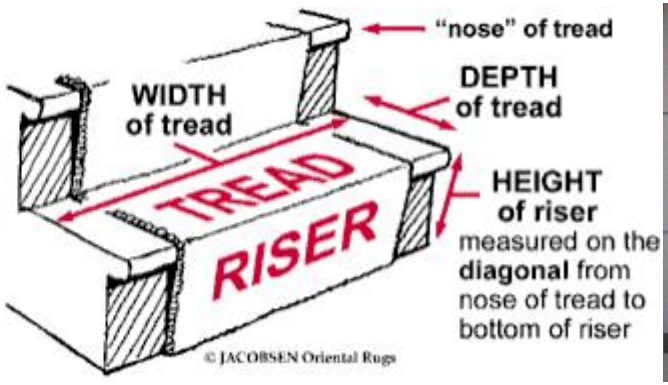




Case Studies of Evacuation Performance Assessment

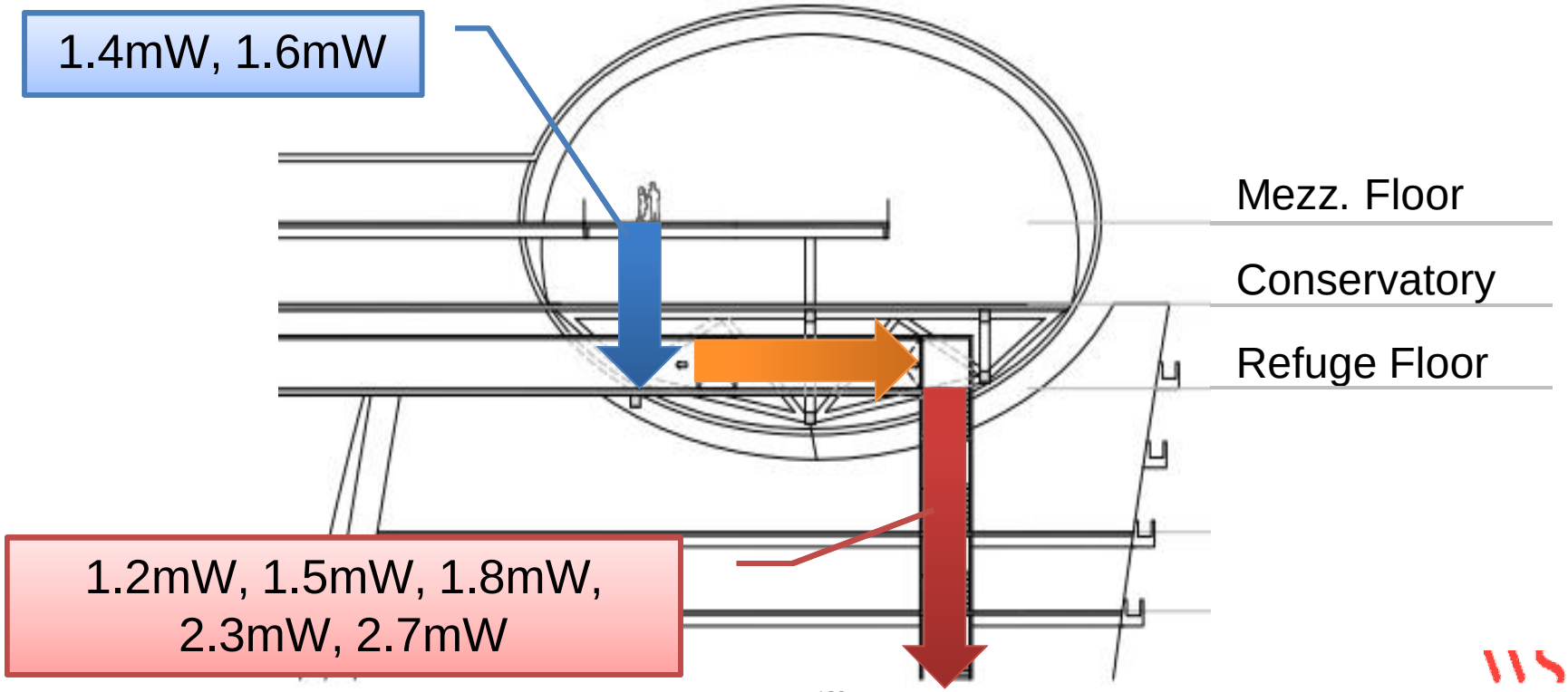
Case Studies of Evacuation Performance Assessment

- Staircase width
- Staircase location
- Staircase tread and riser
- Lift evacuation
- Counter-flow

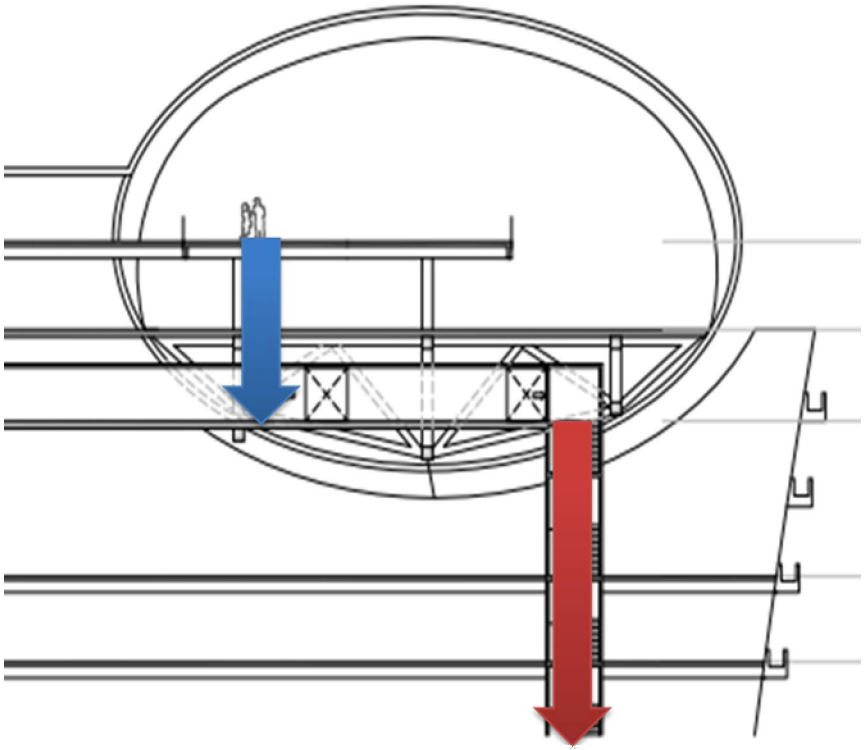


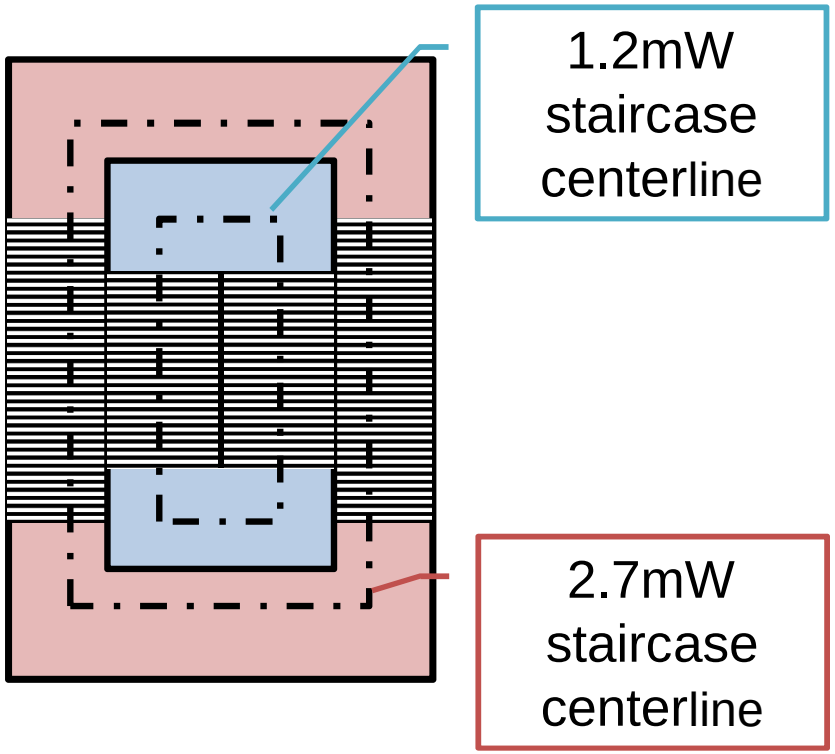
Staircase Width

Type of building	Roof Conservatory
Population	1400p
No of staircase	Mezz. > Refuge: 10nos Refuge > G/F: 6nos



Staircase Width





1.4m (M/F – R/F)			1.6m (R/F – G/F)		
1.2m	1.5m	1.8m	1.2m	2.3m	2.7m
22min 12s	22min 46s	23min 49s	23min 4s	25min 28s	26min 37s

Staircase Location

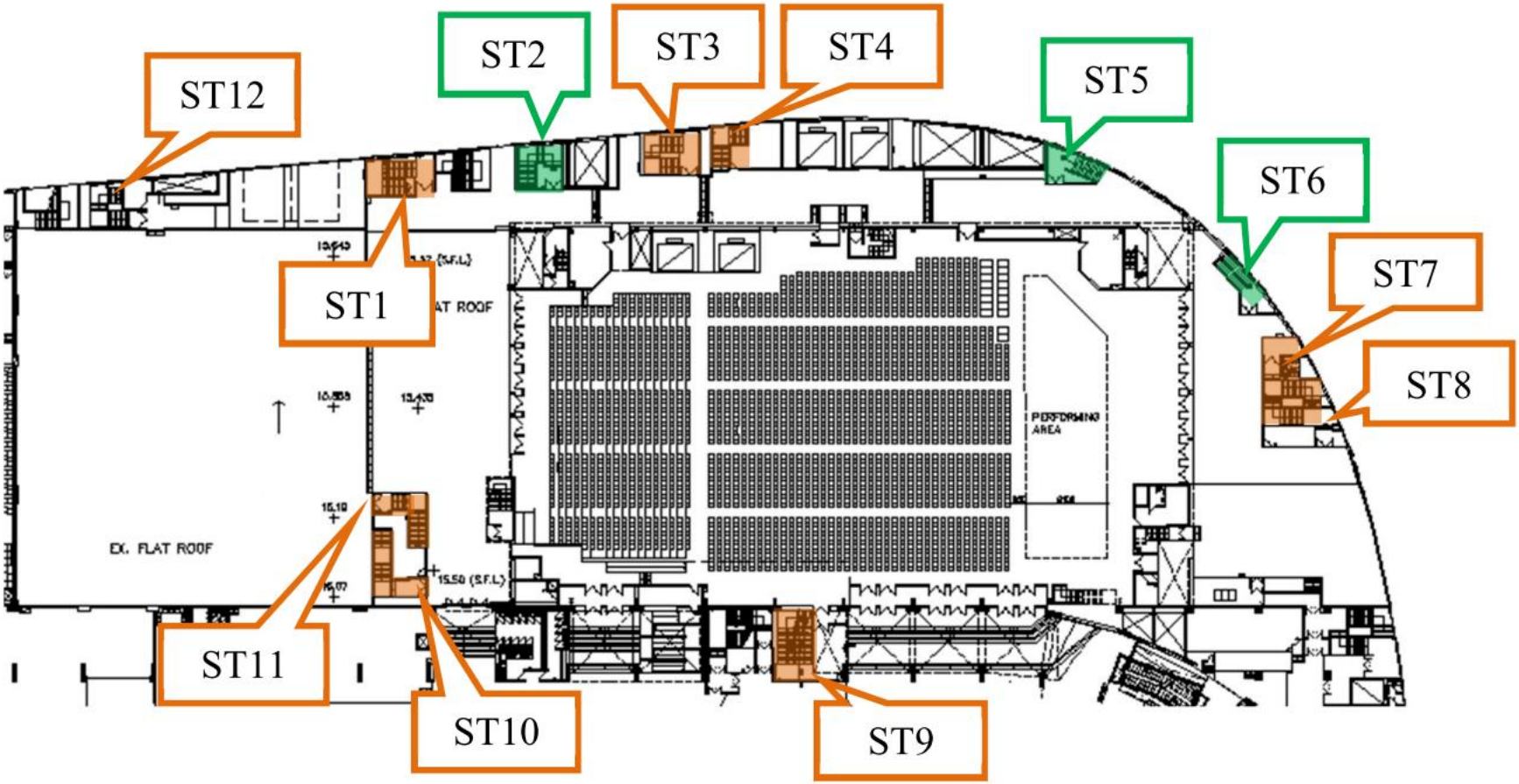
Type of building	Multi-purpose Hall
Population	3000p
No of staircase	12nos @ 1.5m

Table B2

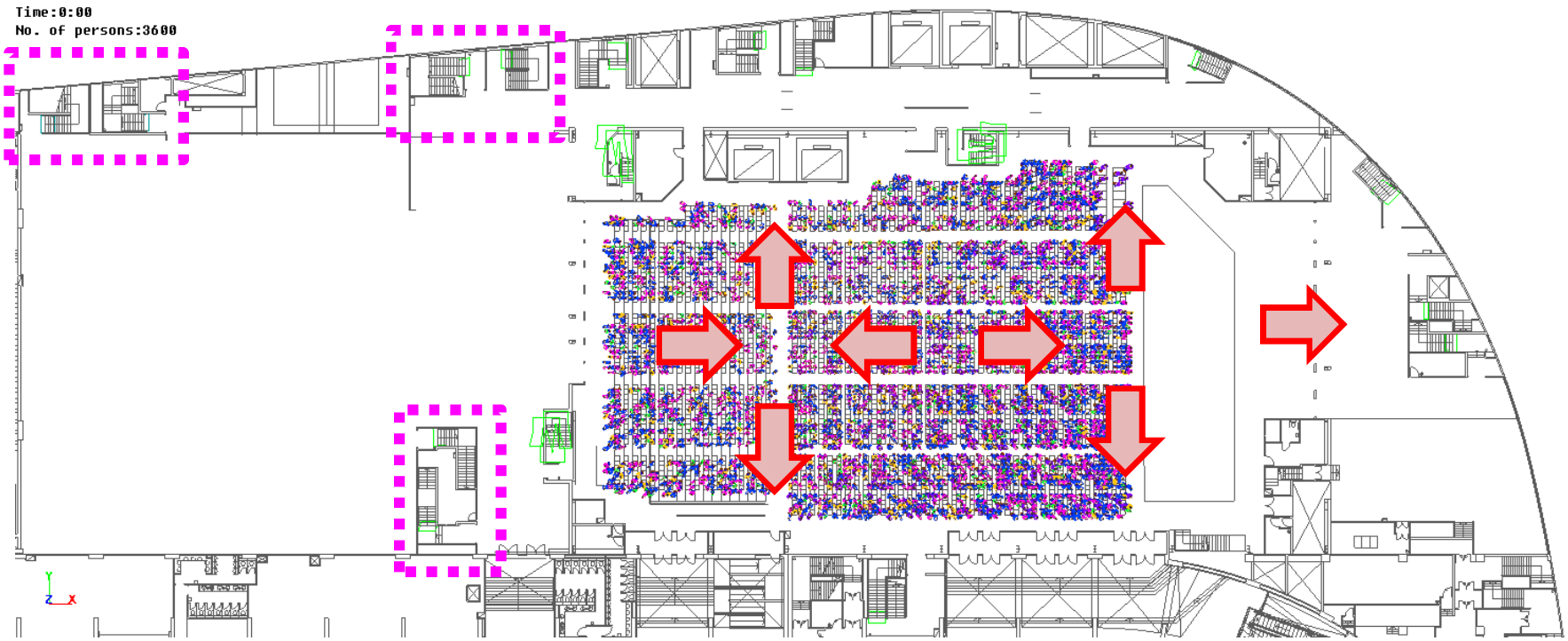
Table B2: Minimum number and width of exit doors and exit routes from a room, fire compartment or storey

Occupant Capacity of room, fire compartment or storey (No. of persons)	Minimum No. of exit doors or exit routes	Minimum total width (in mm)		Minimum Width (in mm) of each	
		Exit doors	Exit routes	Exit door	Exit route
4- 30	1			750	1050
31-200	2	1750	2100	850	1050
201-300	2	2500	2500	1050	1050
301-500	2	3000	3000	1050	1050
501-750	3	4500	4500	1200	1200
751-1000	4	6000	6000	1200	1200
1001-1250	5	7500	7500	1350	1350
1251-1500	6	9000	9000	1350	1350
1501-1750	7	10500	10500	1500	1500
1751-2000	8	12000	12000	1500	1500
2001-2500	10	15000	15000	1500	1500
2501-3000	12	18000	18000	1500	1500
>3000 persons - the number of exit doors, exit routes and their width to be determined by the Building Authority					

Staircase Location



Staircase Location

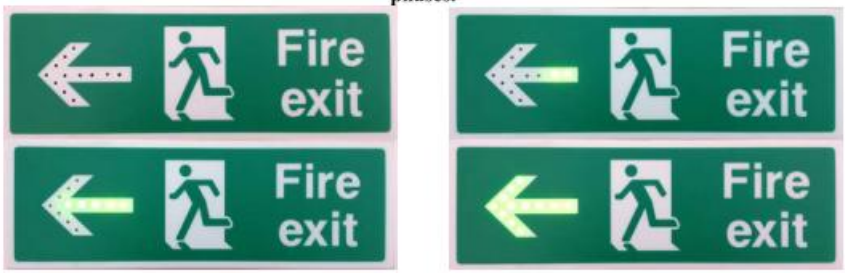


Staircase Location

How to resolve?

1. Exit signs / directional signs
2. Dynamic exit signs (e.g. AVA)
3. Floor photoluminescent directional sign (NFPA)
4. Management guidance

Figure 1: The dynamic exit sign based on the standard exit sign design showing the flashing arrow in four phases.



Staircase Treads and Risers

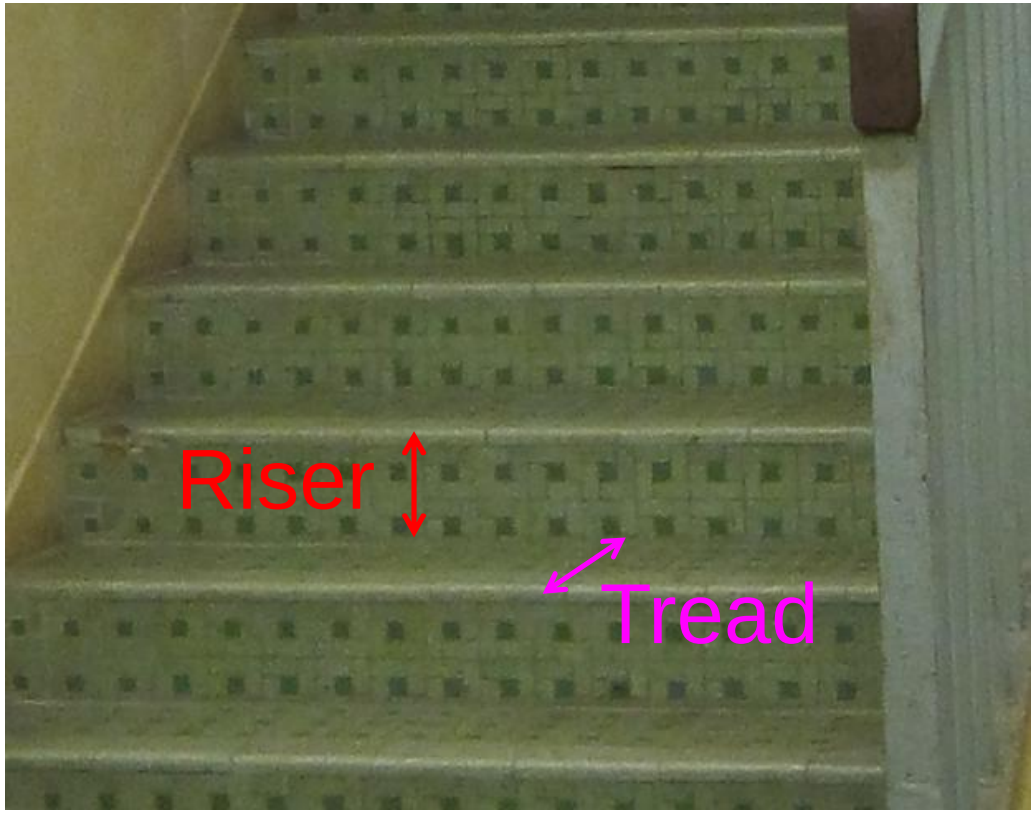
According to FS Code:

<u>All buildings</u>

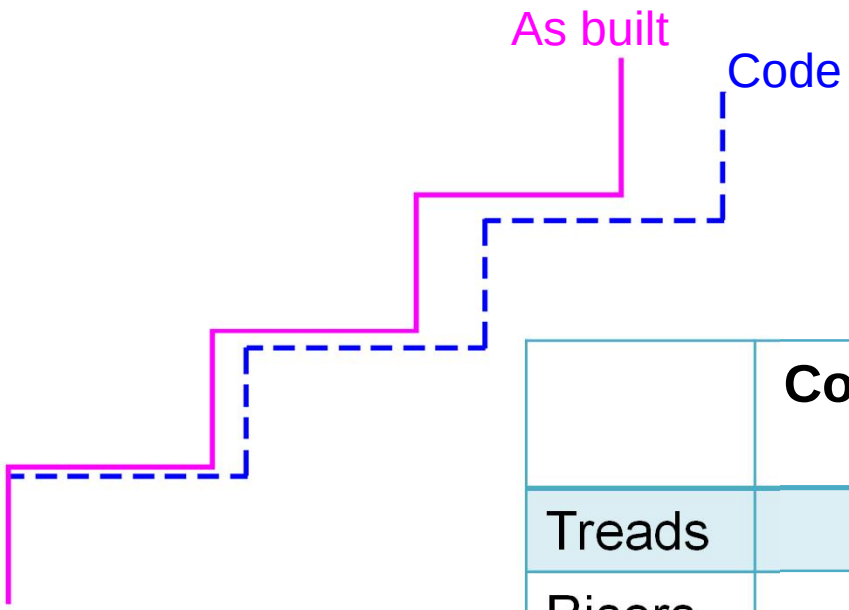
- Treads >225mm wide
- Risers <175mm high

<u>PPE</u>

- Treads: 280mm wide
- Risers: 150mm high



Staircase Treads and Risers

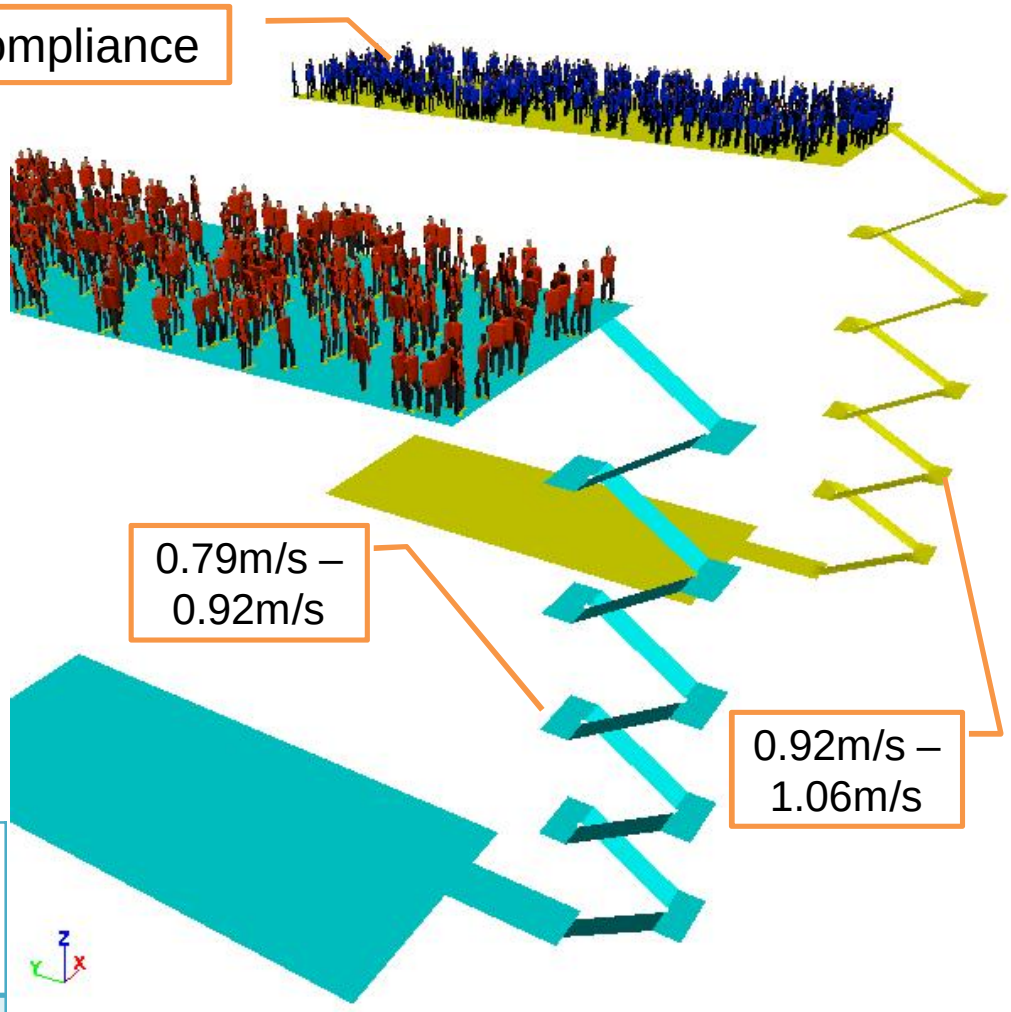


Type of building	Hostel
Population	757p
No of staircase	1no @1.05m 2nos @ 2m

	Code compliance, PPE	As Built
Treads	280mm	240mm
Risers	150mm	160mm

	Code compliance, PPE	As Built
Time for last person to leave staircase	215s	240s

Staircase Treads and Risers



Stair Safety

	Code compliance, PPE	As Built
Treads	280mm	240mm
Risers	150mm	160mm

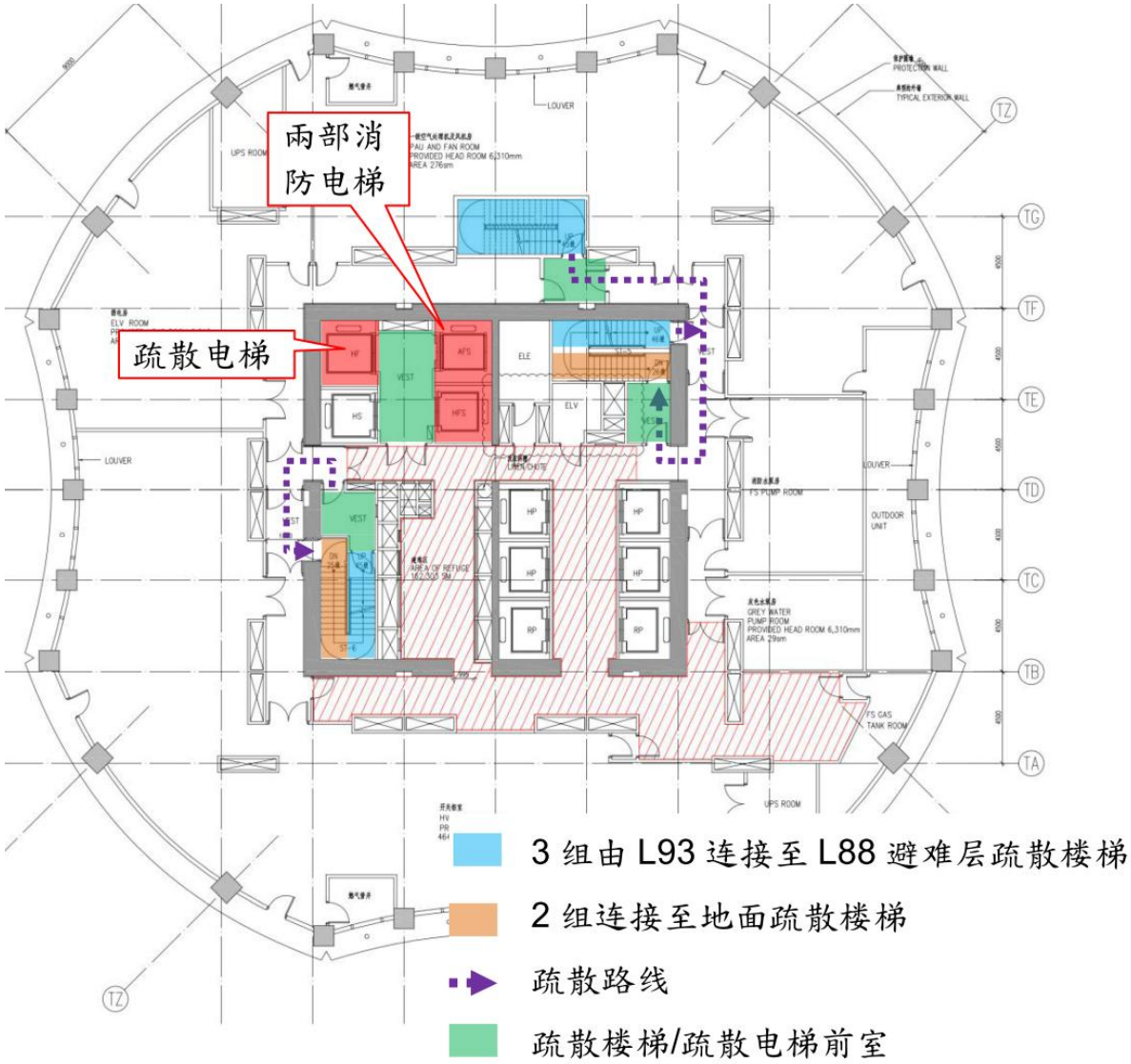
Lift Evacuation

Lift Evacuation

- Not everyone is capable of using stairs.
- Disabled or injured, the elderly who may be unable to descend stairs.
- In super high-rise building, evacuation by stairs alone may be highly inefficient.
- World Trade Centre (USA) – 3hrs to reach street level via stairs

- Lifts as an alternative means of egress from high-rise building.

Lift Evacuation



3 组由 L93 连接至 L88 避难层疏散楼梯

2 组连接至地面疏散楼梯

疏散路线

疏散楼梯/疏散电梯前室

Lift Evacuation
- Lift Response to Fire Signal

Fire alarm signal

↓

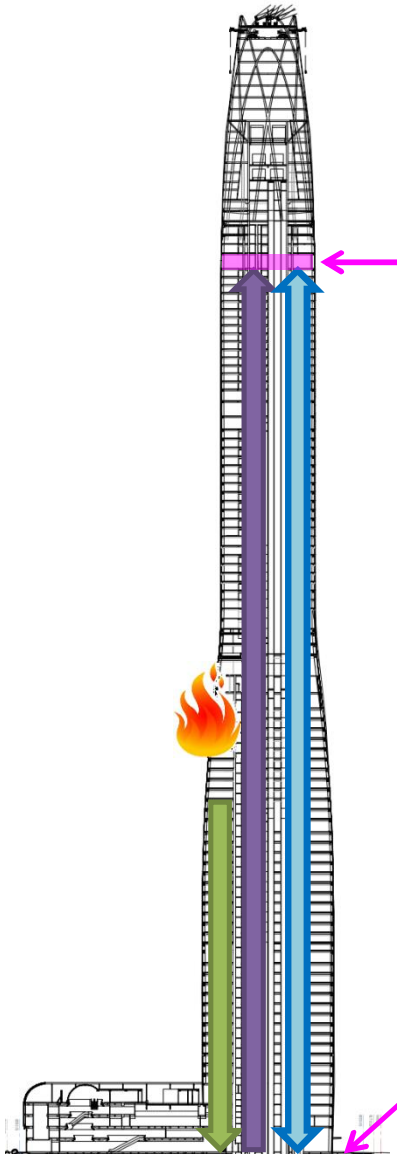
Evacuation lift travel to G/F

↓

Management staff take control of evacuation lift and go to refuge floor

↓

Pick up the evacuees from refuge floor to G/F and back to Refuge floor and so on



Lift Evacuation
- Scenario

	Scenario 1	Scenario 2	Scenario 3
No of person using staircase	902p	672p (75%)	26p
No of person using lift	-	230p (25%)	876p

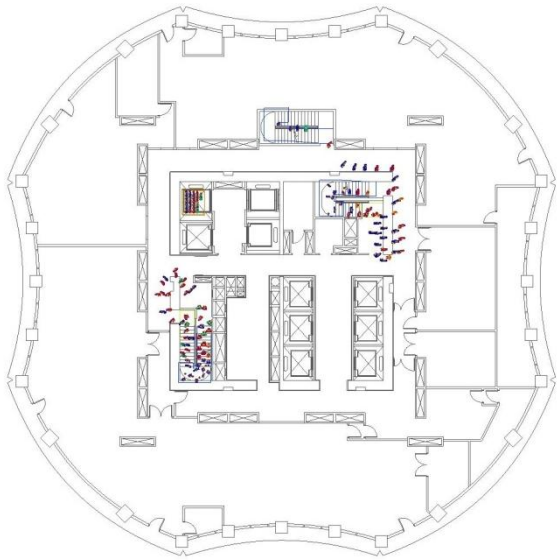
Scenario 2 – Assign 230p waiting on refuge floor using lift evacuation.
Scenario 3 – Let the people select using lift / staircase freely.

Lift Evacuation
- Lift speed

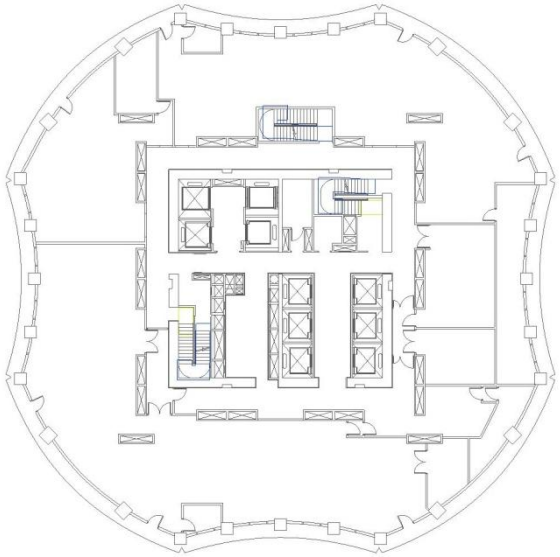
- Lift speed: 4m/s
- Lift capacity: 26p
- Lift acceleration: 1m/s^2

Round-trip time:

- Travel distance: 412.5m
- Travel time to discharge floor: 103s
- Door open and close time: 52s
- Travel time back to refuge floor: 103s
- Total: 103s + 52s + 103s
  = 258s (4min 18s)

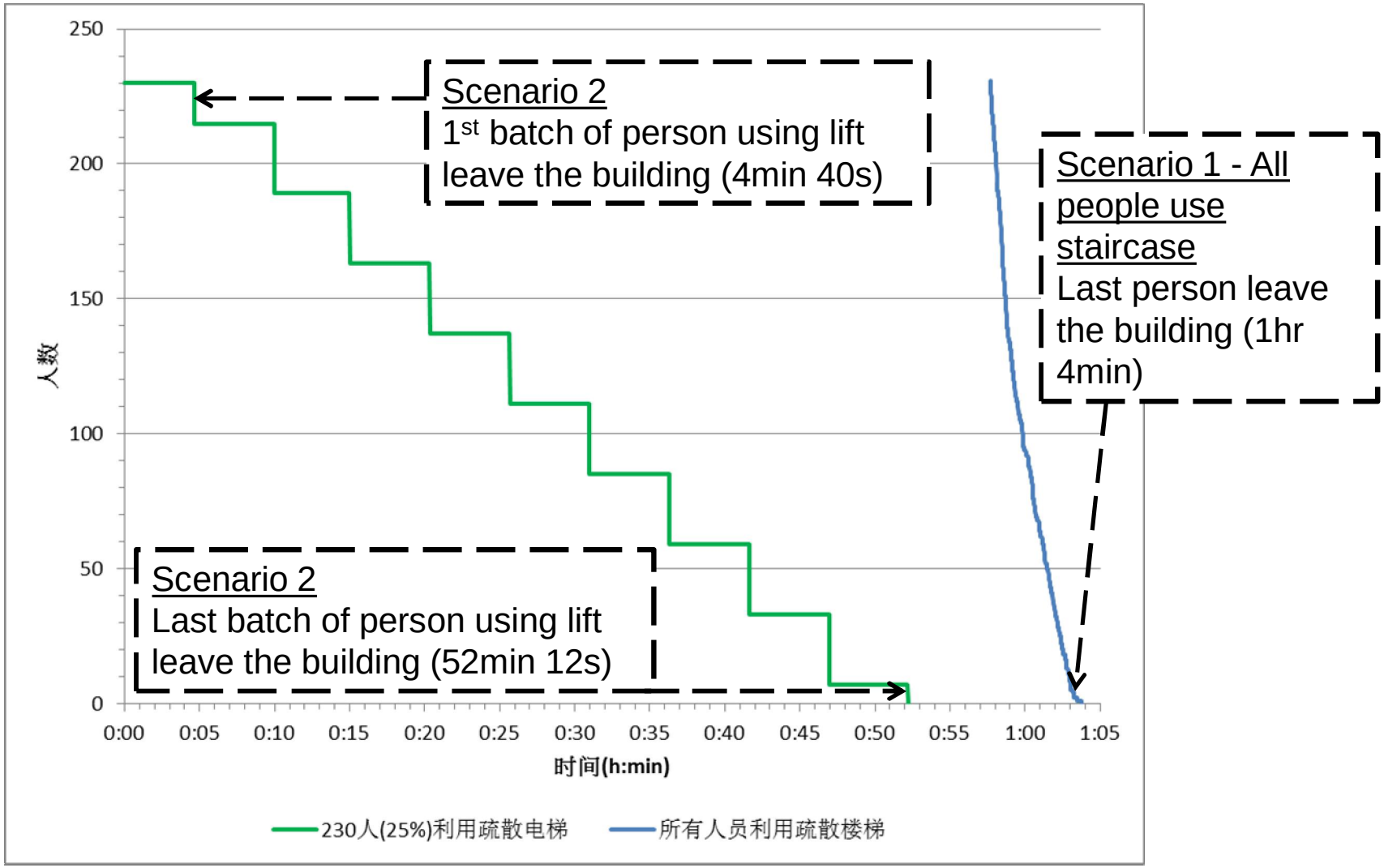


2min 52s

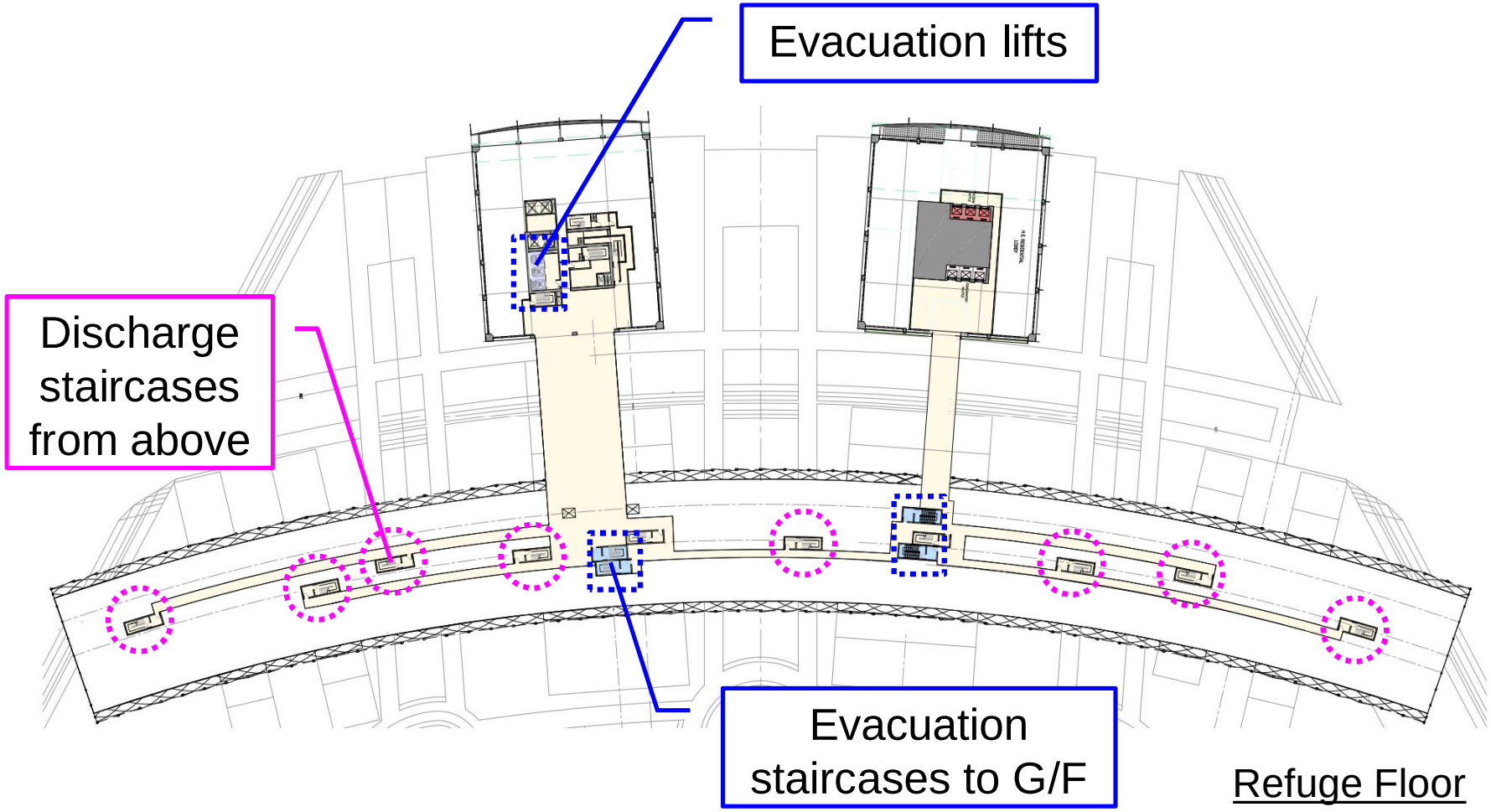


5min 12s

Lift Evacuation



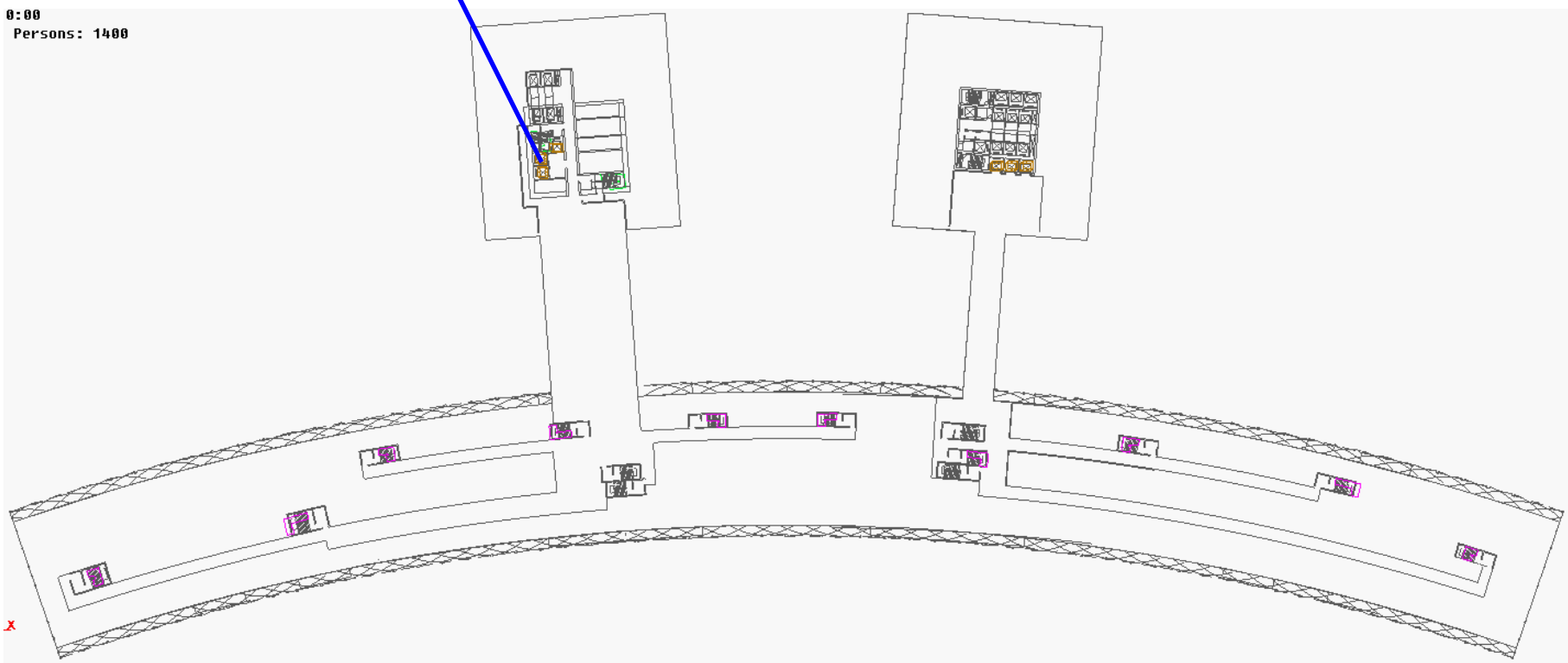
Lift Evacuation
- Lift Location



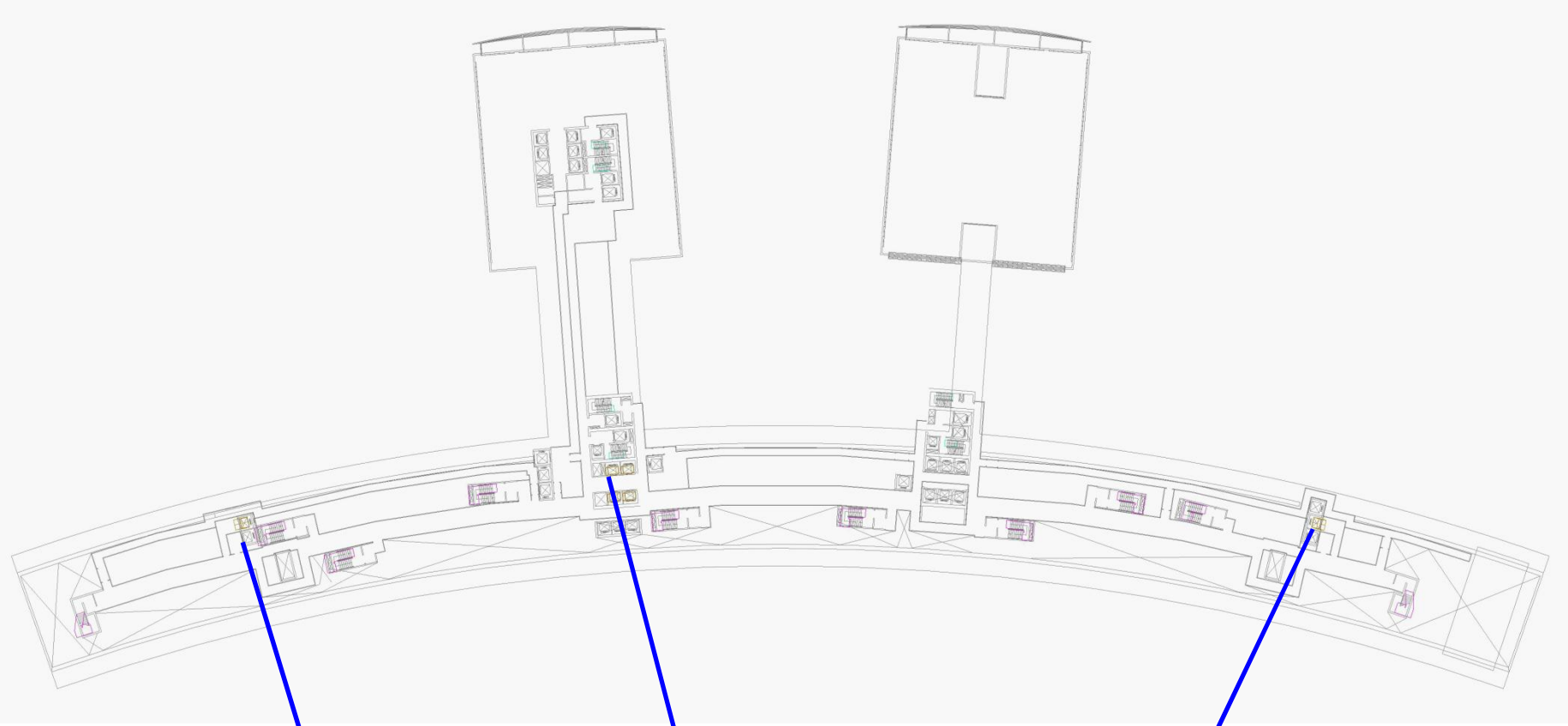
Refuge Floor

Lift Evacuation
- Lift Location

Evacuation lifts



Lift Evacuation
- Lift Location



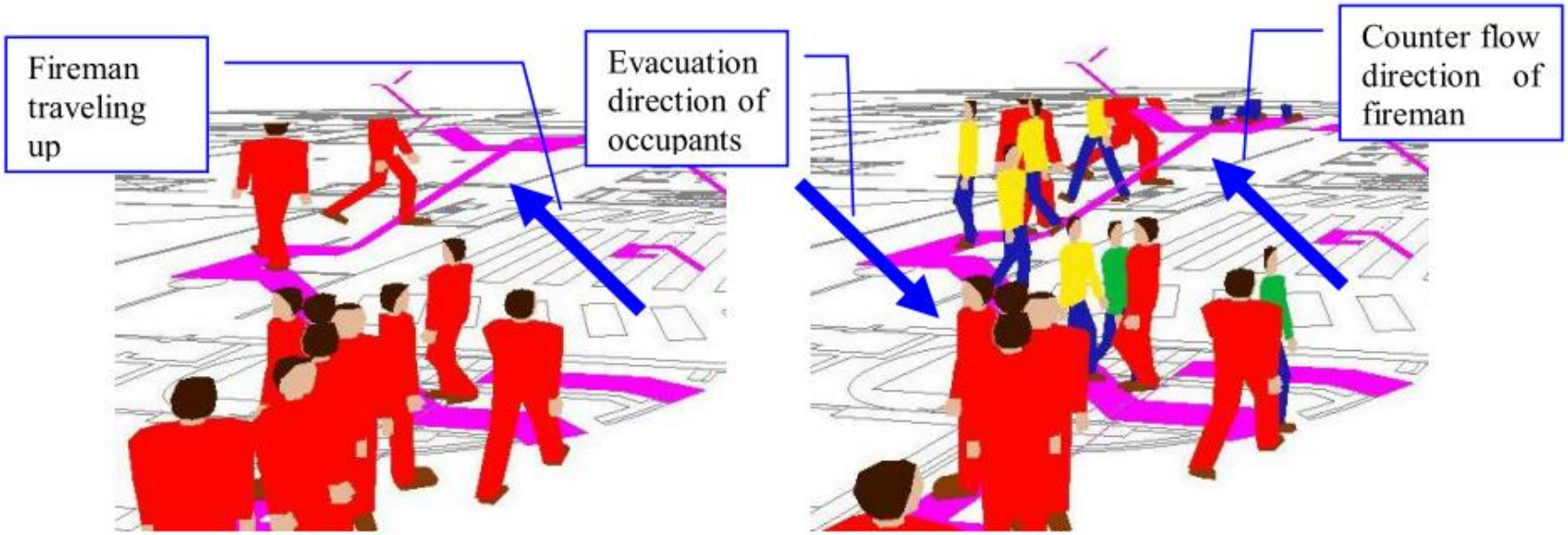
Lift Evacuation
- Lift Protection Requirement

Lift Evacuation
- Other Factors

- Simple evacuation route and clear signage
- Occupants should be trained and encouraged to use alternative means of escape during fire drills
- If escape staircase is co-located with a evacuation lift in the same protected enclosure, occupants have a clear choice of route
- Occupants should be protected and feel protected when they are waiting for the lift. Lift lobby should be large enough to accommodate and not to impede other routes
- Let the occupants know the lift waiting time
- Trained staff help to manage the occupants waiting in the lift lobby

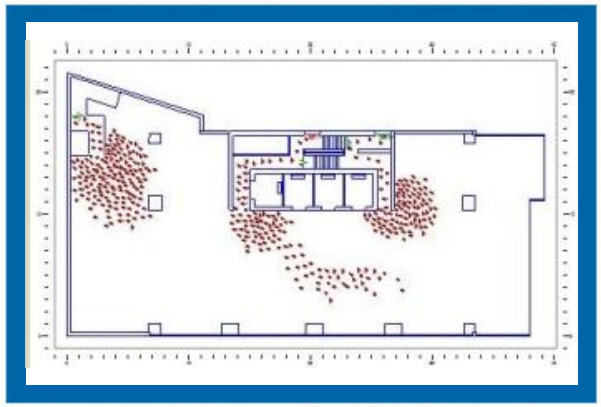
Counter-flow of Firemen

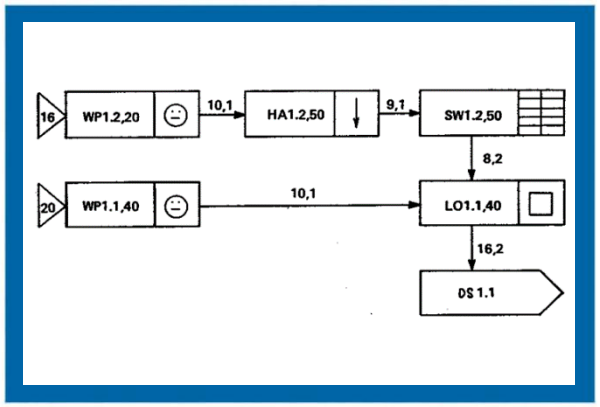
- Firemen travel upwards
- Evacuees travel downwards

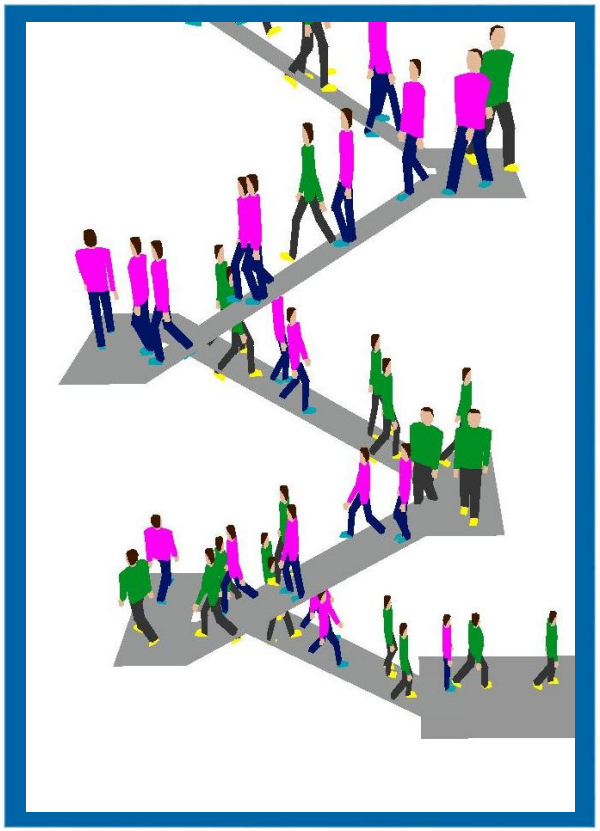


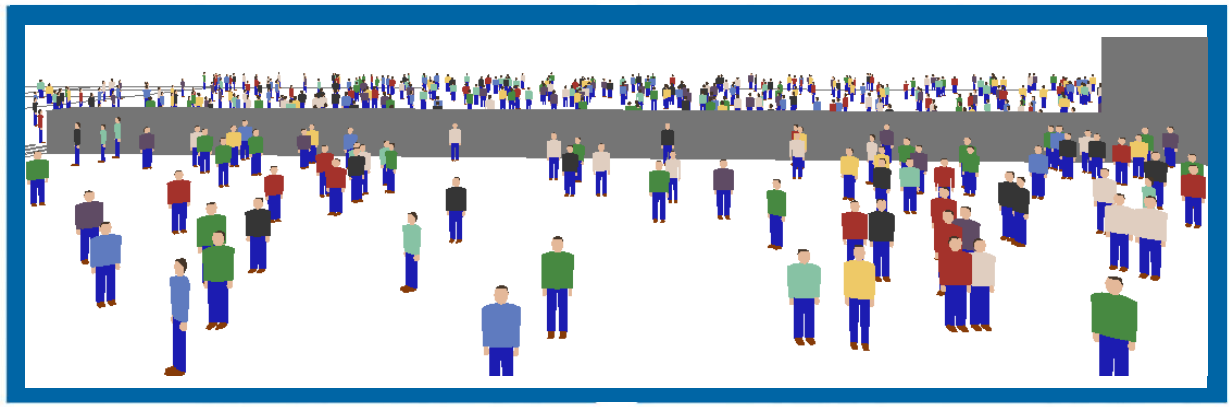
Counter-flow of Firemen

Case	**1**	**2**	**3**
Type of building	3 storeys clinic	16 storeys Hostel	3 Storeys office building
No of persons	100p	881p	671p
Staircase width	Staircase 1 - 1.05m Staircase 2 - 0.95m	Staircase 1 – 1.05m Staircase 2 – 1.05m	Staircase 1 - 1.35m Staircase 2 - 1.20m Staircase 3 - 1.40m Staircase 4 - 1.10m
Assessment method	Counter-flow	Discount staircase width	Discount staircase width
Total evacuation time without fireman counter flow	3min	16min 5s	3min 47s
Total evacuation time with fireman counter flow	3min 18s	17min 50s	4min 47s




16
WP1.2,20
10,1
HA1.2,50
9,1
SW1.2,50
8,2
20
WP1.1,40
10,1
LO1.1,40
16,2
DS 1.1





Thank You