MONTE CARLO AGENT-BASED HOSPITAL EVACUATION SIMULATIONS. THE PRINCIPLES OF PERFORMANCE-BASED INCLUSIVE DESIGN

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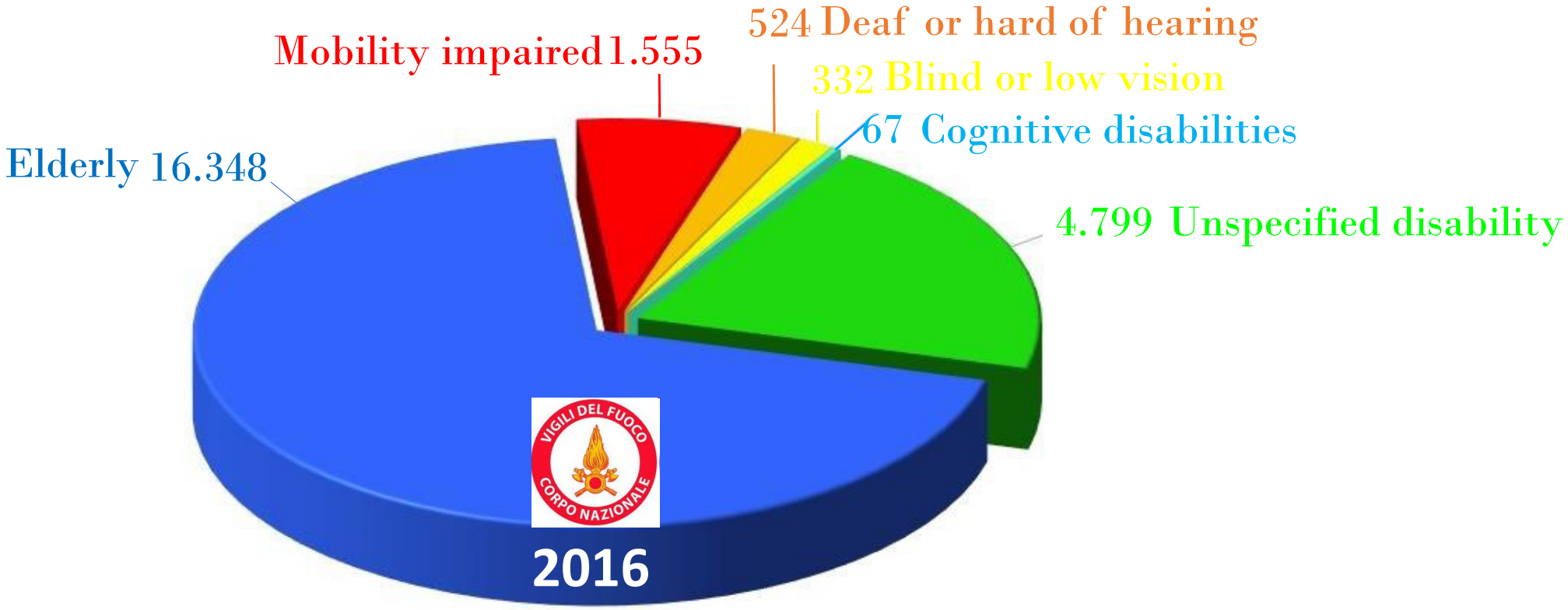
Outline

1. **Introduction**
2. **Evacuation capabilities framework integrating persons with special needs**
3. **Case study: assisted horizontal evacuation of a hospital ward combined with the vertical transfer of one In-patient using a firefighters lift**
4. **PathFinder MonteCarlo simulation results**
5. **Conclusion**

1 Persons with special needs assisted by fire brigades in Italy



Total number of people assisted by firefighters in 2016 in Italy: 74.122 (203 #/day)
Total number of people **with special needs** assisted by firefighters in 2016 in Italy: 23.625

Total number of people assisted by ff's in 2023 in Italy: 99.054 (271 #/day: +33% in 7 years)
(in 1216 cases the emergency service is called to lift and/or carry disabled or obese person)

Disabilities classification

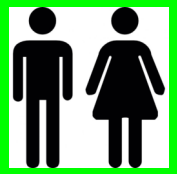
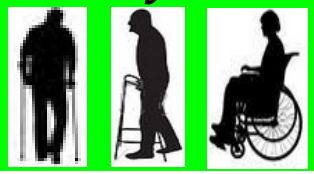
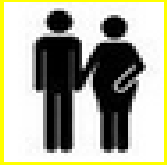
Table 1: Disabilities classification derived from NFPA DARAC Guide (2016).

General category		Examples of mobility devices required
Mobility	*Ambulatory mobility*	Canes, crutches, walkers
	Wheelchair users	Power-driven or manually operated wheelchair
	Respiratory	Depending on the case
Blind or Low vision		Canes, service animals.
Deaf or Hard of hearing		
Speech disabilities		
Cognitive disabilities		Depending on the case
Temporary disabilities		Depending on the case

NFPA DARAC

Establish a link with the assisted: meta-communication

2 Evacuation capabilities framework integrating persons with special needs

MOBILITY AND WAY FINDING CAPABILITIES	MOBILITY DEVICES	STAFF/EMERGENCY RESPONSE ASSISTANCE	REMARKS AND EXAMPLES
1. Autonomous 			• Staff/Emergency response teams • Walking In-patients (priority classif. level 4) • Autonomous occupants Full way finding capability and ability to independently walk on even and uneven surfaces and negotiate stairs
2. Autonomous *with mobility devices* 	Canes, crutches, walkers, rollators, wheelchairs		• Temporary or permanent disabilities Full way finding capability. *Type a)*: move/walk independently through an horizontal accessible route *Type b)*: with the use of a mobility device may also be able to negotiate stairs without supervision
3. Autonomous *requiring assistance in way finding or notification* 		1 or 2 staff operators for each autonomous walking occupant	• Blind or Low vision persons • Cognitive disabilities • Children • Deaf or Hard of hearing (only to be notified) • Walking patients (priority classif. level 3) *Type a):* able to walk and negotiate stairs only with the assistance of another person in way finding or walking. *Type b):* able to walk and negotiate stairs but requiring assistance only to be notified of the emergency.

Evacuation capabilities framework integrating persons with special needs

MOBILITY AND WAY FINDING CAPABILITIES	MOBILITY DEVICE	STAFF/EMERGENCY RESPONSE ASSISTANCE	REMARKS AND EXAMPLES
4. Not autonomous - *mobility devices required*  Hunt (2016) 	Wheelchair stretcher, rescue sheet, emergency stair travel device	1 to 4 operators for each assisted person	• Not autonomous patients (priority classif. level 2) *Type a)*: transferrable only on a wheelchair, a stretcher or a rescue sheet through an accessible route (for relocation on the same floor) *Type b)*: transferrable on stairs with emergency travel devices or by means of a firefighters lift (i.e. complying with EN 81-72:2020, clause 5.2.3) accessible for a wheelchair or stretcher (i.e. types 3 to 5 according to EN 81-70:2018)
5. Not autonomous – *Transferrable only with beds or incubators* 	Bed, incubator	1 or 2 operators for each assisted person	• Critical patients (priority classification level 1) *Type a)*: transferrable only on a bed or incubator through an accessible route (for relocation on the same floor) *Type b)*: transferrable on stairs only by means of a firefighters lift (i.e. complying with EN 81-72:2020, clause 5.2.3) with adequate accessibility (i.e. type 5 according to EN 81-70:2018)

Basic *autonomous* occupant profiles

***Autonomous* occupant profile**	**Unhindered walking speed (m/s) (on level terrain, straight-line movement)**					**Social grouping**	**Remarks**
	Distribution law						
	Type	**μ**	**σ**	**Min**	**Max**		
Active staff ***(in each fire compartment)***	Normal Alonso and Ronchi (2016)	1.35	0.25	μ -2.8σ	μ +2.8σ	Individual or assistance team member	Familiar & Trained
Emergency response ***(in the emergency control center)***	Assumed equal to Active staff					Individual or assistance team member	Familiar & Trained
Generic autonomous occupant	Normal Fruin (1987), Boyle (1999)	1.20	0.20	μ -3.0σ	μ +3.0σ	Individual or groups, eventually linked to one in-patient	Uncertain familiarity & Not Trained
Worker (not in charge of egress assistance)	Assumed equal to Visitor to in-patients					Individual or with co-workers	Familiar & Trained
Autonomous in-patient	Normal Boyle (1999)	0.95	0.32	μ -2.2σ	μ +2.2σ	Individual or linked to Visitors	Uncertain familiarity & Not Trained

Basic *autonomous* but mobility impaired occupant profiles

Autonomous but mobility impaired occupant profile		Unhindered walking speed (m/s) (on level terrain, straight-line movement)					Social grouping	Remarks
		Distribution law						
		Type	μ	σ	Min	Max		
Mobility device	Crutches	Normal Boyle (1999)	0.94	0.30	μ -1.0σ	μ +1.4σ	Individual or linked to visitors	Uncertain familiarity & Not Trained
	Walking stick	Normal Boyle (1999)	0.81	0.38	μ -1.4σ	μ +2.0σ	Individual or linked to visitors	Uncertain familiarity & Not Trained
	Rollator or walking frames	Normal Boyle (1999)	0.57	0.29	μ -1.6σ	μ +1.6σ	Individual or linked to visitors	Uncertain familiarity & Not Trained
	Electric wheelchair	Constant Boyle (1999)	0.89				Individual or linked to visitors	Uncertain familiarity & Not Trained
	Manual wheelchair	Normal Boyle (1999)	0.69	0.35	μ -1.6σ	μ +1.9σ	Individual or linked to visitors	Uncertain familiarity & Not Trained

Basic *assisted* occupant profiles

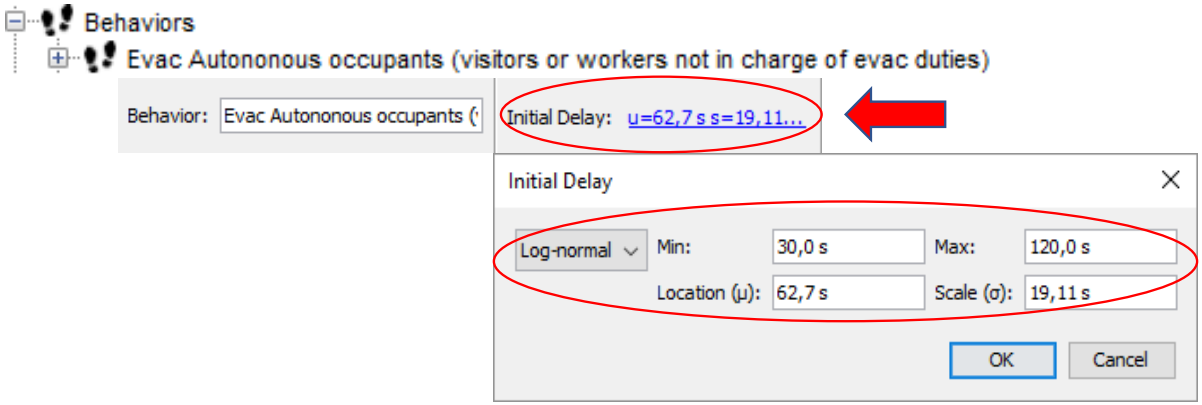
Assisted occupant profile	Assisted travel speed (m/s) (on level terrain, straight-line movement)					Active staff/ Emergency resp. assignment
	Distribution law					
	Type	μ	σ	Min	Max	
Assisted ambulant	Normal Boyle (1999)	0.71	0.34	μ -1.7σ	μ +1.8σ	1 operator [1]
Assisted transported on a wheelchair [2]	Normal Alonso (2014,2016)	0.63	0.04	μ -3.0σ	μ +3.0σ	1 operator [1]
Assisted transported on a carry or evac chair	Uniform Hunt (2012, 2015)			1.34	1.75	1 operator [1]
Assisted transported on a bed [2]	Normal Alonso (2014,2016)	0.40	0.04	μ -3.0σ	μ +3.0σ	2 operators
Assisted transported on a hand-held rescue sheet	Uniform Hunt (2012, 2015)			0.52	1.23	2 operators
Assisted transported on a hand-held stretcher	Uniform Hunt (2012, 2015)			0.91	1.23	4 operators [2]

[1] An additional operator may be needed to prepare the patient for transportation or assist along the travel path

[2] Could be reduced to two operators only to execute the task to prepare the patient for transportation

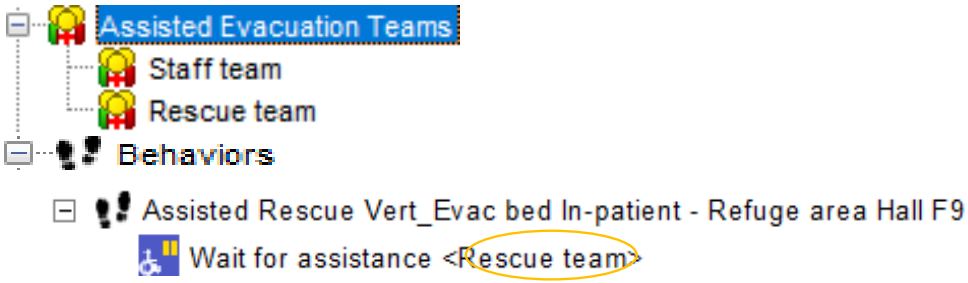
PTAT for *autonomous* occupant profiles

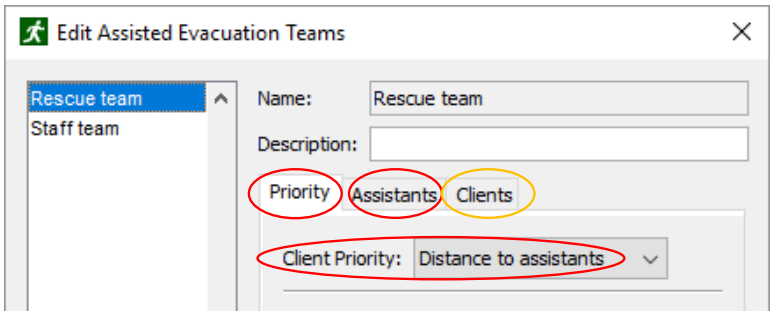
Autonomous occupant profile	PTAT(s)					Remarks
	Distribution law					
	Type	μ	σ	Min	Max	
Other autonomous profiles (Workers, Visitors to in-patients or generic occupants, Autonomous in-patients, Autonomous but mobility impaired)	Log-normal ISO/TR 16738 (2009) data range for awake&unfamiliar profiles in level M1 occupancies	62.7	19.11	30	120	Uncertain familiarity & Not Trained & Not grouped with an assisted occupant



Basic set of evacuation team profiles

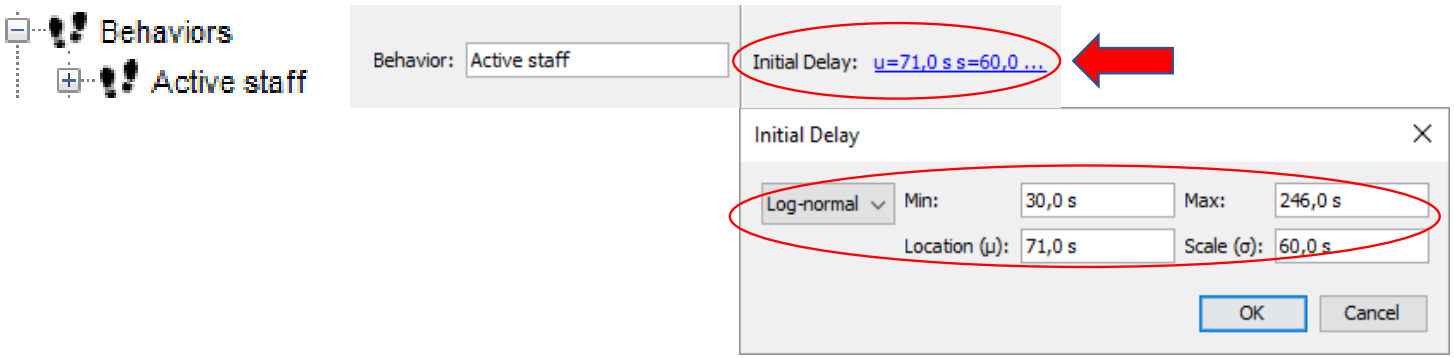
Evacuation team profiles	*Members profiles*	Assisted profiles	Remarks
Active staff team	*Active staff*	All assisted profiles	Cannot use elevators in emergency May have restrictions on travel path choice
Emergency response team	*Emergency response*	Restricted to selected occupant profiles	No restriction in travel path choice Able to use selected elevators in emergency





Pre-travel activity time (PTAT) for assisting operators

Assisting profile	PTAT (s)					Remarks
	Distribution law					
	Type	μ	σ	Min	Max	
Active Staff	Log-normal Alonso (2014, 2016) for health care staff (same mean value in Gwynne et al. (2002, 2003))	71	60	30 Gwynne et al. (2002, 2003)	246 Gwynne et al. (2002, 2003)	Familiar & Trained
Emergency response	Log-normal ISO/TR 16738 (2009) data range for awake&familiar profiles in level M1 occupancies	43	6.44	30	60	Familiar & Trained



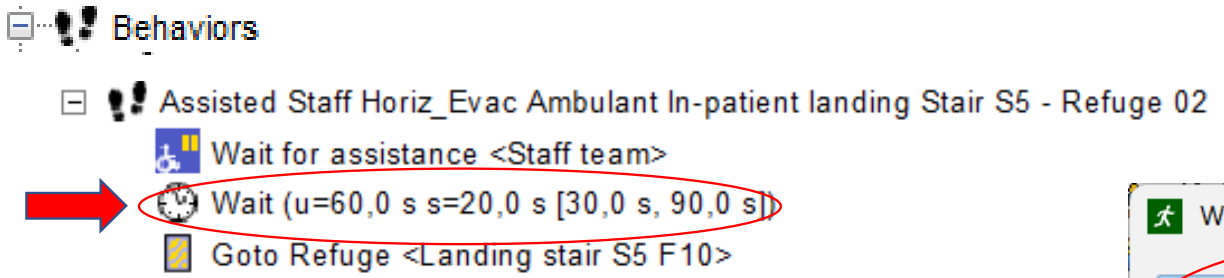
Preparation times for assisted occupant profiles

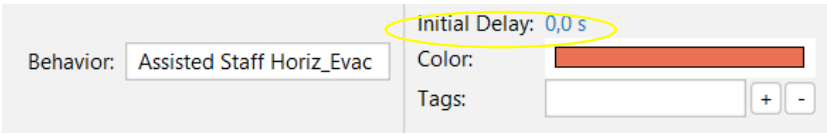
Assisted occupant profile	Preparation time (s)				
	Distribution law				
	Type	μ	σ	Min	Max
Assisted ambulant	Normal Alonso (2014, 2016)	60	20	μ -1.5σ	μ +1.5σ
Assisted transported on a wheelchair	Normal Alonso (2014, 2016)	110	36	μ -0.3σ [2]	μ +0.3σ [2]
Assisted transported on a bed	Assumed equal to assisted on a wheelchair				
Assisted transported on a carry or evac chair	Normal Hunt (2012, 2015) [1]	41.5	7.9	μ -1.2σ	μ +1.3σ
Assisted transported with hand-held rescue sheet	Normal Hunt (2012, 2015) [1]	65.2	14.1	μ -1.4σ	μ +1.5σ
Assisted transported with hand-held stretcher	Normal Hunt (2012, 2015) [1]	77.7	19.2	μ -0.9σ	μ +2.2σ

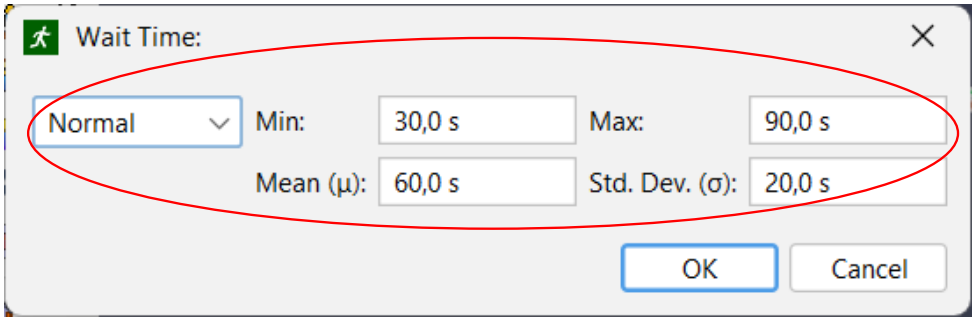
[1] Based on Hunt (2012, 2015) overall data for carry chair for an assisting team of two health care operators
[2] Based on Hunt (2012, 2015) overall data, for an assisting team of two health care operators

Preparation time for assisted occupant profiles - Example

Assisted occupant profile	Preparation time (s)				
	Distribution law				
	Type	μ	σ	Min	Max
Assisted ambulant	**Normal** Alonso (2014, 2016)	60	20	μ -1.5σ (30)	μ +1.5σ (90)







[1] Preparation time starts only *after* an assisting team has taken on duty the client (and all team components are in place)

Basic movement groups schemes

Case study: assisted egress in health care occupancy

Movement groups for occupants having *autonomous* evacuation capabilities
2 or more Visitors to In-patients (or generic *autonomous* occupants)
2 or more Workers (not in charge of egress assistance)
1 *Autonomous* In-patient and 1 or more Visitors to in-patient
1 *Autonomous* but mobility impaired (5 categories) and 1 or more generic *autonomous* occupants

For the assisted profiles, it is stipulated that only one agent of that type can be put in relationship with one or more *autonomous* profiles

Movement groups for *assisted* occupants [1]
1 Assisted ambulant and 1 or more Visitors to In-patients (or generic *autonomous* occupants)
1 Assisted transported on a wheelchair or evac chair and 1 or more Visitors to In-patients
1 Assisted transported with hand-held rescue sheet and 1 or more Visitors to In-patients
1 Assisted transported with hand-held stretcher and 1 or more Visitors to In-patients
1 Assisted transported on a bed and 1 or more Visitors to In-patients

[1] Each group will include also the prescribed number of assisting operators

Modeling issue in *Refuge areas* using PathFinder

However some key points relevant for assisted evacuation simulation could be improved in future algorithm revision:

- *Refuge capacity definition prevents the inlet of the assisting team at the access door if the equivalent occupant count corresponding to the mobility shape of the vehicle and the entering assisting operators exceeds the rated capacity.*

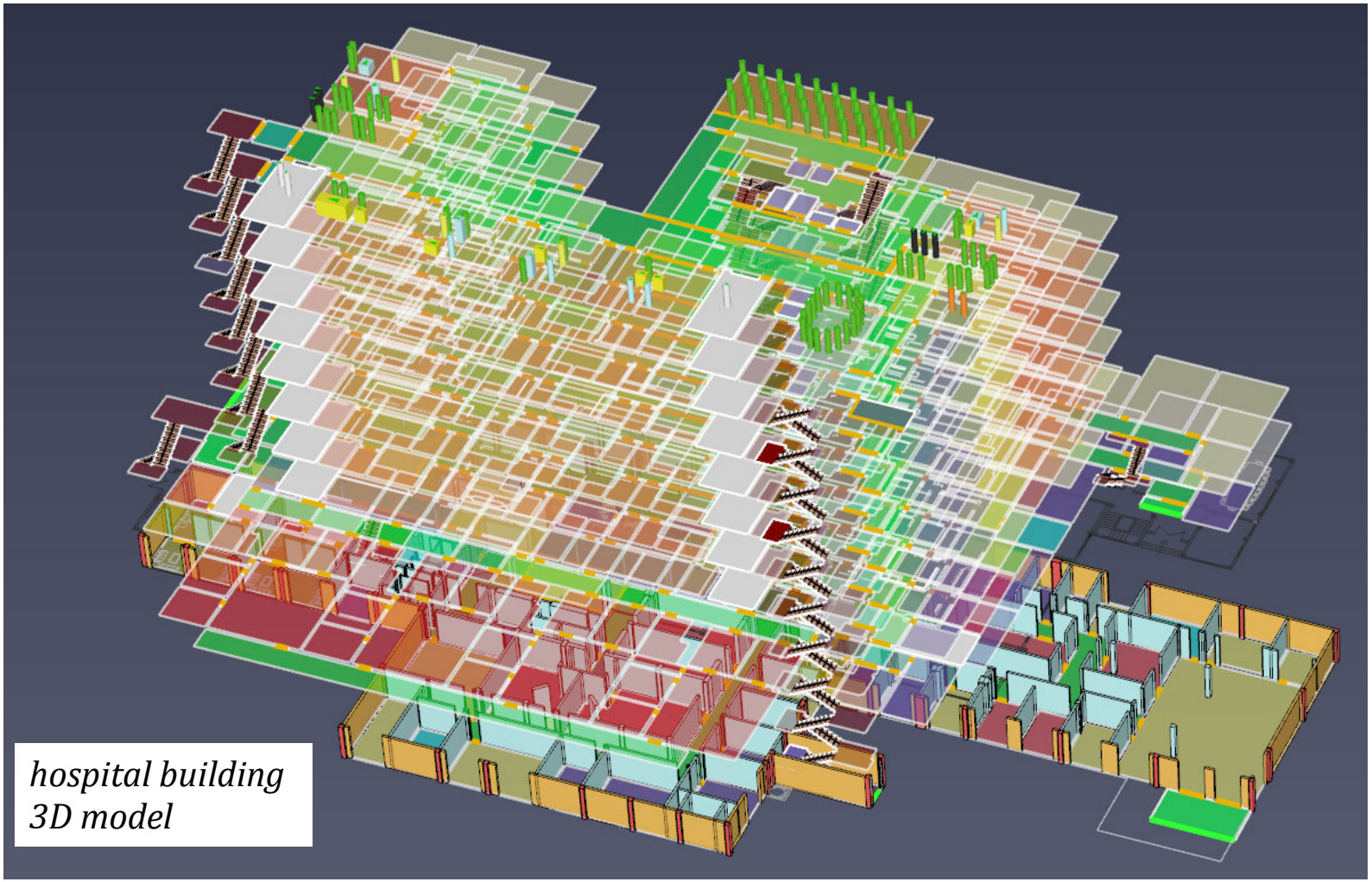
✓ The total number of occupants for should be based on the *effective number* of occupants *without considering the corresponding occupant count for those transported with a mobility device*.
The availability of sufficient *space* in the refuge to host the incoming occupants should be independently checked issuing an error message in case of violation.

Modeling issue in *Refuge areas* using PathFinder

- *Recalling that assisted occupants do not have autonomous movement capability, they remain in the refuge in the position where they are left by the assisting team and can unduly impede the entering of other occupants following them or limit the space availability if not correctly oriented.*

- ✓ If mobility impaired person should be allocated in a refuge area, specific areas of refuge for assisted non ambulant profiles should be defined, providing at least two virtual doors and shaped so that the assisted non ambulant occupant can be allocated properly and the assisting operators can move out without remaining unduly entrapped.

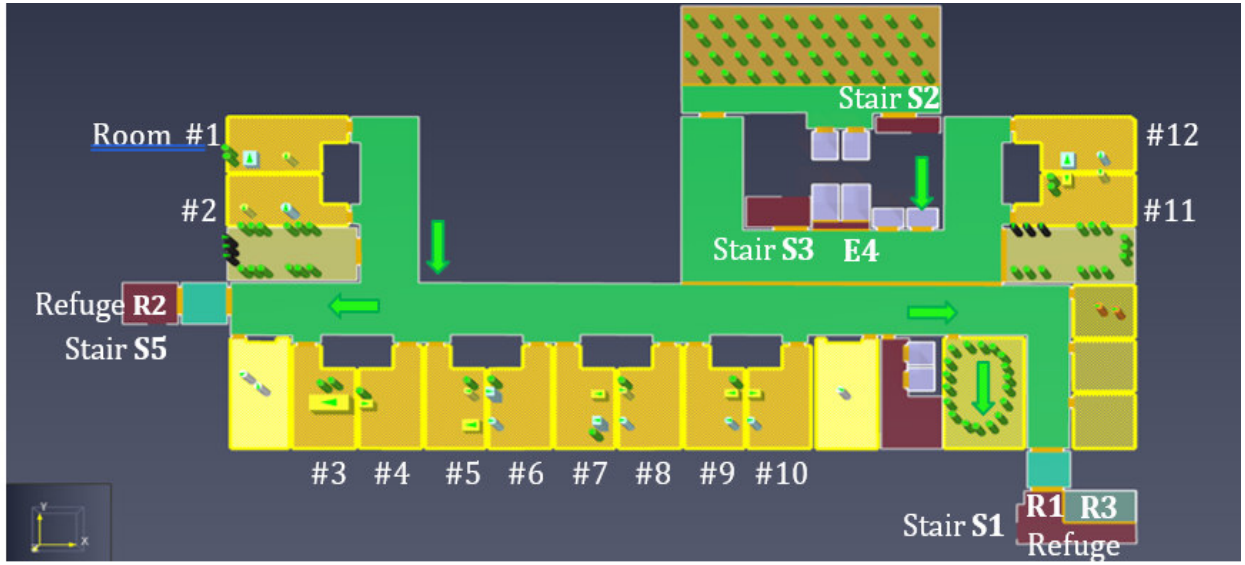
3 Case study: assisted horizontal evacuation of a hospital ward combined with the vertical transfer of one In-patient using a firefighters lift

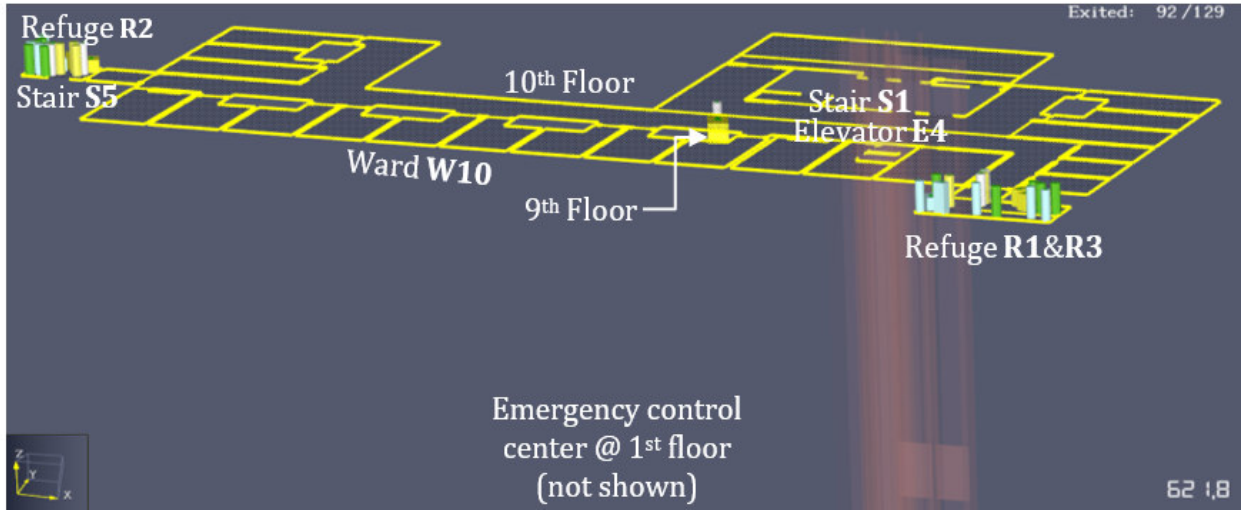


hospital building 3D model

3 Case study: assisted horizontal evacuation of a hospital ward combined with the vertical transfer of one In-patient using a firefighters lift

Model plan view with the initial and final positions of the occupants





22 In-patients (10 autonomous, 12 assisted) with 12 Visitors;
2 workers;
3 active staff operators
88 autonomous occupants

2 emergency responders in command center @ 1st floor with primary task to transfer one In-patient to 9th floor using lift E4 and then collaborate with the Active staff, if needed

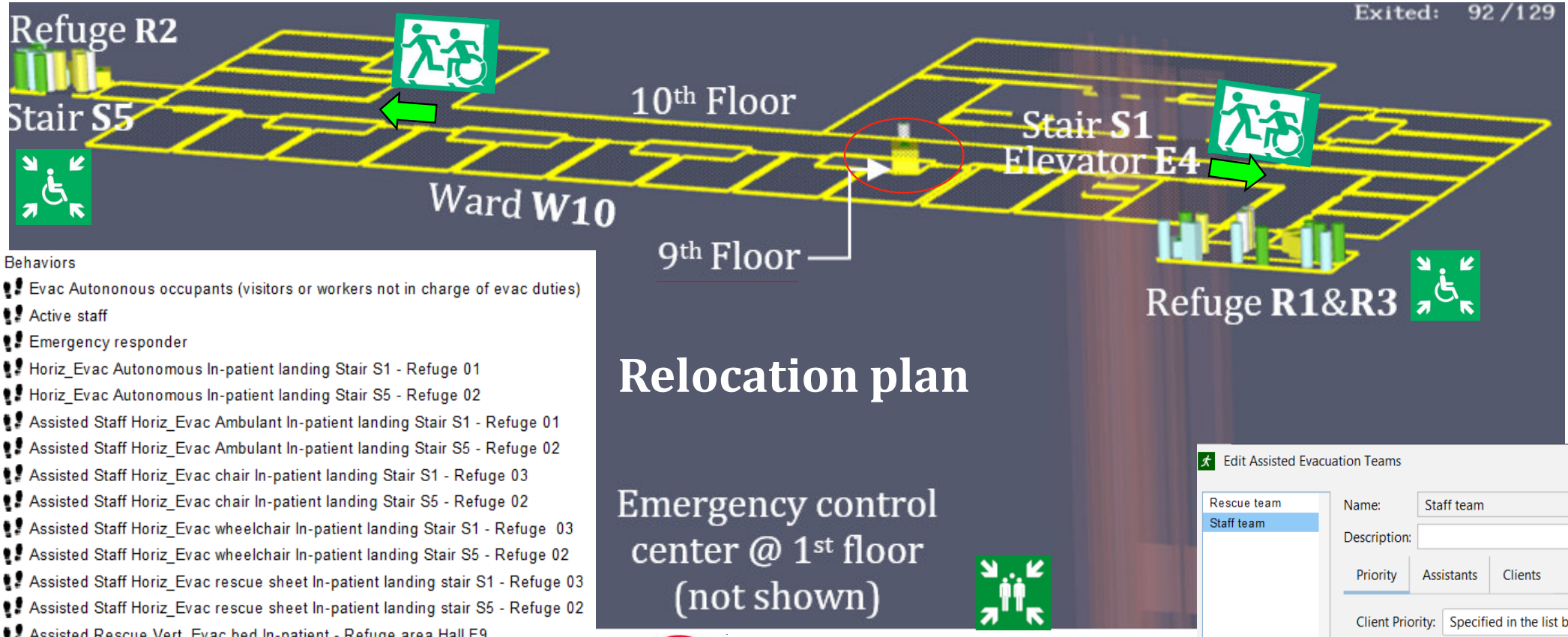
Application floor:
10th floor 912 m²

Ward 10: 310 m²,
12 In-patients sleeping rooms (10 double and 2 single occupancy),
2 Nurse stations
3 service rooms
1 meeting room

Two lobbies and one lounge

Corridor length 60 m,
270-330 cm wide,
with two exit fire doors
180 cm wide

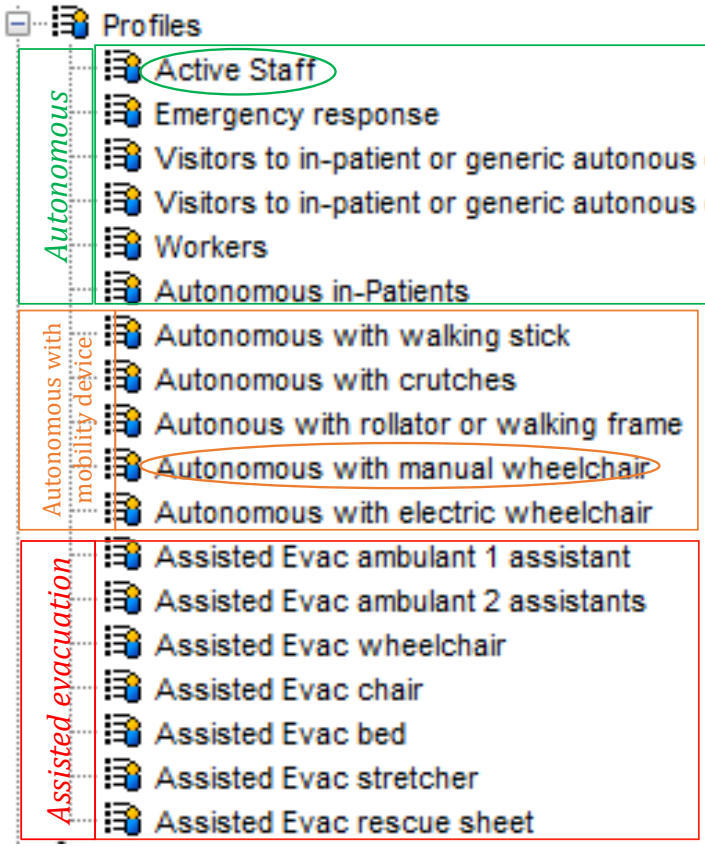
Case study: assisted horizontal evacuation of a hospital ward combined with the vertical transfer of one In-patient using a firefighters lift



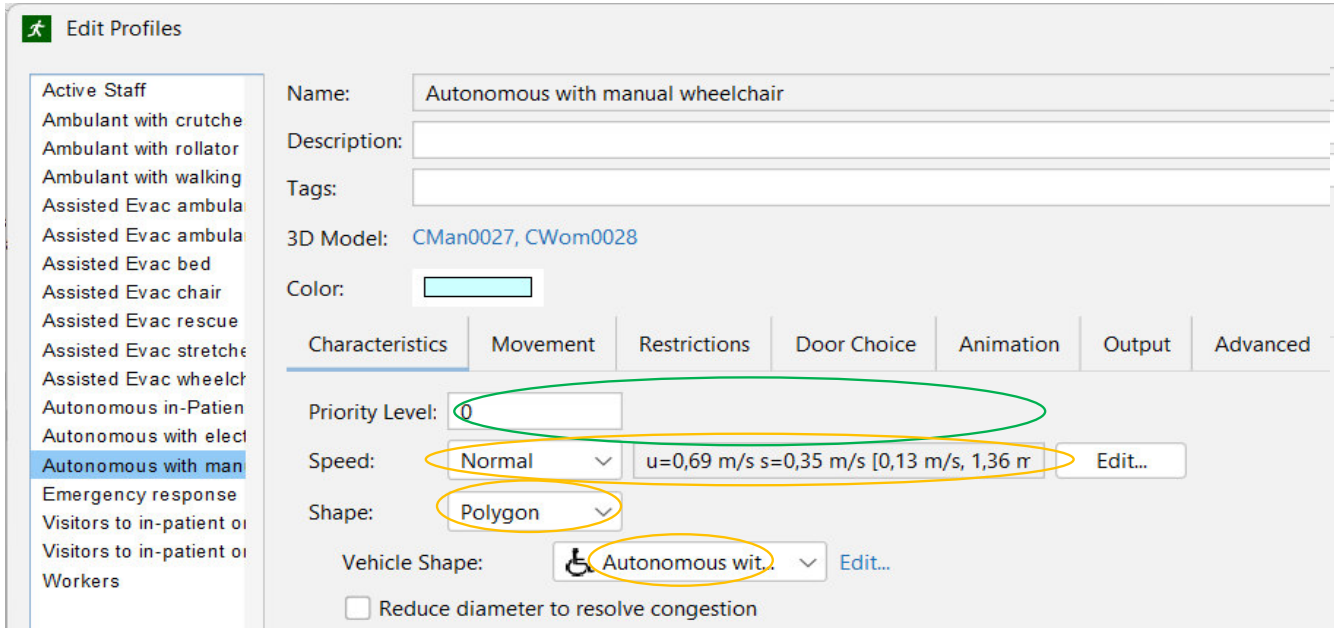
- Behaviors
  - Evac Autononous occupants (visitors or workers not in charge of evac duties)
  - Active staff
  - Emergency responder
  - Horiz_Evac Autonomous In-patient landing Stair S1 - Refuge 01
  - Horiz_Evac Autonomous In-patient landing Stair S5 - Refuge 02
  - Assisted Staff Horiz_Evac Ambulant In-patient landing Stair S1 - Refuge 01
  - Assisted Staff Horiz_Evac Ambulant In-patient landing Stair S5 - Refuge 02
  - Assisted Staff Horiz_Evac chair In-patient landing Stair S1 - Refuge 03
  - Assisted Staff Horiz_Evac chair In-patient landing Stair S5 - Refuge 02
  - Assisted Staff Horiz_Evac wheelchair In-patient landing Stair S1 - Refuge 03
  - Assisted Staff Horiz_Evac wheelchair In-patient landing Stair S5 - Refuge 02
  - Assisted Staff Horiz_Evac rescue sheet In-patient landing stair S1 - Refuge 03
  - Assisted Staff Horiz_Evac rescue sheet In-patient landing stair S5 - Refuge 02
  - Assisted Rescue Vert_Evac bed In-patient - Refuge area Hall F9
  - Assisted Horiz_Evac bed In-parient landing Stair S1 - Refuge 03
  - Assisted Horiz_Evac stretcher In-patient landing stair S1 - Refuge 03
  - Assisted Horiz_Evac stretcher In-patient landing stair S5 - Refuge 02

Basic occupant profiles

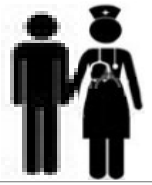
Case study: assisted horizontal evacuation of a hospital ward combined with the vertical transfer of one In-patient using a firefighters lift

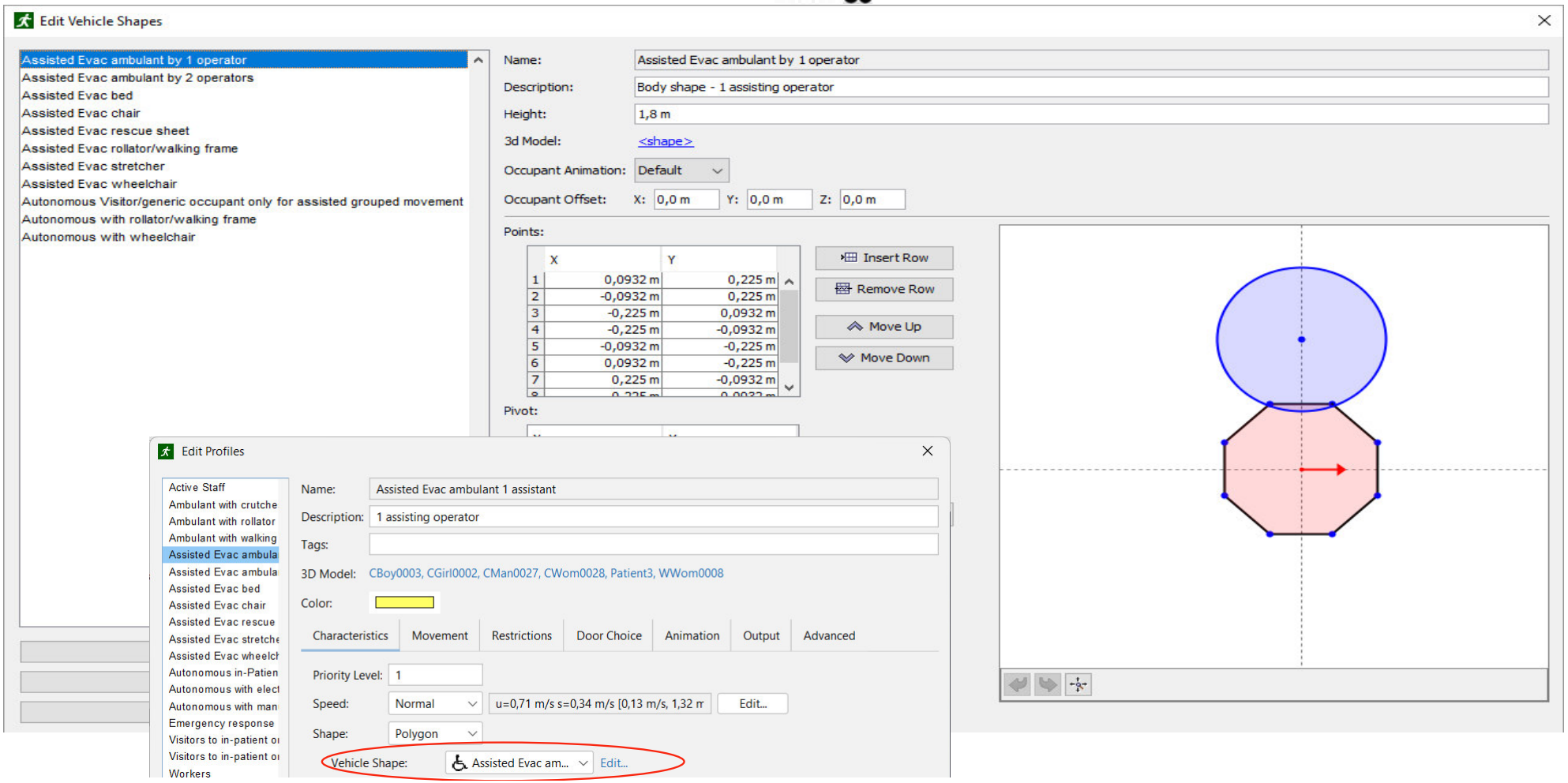


No age or gender differentiation



Modeling issue in *assisted* ambulant evacuation using PathFinder





Modeling issue in PathFinder group movements linking an *autonomous* profile with an assisted occupant

Edit Profiles

Active Staff
Assisted Evac ambulant 1 assistant
Assisted Evac ambulant 2 assistants
Assisted Evac bed
Assisted Evac chair
Assisted Evac rescue sheet
Assisted Evac stretcher
Assisted Evac wheelchair
Autonomous in-Patients
Autonomous with crutches
Autonomous with electric wheelchair
Autonomous with manual wheelchair
Autonomous with walking stick
Autonous with rollator or walking frame
Emergency response
Visitors to in-patient or generic autonous occupants
Visitors to in-patient or generic autonous occupants only for assisted group movemer
Workers

New...
Add From Library...
Rename...
Delete...

Rename...
Delete...

Name: Visitors to in-patient or generic autonous occupants only for assisted group movements
Description:
3D Model: BMan0002, BMan0012, BWom0001, BWom0002, CMan0001, CMan0002, CMan0003, CMan0012
Color:

Characteristics | Movement | Door Choice | Output | Advanced

Priority Level: 0
Speed: Normal u=1,2 m/s s=0,2 m/s [0,6 m/s, 1,8 m/s] Edit...
Shape: Polygon
Vehicle Shape: Autonomous Visitor... Edit...
Reduce diameter to resolve congestion
Reduction Factor: 0,7

Reset to Defaults...

Corresponding occupant count: 1

Case study: assisted horizontal evacuation of a hospital ward combined with the vertical transfer of one In-patient using a firefighters lift

4

PathFinder MonteCarlo simulation results (142 runs)

Refuge areas

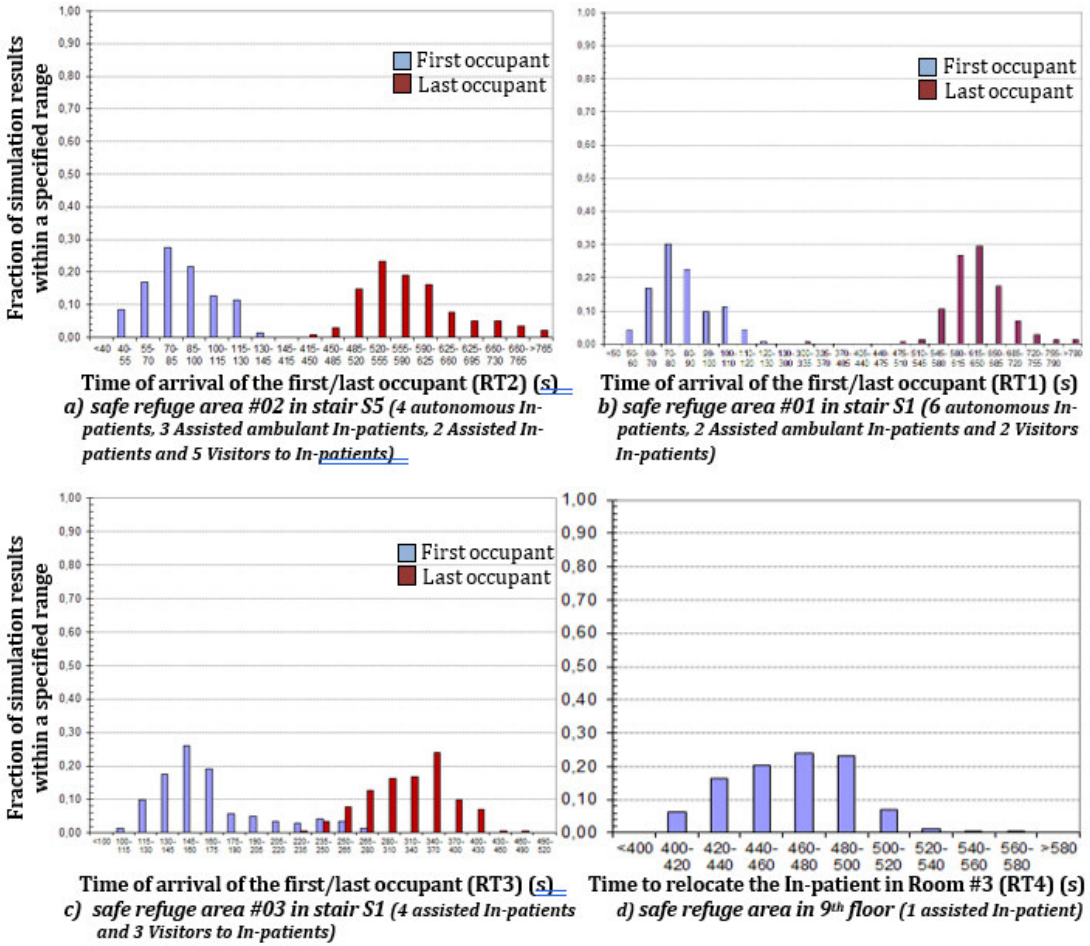


Figure 6: Time of arrival of first/last occupant: a) safe refuge area #02 in stair S5 (4 autonomous In-patients, 3 Assisted ambulant In-patients, 2 Assisted In-patients and 5 visitors to In-patients); b) safe refuge area #01 in stair S1 (6 autonomous In-patients, 3 Assisted ambulant In-patients, 3 Assisted ambulant In-patients and 2 visitors to In-patients); c) safe refuge area #03 in stair S1 (4 Assisted ambulant In-patients and 3 visitors to In-patients); d) 1 assisted In-patients vertically evacuated. Statistics based on 142 Monte Carlo simulations.

PathFinder MonteCarlo simulation results (142 runs)

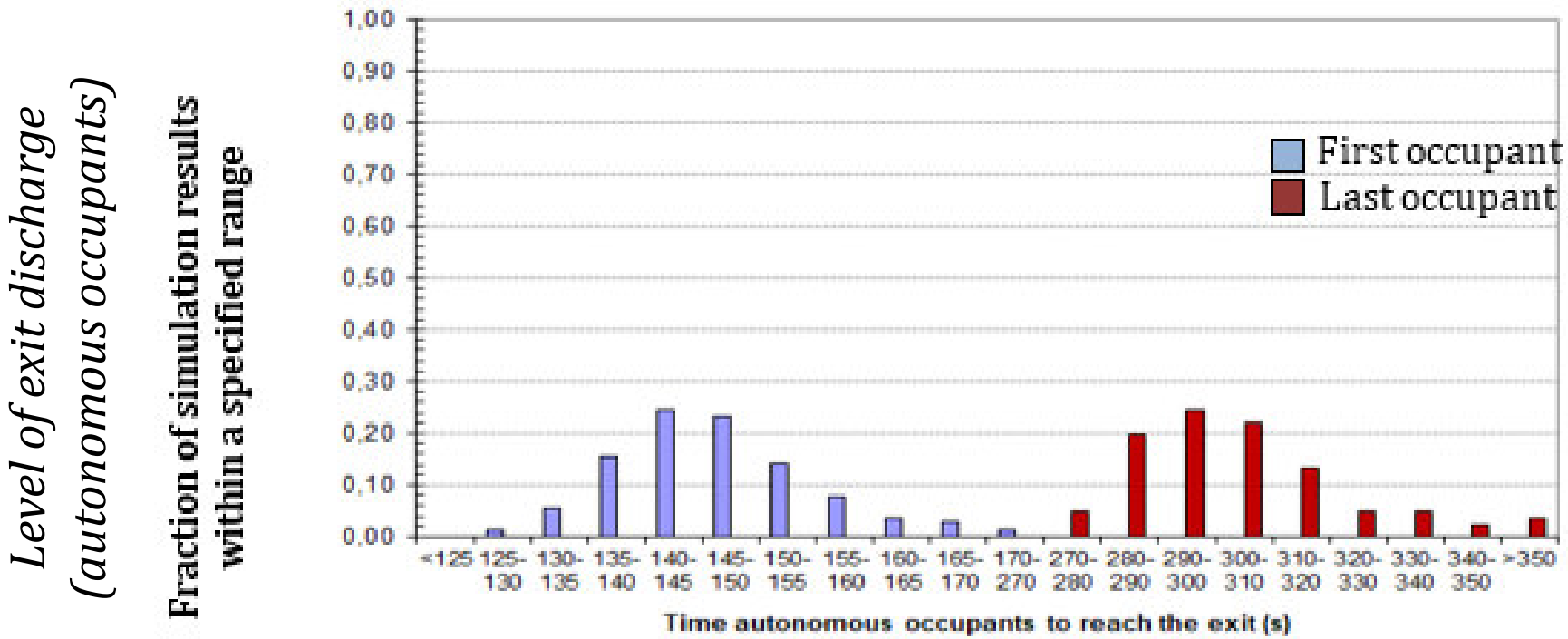
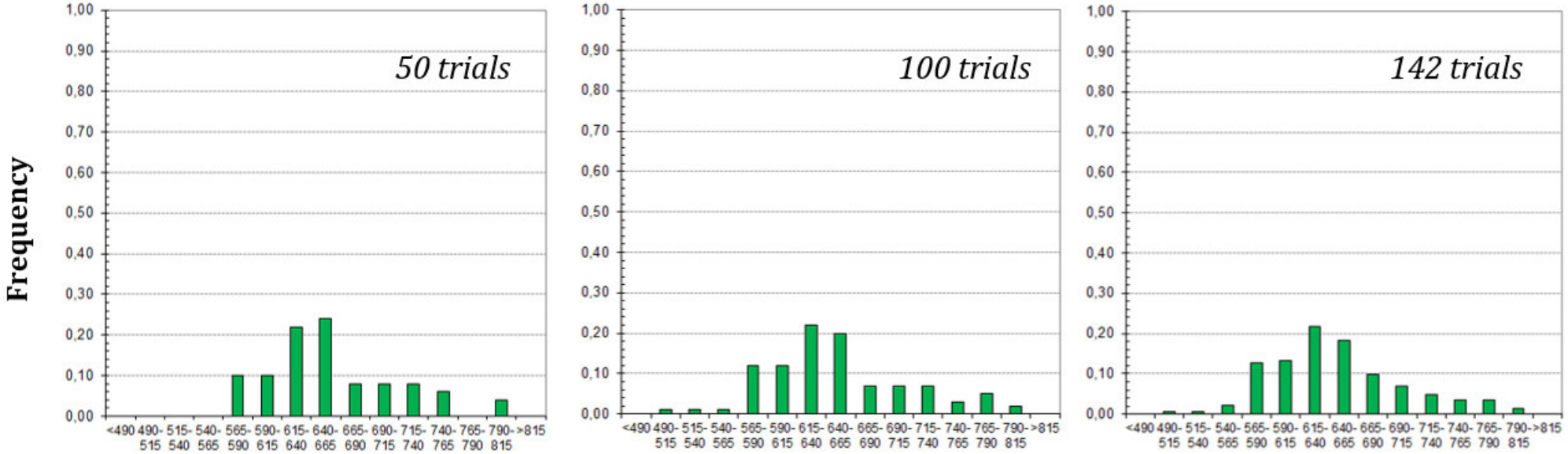


Figure 7: Time of arrival of first/last autonomous occupant to reach the exit (92 occupants). Statistics based on 142 Monte Carlo simulations

RSET (s)

Time required to relocate *all* the In-patients and *all* autonomous occupants to reach an exit



ET statistics		25 trials	50 trials	75 trials	100 trials	125 trials	142 trials
Mean	$\overline{et}$ (s)	648	659	656	651	649	646
Standard deviation	s_{et} (s)	58	55	58	61	58	57
Standard error	$\frac{s_{et}}{\sqrt{n}}$ (s)	11,5	7,7	6,6	6,1	5,2	4,8
95% CI for the mean	$\Delta_{\mu_{ET}}$ (s)	23,7	15,1	13,0	11,9	10,2	9,4
Median	(s)	637	651	649	641	638	637
Minimum	et_{max} (s)	575	575	515	499	499	499
Maximum	et_{min} (s)	805	805	805	805	805	805
Range	(et_{max}-et_{min}) (s)	230	230	290	306	306	306
IQR [Q3-Q1]	(s)	50	70	60	68	66	63
Kurtosis		2,2	0,2	0,3	0,2	0,2	0,3
Skewness		1,4	0,8	0,7	0,5	0,6	0,6

Evacuation time (ET) histograms evolution as a function of the number of Monte Carlo trials

The number of Monte Carlo simulations required to obtain the desired precision

An appealing strategy is to specify a priori the confidence level, α, and the half-interval width of the confidence interval, Δ, and estimate the number of required iterations n to the desired degree of precision, from the application of the formula:

$$n_{\mu_{ET}} = \frac{z^2_{\alpha/2} s^2_{et}}{\Delta^2_{\mu_{ET\ design}}}$$

[95] A. Tinaburri, Principles for Monte Carlo agent-based evacuation simulations including occupants who need assistance. From RSET to RiSET. Fire Saf. J. 127 (2022) 1–21.

RSET (s)

Time required to relocate *all* the In-patients and *all* autonomous occupants to reach an exit

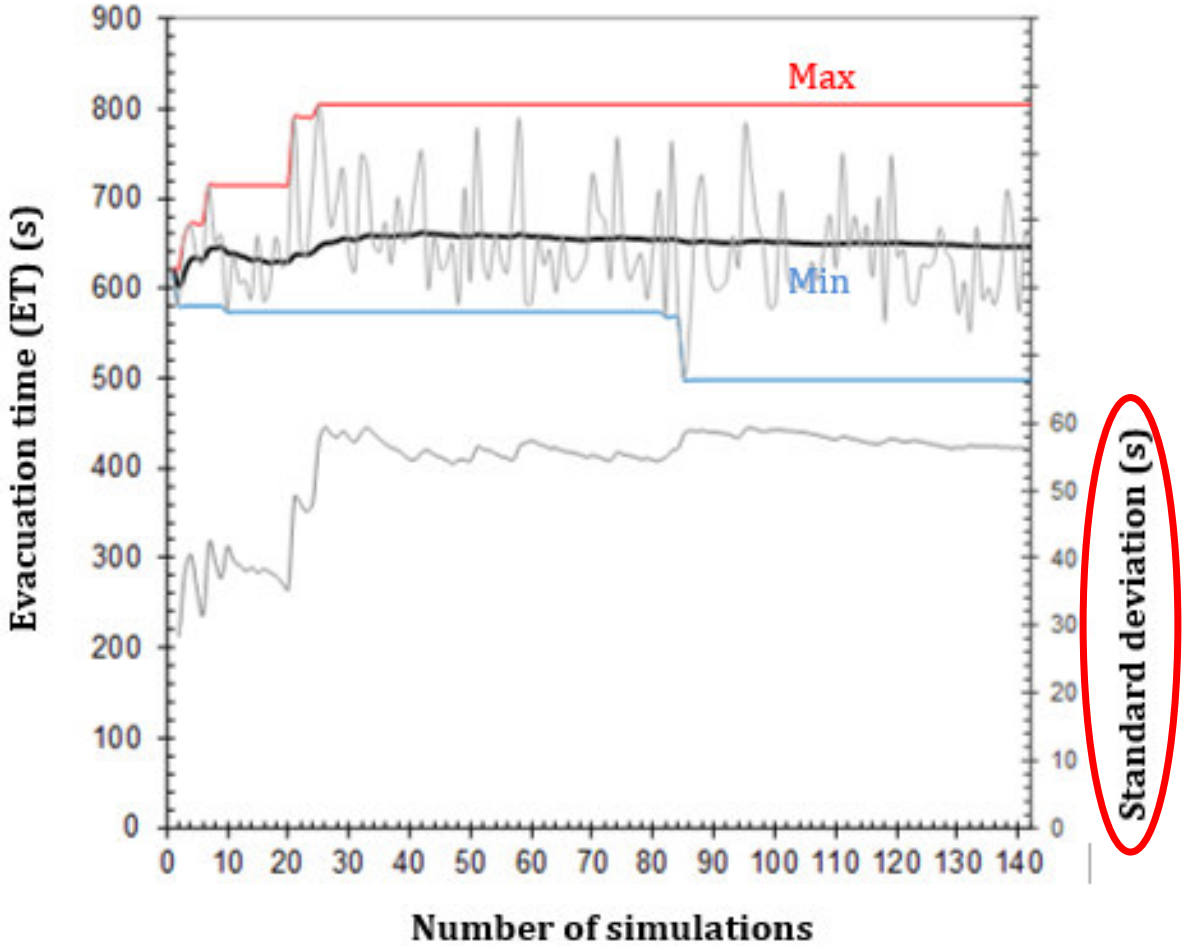


Figure 14: Evacuation time (ET) average ($\overline{et}$) and standard deviation (s_{et}) evolution

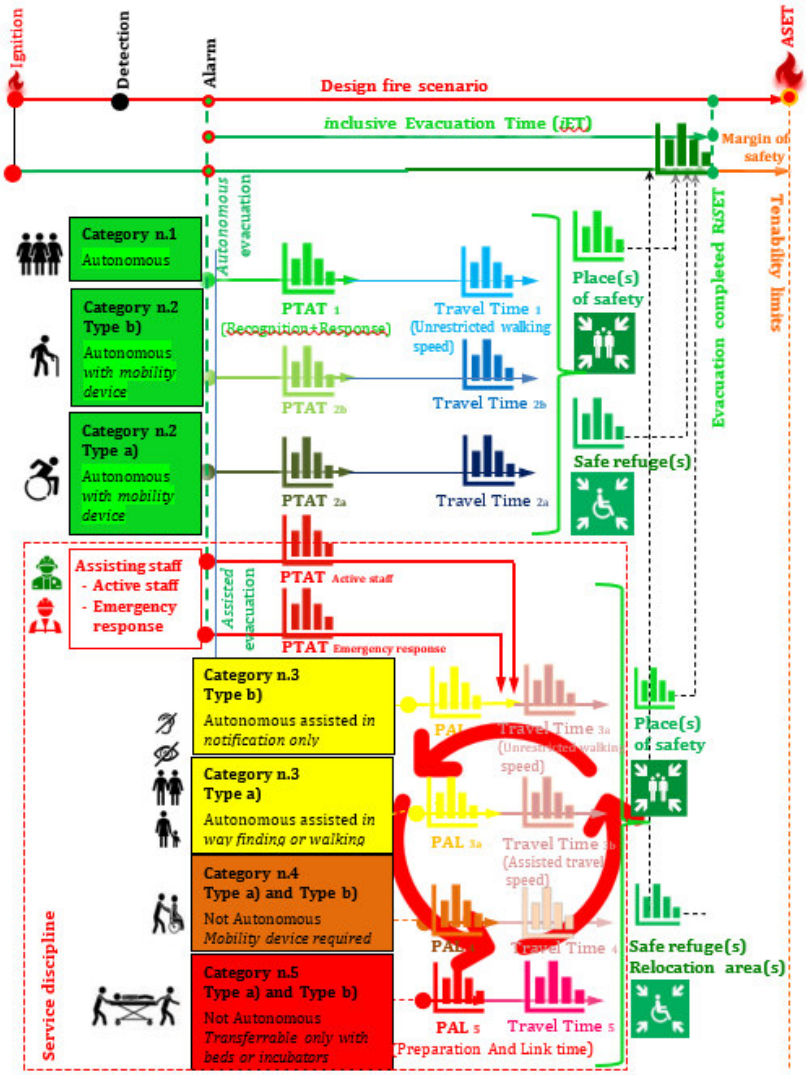
The number of Monte Carlo simulations required to obtain the desired precision

Table 13 Evacuation time (ET) convergence as a function of the Monte Carlo number of trials (design basis: $\Delta_{\mu_{ET\ design}}$=10 s, α = 0.05)

ET	n_1=10	n_2=40	n_3=70	n_4=100	n_5=130	n_{max}=142
$\overline{et}$ (s)	640	649	656	652	649	647
s_{et} (s)	42	55	55	59	57	56
$\Delta_{\mu_{ET}}$ (s)	29.9	20.8	13.0	11,6	9,7 ($< \Delta_{\mu_{ET\ design}}$)	9.2
$n_{\mu_{ET}}$	89	114	117	137	125	123
Normal distribution					No	

5

Inclusive approach. The R*i*SET timeline



5 Conclusion

- There is a need to include assisted evacuation, not only when dealing with health care occupancies, extending the RSET concept to the R*i*SET approach.
- Assisted evacuation simulation can be a valuable tool helping to identify in advance critical issues relating to the adequacy of the staff and of the procedures adopted in emergency planning.
- The model should be calibrated with site specific data.

Thank you

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