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Implementing notification strategies in the urbanEXODUS large-scale evacuation model

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A R T I C L E I N F O

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A B S T R A C T

A key consideration during a large-scale incident that affects a community, is how and when to notify the population regarding what protective actions to take. The effectiveness of a notification method is dependent on many factors, such as the medium used, message content, repetition frequency and target area. Therefore, choosing the optimal warning system, or a combination of them, necessitates careful consideration of these factors. Typically, evacuation models do not represent or consider the notification procedures explicitly and hence cannot determine how the specifics of a given notification method, or a combination of them, may affect the evacuation process. Large-scale evacuation tools incorporate the authorities' notification procedures implicitly by incorporating their effect by increasing the duration of the agents' response phase. In this work a framework is outlined that allows for the specification of notification methods to be defined within an evacuation model, considering parameters such as the notifications' initial success rate, their subsequent success rates, in conjunction with time dependent notification areas and a percentage coverage. Using these parameters, a method is outlined that is flexible enough to cover a wide range of notification techniques, from mass notification systems such as location-based SMS and auto diallers, to area specific personnel-based systems, such as door-knocking or mobile loud hailer systems. The proposed notification model is incorporated into the urbanEXODUS large-scale simulation tool and demonstrated through a practical application during an actual tabletop exercise. The study found that incorporating notification procedures in an evacuation model has the potential to aid emergency managers in assessing the outcomes of different notification strategies. The innovation relates to a methodology that enables subject matter experts, such as emergency practitioners, to define notification response profiles within evacuation models. Furthermore, a novel approach for visually summarizing and presenting the simulation results related to the notification scenario and evacuation outcomes has been developed to facilitate communication to a wider audience.

1. Introduction

Urban-scale evacuations in response to major incidents are often partially spontaneous, but they are not normally conducted in isolation from the emergency services (Chen et al., 2012; NFPA, 2020). Once an incident has been brought to the attention of the emergency services, they will employ a variety of emergency procedures and strategies to identify and control the situation and to reduce risk to life, property, and the environment (usually in this order of priority) (Chen et al., 2012; Marsella et al., 2019; NFPA, 2020). To achieve this, they will draw on established practice and any pre-planned procedures that have been drawn up in advance of the event. Therefore, public authorities, civil protection organisations, and emergency services are key actors during any emergency. They drive the emergency service's response phase, have the means to influence and guide how people respond, and are responsible for deciding on what procedures should be followed and whether a partial or full evacuation should take place (Chen et al., 2012; Mileti and Sorensen, 1990; NFPA, 2020).

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Urban-scale evacuation simulation tools have been developed to assist emergency planners (Bayram, 2016; Veeraswamy et al., 2015; Ronchi et al., 2017; Ronchi et al., 2019) and have been extensively reviewed by other researchers (Intini et al., 2019; Ronchi et al., 2023; Senanayake et al., 2024). However, none of these models can consider the notification actions of the emergency services when making decisions to protect the population (e.g., whether to order a mass evacuation or to recommend sheltering in place), and in overseeing and managing the evacuation process. For example, existing models do not represent actions such as the door–to–door warnings, the use of loudspeakers, or automatic messages or phone calls over progressively varied regions, together with the impact on the simulated agents. This limits the effectiveness of these models in accounting for how different emergency notification strategies may impact outcomes such as the time taken for the simulated agents to start evacuating, to reach a place of safety or the exposure of the population to a given hazard.

Some models incorporate notification actions together with diffusion profiles (Needham et al., 2016; Zhang et al., 2024). These notifications serve as triggers, initiating evacuations in specific regions at predetermined times. This approach allows for controlling when and which groups of people should begin to evacuate. However, these models restrict the notifications to simple regions, defined by a single event time or, at best, a diffusion curve derived from detailed data analysis that indicate both when an agent is notified and responds initiating their evacuation process.

Other models also utilize a single trigger time employ a decision model to determine individual evacuation behaviour. However, these models typically define the notification method as a region with a single event time (Harris et al., 2022). This limitation precludes the consideration of scenarios where the actions of authorities could influence notification effectiveness within an area, such as the introduction of additional notification methods or the deployment of personnel. Furthermore, these models fail to account for notification strategies where notification prioritisation is crucial, such as situations demanding that individuals closer to the incident be notified first, followed by a gradual expansion of the notification zone as the situation evolves (Bayram, 2016).

This paper examines a set of notification procedures as identified by the Italian Department of Fire Corps, Public Rescue and Civil Defence (Dipartimento dei Vigili del Fuoco, del Soccorso Pubblico e della Difesa Civile) (Marsella et al., 2019; CNVVF, 2011; Decreto Legislativo, 2006). Using these notification procedures as a basis, a method of encoding these procedures for use by an evacuation model, namely urbanEXODUS (Veeraswamy et al., 2015; Filippidis et al., 2023; Filippidis et al., 2024), is outlined. An evaluation framework is provided that includes qualitative and quantitative simulation results and evaluation criteria, based on factors such as population evacuation time, travel distance and exposure to hazards. This framework aims to provide a tool for evaluating different notification actions, taking into account all the aforementioned factors, in order to evaluate the effectiveness of a given protection strategy. Therefore, explicitly modelling the notification procedure, including the initiation time, the evolving coverage area, and the notification rate, effectively represents the implicit actions of the emergency crew or notification device.

A use case is presented that formed part of a tabletop exercise (TTX) for the EU Horizon 2020 project IN-PREP (Marsella et al., 2019; IN-PREP, 2021). In this exercise, an evacuation model was used to forecast the likely evacuation performance of an area of Spoleto, Italy, due to a chlorine (Cl) spill. As a preparation for the TTX a total of 32 different scenarios were evaluated, where a door knocking, and autodialled strategy were used to notify the population. During the TTX, one scenario was selected and executed. The selected scenario is further examined in this work to provide a detailed analysis that goes beyond the summary evacuation results that were presented during the TTX as well as to provide an indication of model variability. This is followed by an investigation into the impact that the notification methods employed during the TTX had on the evacuation scenario and whether an alternative strategy could have produced a better outcome offering greater levels of safety to the affected population.

This paper outlines a method that allows the notification procedures to be represented explicitly within the evacuation model rather than implicitly by using a pre-evacuation time model (Lovreglio et al., 2019; Bernardini et al., 2019) that incorporates the notification times of the simulated agents as part of their overall response time. The outlined strategy is flexible enough to cover a wide range of notification techniques. These range from mass notification systems such as SMS and auto diallers to area specific personnel-based systems, such as door-knocking or mobile loud hailer systems. The proposed framework contributes to several stakeholders (AL-Fazari and Kasimm, 2019), including emergency managers, decision makers, and model developers, by providing a method for defining notification specifications that can be integrated into large-scale evacuation simulation software. Emergency managers and decision makers can use the simulation results to inform their planning and resource allocation strategies, while model developers can incorporate this framework into their models to enhance their capabilities. Also, as the ultimate benefactor of the proposed system is the public and the community. They benefit from a detailed representation of the strategies and processes involved during large-scale evacuations as this improves preparedness and planning that can result in enhancing the confidence and trust of the public in the actions of the authorities. The results generated, can be visually summarised, condensing a high volume of complex information in graphical form regarding a proposed notification response to a possible hazard threat. This condensed information could be utilised by crisis management authorities to evaluate a given response or to formulate educational material for the wider public.

The study presented in this paper addresses gaps in the literature related to simulating notification procedures in evacuation models by focusing on how to represent the notification time as a separate time distribution together with time-dependent variables. The variables considered are related to notification rates, notification sequence and operational area. The proposed solution provides a practical way in which a subject matter expert can provide estimates in situations when formal data may or may not available. Furthermore, in collaboration with emergency practitioners, a novel evacuation process graph and key summary information have been developed. These facilitate the understanding that the impact of various notification methods have on an evacuating population and provide a summary of key data for comparing and communicating simulation results.

A key consideration associated with human vulnerability at an urban scale is the assessment of the population's possible reactions and behaviours in case of an emergency evacuation (Haghani et al., 2022). These will inevitably be impacted by the notification techniques employed by the emergency services. It is therefore important to understand the emergency response processes, including the methods of early warning and notification of the public of an incident. For example, if we exclude direct experience of the hazard, people may become aware of incidents through a number of cues (Mileti and Sorensen, 1990; Ryan, 2018). These cues may include emergency warning systems, alarms, warning and diversion signs deployed near the incident area, coverage from mass and social media, the use of loud hailers and public address systems, communication between members of the public and emergency responders, witnessing the incident or observing people's reactions to the incident.

Emergency managers can issue warnings to the public in various forms, such as loudspeakers, public address systems, telephone (mobile or landline), radio, or television, as well as more direct methods where groups of people deliver individual warnings, such as emergency staff knocking on doors. When considering the available warning methods, the emergency services will need to decide not just on the message to convey, but also the communication approach and where appropriate the frequency with which the warning will be given (Mileti and

Sorensen, 1990; Sorensen, 2000). Furthermore, the various communication strategies may have different success rates and may be used to target different areas or regions. Hence a combination of warning strategies will often need to be utilised to ensure an efficient notification procedure for the population at risk. In addition, due to the hazard evolution and the availability of emergency personnel, which could vary over time, the area over which the notifications operate is likely to change during the incident. In turn, the notification strategy may also need to be adapted to the new hazard conditions or availability of emergency personnel.

The primary objective of a successful notification system is to maximise the number of people who will receive and respond to authorities' messages. The effectiveness of such a notification system is not solely determined by the chosen method, but also by factors like message content, repetition frequency and target area. Therefore, choosing the optimal warning system necessitates careful consideration of these factors. The success rate of a notification method depends on how many people or households can be contacted within a given time period, how many will comprehend the message, and how many will subsequently respond (Sorensen, 2000). The combined effect of these factors determines the number of people initiating their evacuation phase or take alternative protective actions. Furthermore, the repetition of the warning message is expected to have different success rates to that of the initial warning. Additionally, the area over which the notification is active, should be taken into consideration, as well as how it may evolve as a result of the hazard evolution and the actions of emergency personnel. Consequently, these factors are a key consideration for deciding on what notification methods to employ, along with how different combinations of notification methods may operate in unison.

Since computer modelling is a valuable tool for evaluating emergency procedures and their impact on evacuation processes (Bayram, 2016; Veeraswamy et al., 2015; Ronchi et al., 2017; Ronchi et al., 2019), it stands to reason that factors related to the notification methods should also be considered within the evacuation model. Furthermore, utilising a computer model will allow emergency planners to evaluate the effectiveness of selected notifications methods in conjunction with other factors such as population response times, travel times and hazard characteristics. It should be noted that where computer models have been employed previously their focus has been to represent the population's pre-evacuation times, movement rates and evacuation behaviours, the routes taken, travel times, and in some cases the impact of the hazards. More recently coupled vehicle and pedestrian models have started to be utilised (Ryan, 2018).

Several modelling tools and approaches exist to perform analysis of urban scale emergency evacuation, such as WUI-NTY (Ronchi et al., 2019; Wahlqvist et al., 2021; Ronchi et al., 2017), ASERI (Könnecke and Schneider, 2011), Pedestrian Evacuation Analyst (Jones et al., 2002), and MATSIM (Lämmel et al., 2010). The majority of these large-scale evacuation models (Ronchi, 2020; Ronchi and Nilsson, 2016) represent the main phases of the evacuation process, namely the time elapsed before the agents purposively move towards a safe place, called pre-movement or response time, and the agents' movement phases (Purser and Bensilum, 2001). The pre-movement time of people responding and starting to evacuate is often achieved using sampling from a predefined time distribution to account for behavioural uncertainties (Jullien et al., 2020; Ronchi et al., 2014; Smedberg et al., 2021). For example, the cumulative evacuation response curves are assumed to follow several distributions, typically of the form of a sigmoid curve or S-curve (Bayram, 2016). Researchers studying urban scale evacuations have also observed that the response distribution will typically have a long tail and found that their data could be best approximated by an exponential family of Cumulative Distribution Function (CDF) distributions, such as a Rayleigh distribution (Hobeika and Kim, 1998; Solís and Gazmuri, 2017; Takabatake et al., 2017; Mas et al., 2012).

Other approaches have adopted an evacuation decision-based model (Kuligowski, 2020; Kuligowski et al., 2022; Lovreglio et al., 2015, 2016) to represent pre-movement evacuation behaviour and their associated durations. However, such techniques require comprehensive and detailed behavioural datasets which are often scarce or difficult to obtain (Kuligowski, 2020). Despite the advancements in large scale evacuation simulation models, they do not take into account how the notification method can evolve or alter as a result of the actions or procedures put in place by the authorities (Wahlqvist et al., 2021).

A method for the integration of various notification methods within an agent-based computer model, namely urbanEXODUS (Veeraswamy et al., 2015; Filippidis et al., 2023; Filippidis et al., 2024), is outlined next. The input parameters for the notification methods will utilise factors that are familiar to emergency personnel and crisis managers. This innovation goes beyond what has been performed in previous studies and offers a detailed representation of notification strategies in large-scale evacuation modelling. This enables simulation tools to model the effects of the notification methods employed and generate summary data about their effectiveness. In addition, the work sheds light on the importance of considering notification procedures in evacuation modelling and how to summarise evacuation modelling results in a format which can be communicated to a wider audience.

2. Method

Typically, the response time (or pre-evacuation time) profile for a population defined within existing evacuation models incorporates both the notification time to the affected community (e.g., from the authorities) and the time that each individual eventually responds to the call to evacuate from the affected area. This response time signifies the start of their purposeful movement towards a safe location or a location outside the impacted area. In these models, the notification time is therefore only implicitly represented as it is part of the population's overall response time profile (see Fig. 1a) (Kinateder et al., 2015; Wahlqvist et al., 2021; Galea et al., 2013) However, the proposed notification model presented here, separates the time to receive the notification from the population response time profile. Thus, the time that a person is notified is explicitly represented (see Fig. 1b).

The implemented methodology utilises a technique that enables the modelling of the characteristics of a given notification method and thereby its impact on how people respond. This is based on the assumption that the notification methods follow a cumulative distribution function (CDF) for an S-shape curve, such as an exponential or Weibull distribution (Needham et al., 2016; Hou et al., 2024; Hou et al., 2020). This approach was selected since previous research (Mileti and Sorensen, 1990; Needham et al., 2016) has demonstrated that the cumulative proportion of people receiving warning information can be expressed as an S-curve. Furthermore, it was found (Hou et al., 2020) that a Weibull, distribution was suitable for representing the cumulative proportion of the number of people receiving warning information.

The proposed notification model as illustrated in Fig. 1b divides the response phase into two parts: a pre-notification time and a response time which is applied after the person has been notified to evacuate. During the response phase, a person may perform actions such as comprehending the information, collecting personal belongings, or gathering people in the household and forming groups prior to engaging in evacuation. Therefore, from now on, in this paper, the time between the start of the simulation and a person responding will be referred to as pre-evacuation time and the time between being notified and starting to evacuate as their response time.

The design of the notification specification focuses on how to model the communication aspects of the emergency plan related to alerting the citizens of the existence of the risk or hazard. These strategies are related to two key factors, namely (1) the physical area where the notification is communicated, and (2) data parameters, such as the expected/estimated success rate and percentage of people notified in a specified time interval. Furthermore, a key consideration was to choose a flexible specification format that allowed a subject-matter expert to specify the

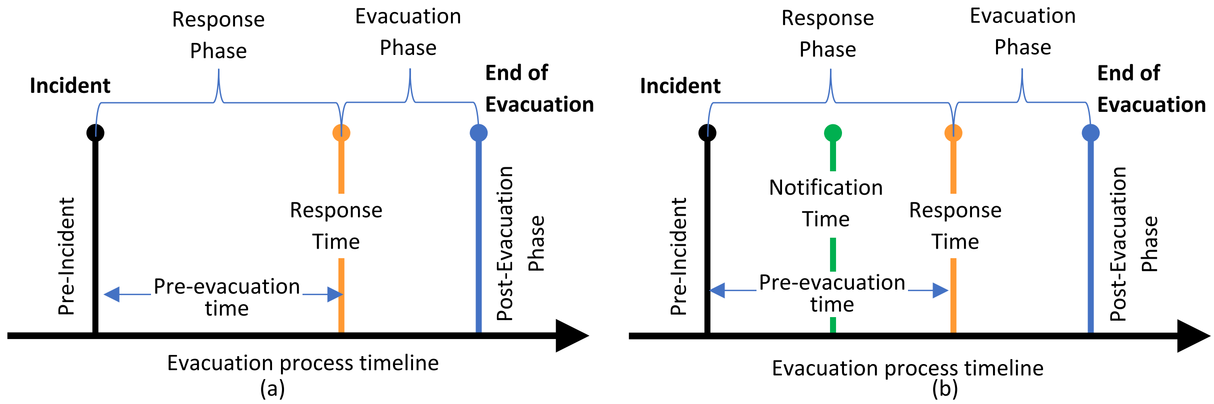


Fig. 1. (a) Typical evacuation timeline employed by evacuation models where the evacuation timeline is split in two broad phases, the response and the evacuation phases (b) proposed modified evacuation timeline that explicitly represents the *Notification Stage* as a subcomponent of the *Response Phase*.

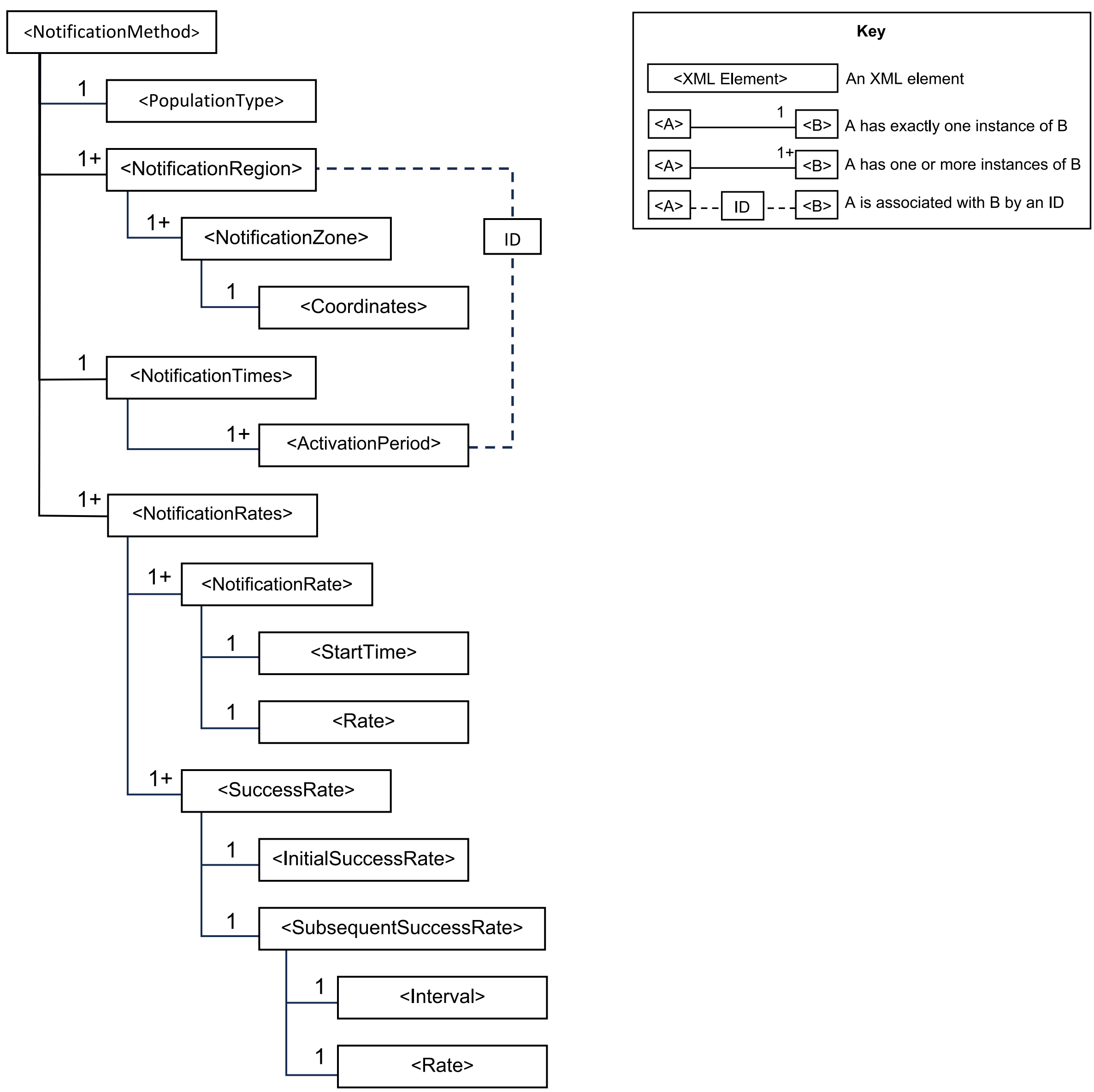


Fig. 2. XML Structure of Notification Specification.

notification method characteristics using their expert judgement and integrate those within the evacuation model.

In Fig. 2 the hierarchical structure of the XML notification specification format is shown, which is initially split into regions and notification rates. Key parameters of the notification method specification are outlined in Tables 1 to 8.

The *Notification Method* is the top level of the hierarchical structure (see Fig. 2). It includes basic information about the method of notification (see Table 1), such as its unique *ID* and *name*, for example, *Loudspeaker*. Additionally, the *Population Type* enables the people receiving the message to be defined. This can be specified as all people within the specified notification region, or it can be narrowed down to only those within streets or buildings (residential) within the region. Furthermore, the order in which the people are notified within the notification area can be specified as either random or distance based. In the distance-based approach, the notification method is disseminated first to those closest the centre of the currently active notification region, progressively notifying locations further from the centre over time.

The next level of the notification method structure includes both the *Notification Regions* and *Notification Rates*. Each *Notification Method* can potentially be time dependent, with the area within which agents are notified potentially changing over time. Hence, each *Notification Method* consists of a number of areas called *Notification Regions (see* Table 2*)*. Each *Notification Region* can have one or more geographical polygon zones, called *Notification Zones*, where each polygon is simply defined by a list of corresponding coordinates (see Table 3).

Each *Notification Region* will have associated activation times, consisting of several *Activation Periods* (see Table 4), representing the evolution of the area being notified. For example, the notification area may change as the hazard evolves or as more personnel arrive to manage the situation. Each *Activation Period* directly references the *Notification Region* to which it applies via the region's corresponding unique ID, shown as a dashed line in Fig. 2. The link between *Activation Periods and Notification Region* is represented by the dotted line in Fig. 2. If a *Notification Region* has no associated *Activation Periods* defined it is assumed inactive throughout the simulation.

Each *Notification Method* is also associated with the *Notification Rates* (see Table 5), which are specified in two ways. Firstly, the initial rate, which specifies an initial success rate and secondly, the subsequent success rates. These two rates allow for the case when the initial impact of a notification system may differ from subsequent activations. For example, in the case of a public announcement system, the initial message may be expected to have a greater impact than any repeated message that follows.

The Notification Method parameters that specify the time interval between notifications (i.e., how often the notification is sent) and a percentage coverage and/or notification order (see Table 7 and Table 8). Then any further additional rates can be specified, which simply consist of a start time, relative to the start of the simulation and a new success rate, (see Table 6). These additional rate specifications allow for more complex notification patterns to be defined, for example, the addition/reduction of resources to perform a given notification method, such as by the arrival or departure of emergency personnel.

It is important to note that the *Notification Rates* are not directly associated with a given *Notification Region*. Hence, when the *Notification Rates* are applied within a given simulation, they are assumed to relate to the currently active *Notification Region*. The notification rates and regions are associated by being defined within the same *Notification Method parent tag*. Both notification rates and regions have their own active time ranges. Thus, the model applies the current active rate to the current active region(s). This means the area over which a notification method is active is independent of the notification rate. For example, while a notification area may remain static, the notification rates may change as more emergency personnel arrive on the scene. Conversely, a

Table 1
Notification method.

Parameter	Description
Method ID	A unique identification number associated with the *Notification Method*.
Name	Name Associated with the Method e.g., *Dialler, Ring the Intercom*.
Order	The order in which locations will be notified, can be *random* or *distance* based (nearest first).
Population type	Location of people that will be notified, i.e., in the street, inside buildings (residential) or all locations.

Table 2
Notification region data.

Parameter	Description
Region ID	A unique identification number associated with the *Notification Region*.
Name	A user-defined name identifying this region.

Table 3
Notification zone data.

Parameter	Description
Zone ID	A unique identification number that is associated with the *Notification Zone*.
Units	The coordinate format used to define the region, for example, metres or latitude/longitude.
List of coordinates	List of locations identifying the active region. *Note there can be several lists of coordinates defining multiple zones with can be active simultaneously*.

Table 4
Activation period data.

Parameter	Description
Region ID	The ID of the *Notification Region* these times apply too.
Unit	Time unit utilised, e.g., seconds, minutes
Start time	The activation time of the region, relative to the start of the simulation.
End time	The time at which this region is no longer active. *If set to -1 then once activated, it remains active for the duration of the simulation.*

Table 5
Notification rates specification.

Parameter	Description
Rate ID	A unique identification number associated with the notification rate.
Name	A user-defined name or other attribute identifying this notification rate.

Table 6
Success rate basic parameters.

Parameter	Description
Start Time (Optional)	Start time when this rate is active relative to the start time of the notification method. Used to specify when this particular rate is used after the notification method is activated. *If not specified assumed to start when the notification method is activated. Used when multiple notification rates are used which vary over time.*
Coverage (optional)	Percentage of the population that will receive the notification each time it is activated. *Used in conjunction with the Start Time parameter to specify a rate change from the initial rate specification. If not specified coverage is 100%*

Table 7
Initial success rate parameters (specified for the initial notification rate).

Parameter	Description
Units	Either a rate or percentage, i.e., residency/minute or percentage
Initial success rate (optional)	Rate or percentage of the population that receives the notification at which notification method is first activated. *If not specified it assumes 100% of people notified will respond.*

Table 8
Subsequent rate parameters (specified for the initial notification rate).

Parameter	Description
Subsequent interval (Optional)	Indicates how often the notification method is repeated. *If not specified, notification is only fired once at the specified start time.*
Subsequent rate (optional)	When the notification is repeated this value defines the proportion of locations that are subsequently notified once the first notification is sent. *If not specified uses the Initial success rate parameter* (see Table 7).

notification region may remain static while the notification rates change as additional notification methods are employed.

To examine how this notification specification can be used in practise, three types of notification methods will be considered (1) *Emergency Personnel-Based Notification* – where the first responders and emergency personnel visit a number of locations contacting residents and issue evacuation instructions, (2) *Area Notification System* – such as a telephone automatic diallers or SMS messaging system, and (3) *Spontaneous* – to account for people responding on their own, for example after witnessing the incident or observing others evacuating (Lindell et al., 2011).

2.1. Emergency personnel-based notification

During an incident, the first people to reach the scene, other than the civilians experiencing and reporting the incident to the authorities, are normally the first responders (e.g., the fire service, police, paramedics). The emergency personnel establish an emergency cordon, which is used to keep people and vehicles away from the incident. Their duties also include communicating with their control centres to report the situation, possibly escalate the response and request additional resources, if required. Furthermore, their duties also include warning the population of any hazard and instructing the population to take appropriate protective measures (Chilcott, 2014). As a result, the process of notifying people in the surrounding buildings does not start immediately. The most basic method of notifying the population in the immediate vicinity of the incident is by going door to door, for example, knocking on doors, ringing the bells or intercom.

Processes based on a door-to-door notification method may involve officers being assigned buildings to notify in the form of a *priority list.* The sequence of alerting residents would depend on the nature of the hazard and could thus prioritise those nearest, those downhill (e.g., in the case of a heavy gas release), those uphill (e.g., in the case of a WUI fire), those in the direction of the wind, or those in the line of sight (e.g., in case of an imminent explosion) (Marsella et al., 2019; Decreto Legislativo, 2006). Here a *Ring the Intercom* notification method is represented using an initial and subsequent notification rate, see tables 7 and 8. In circumstances when further officers join the scene, they may assist in the alerting of people. To accommodate this factor the notification rate can vary over time, using the rate and starting time, as specified in Table 6. It should be noted that the current system can represent a random notification pattern, or one based on notifying people from the centre of the region outwards.

Another common notification method is the use of loudspeaker systems (Mileti and Sorensen, 1990). These systems could include existing public address systems as well as portable systems as used from a vehicle to warn the nearby population. The repetitive nature of these kinds of message systems fits well with the proposed *initial success* and *subsequent success* rate method as outlined earlier. Similar to a phone or SMS based notification method, outlined next, the loudspeaker or PA system would have a similar but smaller corresponding notification area.

2.2. Voice and text message area notification systems

The area notification system such as the telephone automatic diallers and SMS messaging systems have the potential to reach a considerable number of people in a relatively short time frame (Mileti and Sorensen, 1990). In most cases, current technology could allow simultaneous call messaging to the local landlines or mobiles using the local phone or cell network. Sometimes the operators may limit message delivery to avoid system overload. Advanced systems can automatically hang up phones that are currently in use or block out all incoming calls (Mileti and Sorensen, 1990). These systems can deliver a massive number of warning messages to pre-defined zones using either voice or text messages.

A voice-based system has a defined rate at which it can call people and a maximum number of people it can call within a specific time period. For this type of system, the message is assumed to be acknowledged once the call is answered, even though it is impossible to verify whether the recipient understood and would act on the information received. Once the voice system has attempted to call all numbers in the target area, it repeats the process for those numbers that did not answer. When modelling a voice-based message system, an initial success rate is assumed, and a subsequent success rate is defined.

For a text-based messaging system, an initial message burst would be sent out. This initial burst of messages would be expected to have the most impact, with the majority of people receiving it, and once their response time elapses, acting on it. This process of receiving the warning message and responding to it is represented by an initial success rate. The effect of the text-based messaging system is expected to diminish as the number of people acting on any subsequent message or responding to the initial message is expected to be lower. This would be represented by a subsequent success rate that is lower than the initial success rate.

The area over which the message is broadcast is defined by a geographical polygon region. The messaging system may have a number of regions defined, as the area being contacted could change over the course of the emergency as the hazards evolve, or the environmental conditions change. The system would have an initial success rate and a time interval based on how quickly the system can contact phones and mobile devices within the area. The maximum number of calls and messages sent could be represented by a specified rate which could be a percentage of people in the area or a household rate per a given time interval. The selection of locations may be based on a random choice.

2.3. Spontaneous (or autonomous) evacuation

An additional notification method can be included to account for people who evacuate without, or prior to, being notified by the authorities. This method is used to represent all those who decide to evacuate without receiving a formal notification instruction to evacuate, e.g., after having witnessed the incident or after observing others evacuating. For modelling purposes, a spontaneous evacuation profile can be defined with a start time equivalent to that of the time of the incident (i.e., at time zero) that covers the entire population.

This spontaneous evacuation behaviour can be modelled in an analogous way to the formal notification procedure mentioned previously. The spontaneous response initial success rate, which is hazard dependent, would be specified representing the initial impact of the situation on the population. For example, an explosion may have more of an initial response compared to a slow evolving incident involving a hazardous gas release. The subsequent success rate would then represent how people may react on observing other responding to the event or being informed by other members of the public about the situation. The area over which the spontaneous notification specification would cover, would be dependent on the type and extent of emergency conditions. An example of this will be covered in the Case Study and TTX section outlined later in the paper.

It should be noted that many external factors influence evacuation decisions, such as social or economic, which may affect an individual's decision to act or not. For example, a person may choose to stay and defend their property, distrust the information provided by the authorities, choose to evacuate using their own means or take public transport (Labhiri et al., 2024; Zhang et al., 2024; Katzilieris and Wang, 2022). Modelling this kind of behaviour in detail requires the collection or inclusion of comprehensive behavioural data, such as (Vaiciulyte et al., 2021, 2022; Hulse et al., 2020; Gallego et al., 2019). Therefore, if such information is available and is transferable to the area being modelled, it could be utilised to inform parameter settings, as described in this section.

2.4. Integration into an urban scale simulation tool

The proposed notification modelling methodology is incorporated into urbanEXODUS. urbanEXODUS is a rule-based evacuation model utilising the EXODUS Agent Based Model (ABM). Within the model each agent has its own distinct physical, psychological, and experiential characteristics, with some being fixed and other being dynamic. The software takes into consideration people-people, people-hazard(s), and people-outdoor environment interactions. The behaviour and movement of each agent is determined using a set of rules. These rules are grouped into distinct sub-models, namely the *Agent*, *Movement*, *Behaviour*, *Hazard*, and *Toxicity* sub-models. The model is stochastic in nature due to the randomisation of the population's demographic characteristics, starting locations, as well as the decisions that those individuals may make during the simulation and their interaction with others, such as in congested areas (Galea et al., 2017).

urbanEXODUS can concurrently utilise all the spatial representations developed in EXODUS, i.e., continuous, fine-node and coarse (Chooramun et al., 2018) representations of the space that the agents and vehicles can use and navigate. This spatial data is typically imported from OpenStreetMap (Lawrence et al., 2016). The road and foot-path network are meshed using a fine grid of nodes. The structures included within the area are represented as coarse regions with only the occupancy and flow out of the structure being modelled. If hazard data (e.g., fire data) has been included in the model then the software determines the physiological response to the hazard based on each agent's attributes. This ability to represent hazards, such as wildfires or other toxic agents allows urbanEXODUS to measure the impact of that hazard on the simulated population. This allows different scenarios to be evaluated not just based on travel times, congestion, or distance travelled, but also on how many agents are exposed to danger. Users can then rate the results based on an estimate of the predicted number of injured or fatally injured individuals including the number of people that may need further treatment by the emergency services post evacuation, such as hospitalisation (Filippidis et al., 2023; Filippidis et al., 2024).

Furthermore, urbanEXODUS can simulate both linear scenarios (where all the input parameters are known and are specified prior to the simulation) and non-linear scenarios (where scenario parameters can also be specified during run-time). The simulated scenario can thus be dynamic and can be modified during runtime (e.g., assigning new itineraries to a group of agents, closing of exits, blocking of exit routes or regions to accommodate for decisions made by the user (i.e., crisis managers) or as a response to information related to the incident (e.g., building collapse, the presence of a hazard at a particular location, etc.). This makes urbanEXODUS suited to applications for evaluating emergency procedures, such as during a tabletop exercise (TTX) (Filippidis et al., 2024).

The urbanEXODUS model is based on the EXODUS (Galea and Perez Galparsoro, 1993) evacuation model which has undergone and continues to undergo continuous validation and behavioural enhancements based on extensive data/behavioural studies since 1993. This has involved direct comparison of model predictions with historic experimental data, comparisons of "blind" model predictions with experimental data and comparing the nature of predicted human behaviour with expectations. The urbanEXODUS behavioural model has been developed based on a number of behavioural studies, related to large scale evacuations (Vaiciulyte et al., 2021, 2022; Hulse et al., 2020; Gallego et al., 2019).

An overview of the key input and output data files for urbanEXODUS is depicted in Fig. 3. These include the *Area Information* map data file obtained from OpenStreetMaps (OSM), the *Population Distribution and Characteristics* file, the *Hazard Information* file and, and the *EXODUS Model Data* that defines the pedestrian space. The *Notification Data* specification file adds one additional input file to the existing set of input files, and it fulfils the needs of the notification model presented in this work.

The urbanEXODUS model outputs both qualitative (e.g., evacuation paths, congestion contours) and quantitative data (e.g., numerical data that represent the evacuation performance, evacuation times, exit route usage). Numerical data representing all aspects of the evacuation performance is produced in three different formats. The first, a human readable text-based data file, which can also be processed further for statistical analysis. Secondly, an XML data file containing details about urban scale time dependant pedestrian data, that can be utilised by third party applications to visualize evacuation related information, for example, in a Command-and-Control platform as demonstrated during the EU IN-PREP project (IN-PREP, 2021). If more specific data is required, the user can select to generate specific simulation time dependent data in a comma-separated values file for further analysis. For example, this data may include the time that each location was notified and by which method, the time that the agents at those locations responded and the time that those agents that responded reached safety or evacuated from the area.

The notification functionality presented in this work is directly integrated into the urbanEXODUS model, which loads a notification specification (in XML format) that specifies the various notification techniques. This information is used during the simulation runs as an *instruction set* that specifies when to notify the agents to evacuate, thus triggering their response phase (see Fig. 2). At each time step urbanEXODUS identifies which notification methods are currently active and the areas over which they are active. For each active notification method, urbanEXODUS determines whether the notification method should be applied at the given time step based on its defined notification rate. If the notification method should be applied, it then identifies all the non-responding agents or households within the specified area. From this set of non-responding agents, it selects a subset of agents, based on the specified notification rate. These are the agents that will be notified in the current time step. This is performed either on a random or distance-based criteria, as specified by the order parameter (see Table 1). Based on the success rate specified (see tables 7 and 8), a percentage of this subgroup is then identified as successfully notified. These successfully notified people are then assigned a response time, based on the response profile assigned at that location.

Typically, multiple notification methods can be applied at the same time over a region, and their combined effect on the resultant response of the population can be examined. However, the model is flexible enough to allow the user to examine and compare a single or arbitrary number of notification strategies with each other. It should be noted that the model functionality was verified during development and reported during the IDIRA and IN-PREP projects (Veeraswamy et al., 2015; IN-PREP, 2021).

2.5. Hazard model

Large-scale hazards, such as fire, smoke and other hazardous substances are represented in urbanEXODUS using ground-based polygons, or isochrones (Filippidis et al., 2023). The urbanEXODUS model can import hazard-model data from a variety of models including FARSITE (Finney, 2004), Sparks (Miller et al., 2015), PHOENIX (Tolhurst et al., 2008), Prometheus (Tymstra et al., 2010) and Wildfire Analyst (Monedero et al., 2019).

Each isochrone depicts a zone with uniform hazard concentration or

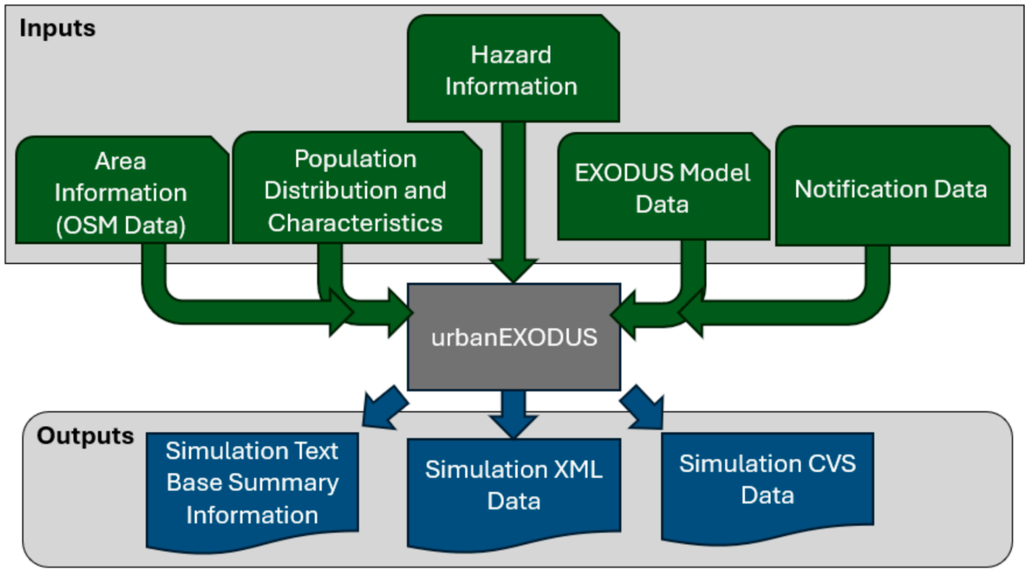


Fig. 3. System input and output data. The Notification Data is added as an additional input to the urbanEXODUS OSM, in conjuction with the Model and Population Data files.

intensity at roughly head height or at ground level. For example, a wildfire is represented by a series of time-dependent isochrones representing how the fire front propagates and therefore indicating the evolution of the burned area. In the case of smoke or other airborne hazards, similar isochrones depict varying concentration levels across the affected area, with each zone representing an average concentration (e.g., $PM_{2.5}$, NO_x, etc.) within its boundaries. Since the hazard will be evolving during the simulation, each hazard isochrone is associated with a time period, controlling when it is active and therefore possibly impacting the population it encompasses.

For hazards related to fire products (e.g., PM_{10}, $PM_{2.5}$) or chemical spills (e.g., Chlorine, LPG) the urbanEXODUS model can calculate the duration of exposure of the population at risk, for those hazards (Marsella et al., 2019; Filippidis et al., 2023). A level of exposure is then calculated for each agent, during a simulation, based on the individual's exposure time within the time-based hazard isochrones (i.e., concentrations). The *Acute Exposure Guideline Levels* (AEGL) method (US EPA, 2025) for a given hazard is then used to categorize the exposure time of each individual at each AEGL level.

For example, the AEGL levels used for chlorine in urbanEXODUS are set out in Table 9, which is defined by the U.S. Environmental Protection Agency (US EPA, 2025). It is worth noting that the same exposure level can be achieved by different combination of chlorine concentrations and exposure durations. This is shown in Table 9, where there are two chlorine concentrations and exposure durations for AEGL-2, AEGL-3 and LC_{LO}. For example, an exposure duration of up to 240 min to a chlorine concentration of 1.0E-6 kg/m^3 or an exposure duration of more than 240 min to a chlorine concentration of 1.0E-7 kg/m^3 leads to the same end point, i.e., an exposure level of AEGL-2. Note an exposure of 1.0E-6 kg/m^3 for more than 240 min, would result in an AEGL-3 exposure level.

The data generated by urbanEXODUS regarding the agents' AEGL during a given simulation; is the number of agents exposed at each AEGL exposure level, and the time spent by each particular agent at each AEGL exposure level. The agents' movement rates or behaviour is currently not altered during exposures ranging from AEGL 1 to 3. However, if during a simulation, an agent is exposed to an LC_{lo} exposure level they are then removed from the simulation, as this level of exposure is considered to be potentially fatal. Information on AEGL levels can be used as an estimate of how many people may need follow-up care, such as requiring further observation or possibly hospitalisation.

Some hazard modelling tools may consider weather conditions (Oliveira et al., 2021) (i.e., wind, extreme temperatures, or heavy rain) as part of their hazard propagation calculation. Hence, the propagation of a hazard (e.g., chemical spill, flood waters, wildfire) can be directly affected by the assumed weather conditions. However, the direct impact of weather conditions on an individual's behaviour is currently not modelled in urbanEXODUS.

Table 9
AGEL bands for chlorine.

Exposure level	Clorine concentration (kg/m^3)	Duration (minutes)	Injury level
AEGL-1	Above 1.0E-7	0 to 240	Non-disabling effects. Noticeable discomfort, irritation, effect transient and reversible upon cessation of exposure.
AEGL-2	Above 1.0E-7 Above 1.0E-6	> 240 0 to 240	Impaired ability to escape. Irreversible and long-lasting adverse health effects.
AEGL-3	Above 1.0E-6 Above 1.0E-5	> 240 0 to 240	Life-threatening health effects or death.
LC_{LO}	Above 1.0E-5 Above 1.0E-4	> 240 > 0	Lethal Concentration$_{(LO)}$ (LC_{LO}) The lowest concentration to cause death in test animals

3. TTX case study

As part of the EU Horizon 2020 IN-PREP project (IN-PREP, 2021) a formal tabletop exercise (TTX) was conducted by the Italian National Fire Corps in collaboration with the Municipality of Spoleto, in Spoleto, Italy. The aim of the TTX was to provide first responders and emergency managers with a more efficient emergency planning platform while contributing to improving preparedness and response to complex disasters in sensitive environments. For this training exercise, a scenario involving a HazMat leakage in an urban environment was selected.

Since during the preparedness phase of an emergency crisis managers are meant to explore and prepare for a variety of different but plausible eventualities (Chang et al., 2008; CNVVF, 2011; GSCP, 2020), the TTX considered 32 scenarios in total. The 32 scenarios included a traffic accident involving an overturned truck, releasing either chlorine or LPG, with various release rates. Furthermore, three different weather patterns were considered affecting the spread of the leakage. These scenarios also differed in regard to both the time of year and time of day (i.e., day or night). Three specific days were considered, namely the 1st of November 2017, and the 11th and 19th of July 2018. The 1st of November 2017 was included as this was a winter public holiday. In contrast, the July dates represented two summer peak season days. The variation in the time of year and time of day affected the population distribution in the area and their response to the notifications. While 32 scenarios were defined and simulated in preparation for the TTX, only one scenario was executed during the day of the TTX. The TTX coordinator selected this case at random, and it is the case reported here.

3.1. Scenario overview

The proposed incident selected for the TTX was specified as a road accident involving a truck carrying chlorine (Cl) that leaks into the surrounding area for 80 min at which point the leak is assumed to be contained. The area is assumed to be safe for the population at 90 min at which point the TTX was terminated. The area of Spoleto represented in the TTX and therefore selected for modelling is shown in Fig. 4. This part of Spoleto covers an area of approximately 1.82 km^2, with an approximate length and width of 3.25 km and 1.37 km, respectively (see Fig. 4). The exit points from the area, the refuge locations and the incident location are shown in Fig. 5.

3.2. Population specification

The date selected for the simulated scenario was during the day, on the 19th of July 2018. Based on data from 2009 collected by the Municipality of Spoleto (Marsella et al., 2019) the resident population of the modelled area on the selected day was estimated to be around 6876 people. Similarly, the number of people working in the area was estimated at 1108, i.e., approximately an additional 16 % of the overall population. The estimated possible visitor numbers were based on the hotel capacity within the region and were estimated at a further 1182

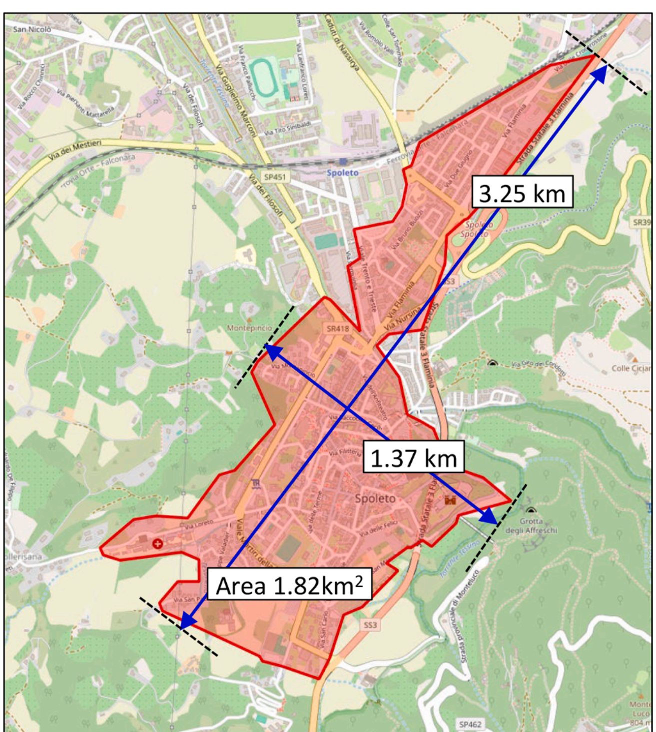


Fig. 4. The shaded area represents the region of Spoleto that was modelled in urbanEXODUS.

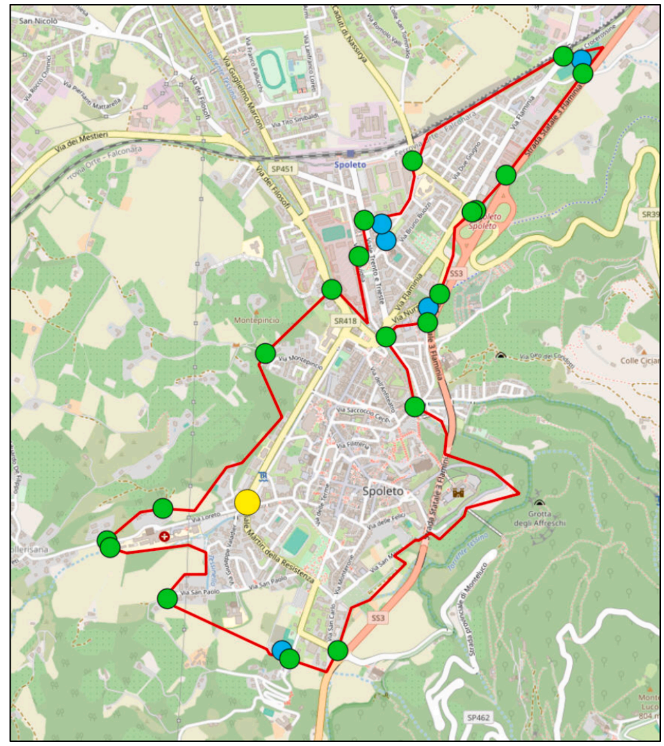


Fig. 5. The exit roads are highlighted with green circles, the gathering/refuge locations with light blue and the event location with a yellow circle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

people. Since the exact distribution of the population was not known, the TTX committee assumed that the hotels were at 70 % occupancy, approximately 827 people. It was also assumed that 55 % of the residences, 75 % of workers, and 10 % of hotel guests would be inside. Approximately 4696 people would be inside the buildings. For the people in the street, it was assumed that 40 % of residents and 90 % of hotel guess would be outside, which was approximately 3495 people.

The demographics of the population assumed that 50 % were males and 50 % were females. The agents' ages ranged between 20 to 60 years old (average 40). The agents' unimpeded travel speeds ranged from 0.8 m/s to 1.5 m/s (average 1.15 m/s). When encountering congestion, the agents' impeded travel speeds ranged from 0.72 to 1.35 m/s (average (1.03 m/s). This population information was coded and imported to urbanEXODUS in the form of an XML *Population Specification* file. Further to the population's demographic information the *Population Specification* file also includes information of the initial location of the agents that will reside within buildings. It should be noted that the agents initially residing within buildings are not created prior to the simulation run but are generated during run-time once the simulation has started and once the agent's notification and response time has elapsed. The initial distribution of those agents is defined in the *Population Specification* file and is depicted in Fig. 6. The agents that are deemed to start from an outdoor location, are generated by the user prior to the simulation run. The boundary of the evacuation area of Spoleto is also highlighted. It is assumed that once the simulated agents reach the exit points or the refuge locations (see Fig. 5) that they have reached safety and are thus removed from the simulation. As part of the population is generated at run-time the XML *Population Specification* file acts only as a guide as to where and when the model's agents should be generated. Therefore, when the simulation ends the number of agents generated may not be equal to the number of agents specified in the *Population Specification* file. As the TTX scenario ends at 90 min the number of agents generated are less than the number of agents specified

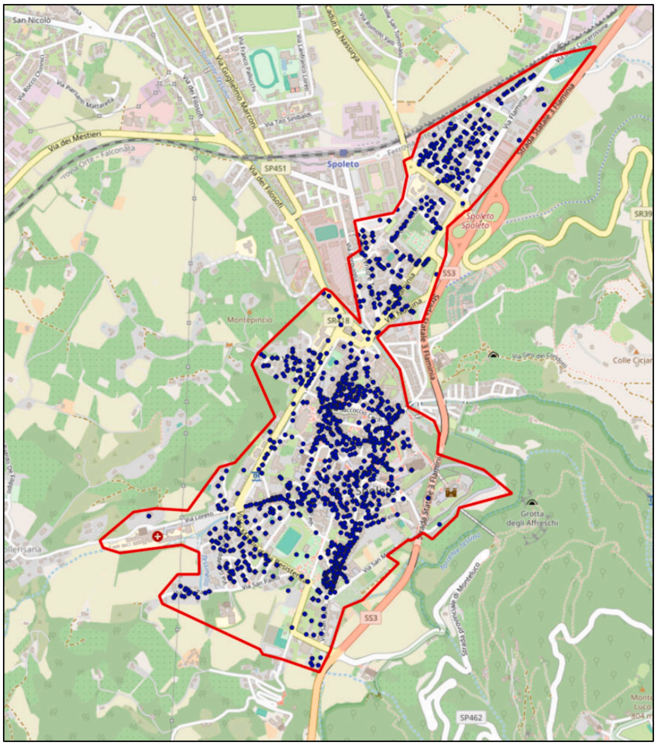


Fig. 6. The boundary of the evacuation area of Spoleto highlighted in red. The dark blue dots represent the initial population location. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the *Population Specification* file.

3.3. Scenario hazard

For the TTX the selected hazard was based on a chlorine gas release from a truck with a capacity of 8000 L. The chlorine gas was assumed to leak at a rate of 0.15 kg/sec from 0 to 80 min. The weather conditions identified for the TTX scenario were as those recorded on the 19 July 2018 with a weak southwest wind.

Using the weather patterns as specified for the TTX, a kinematic spreading of the toxic hazards was simulated using FARSITE (Finney, 2004) by IN-PREP partner IESC (IESC, 2018). The resulting hazard data was generated from 15 min to 90 min. The FARSITE hazard data was then converted to a set of isochrones at 15-minute intervals. In total, this consisted of 20 Isochrones (Finney, 2004), with each time interval having multiple isochrone regions. At any one point, more than one isochrone can be active. Concentration levels in these isochrones have two values 10^{-4} or 10^{-6} kg/m^3. It is assumed that for each isochrone the chlorine levels are uniform throughout the hazard area. Fig. 7 shows the chlorine hazard spread at three different time steps for the TTX scenario influenced by the assumed weather conditions of 19 July 2018.

It should be noted that the hazard isochrones generated by IESC for the purposes of the TTX only included isochrones with two chlorine concentration values of 1.0E-6 kg/m^3 and 1.0E-4 kg/m^3 which correspond to the upper levels for AEGL-1 and AEGL-3 exposure values, respectively. For the other AEGL exposure levels to be triggered (i.e., AEGL-2) the exposure time would need to be greater than 240 min, see Table 9.

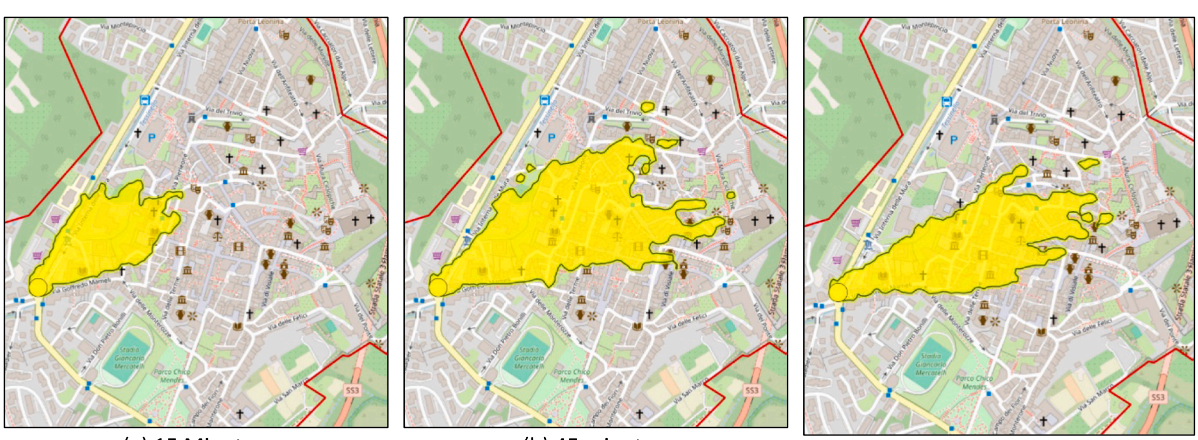
3.4. Hazard stand-off distances

The results from the hazard simulations were used by the emergency managers to define the standoff distances (US EPA, 2025) that were applied during the TTX. The standoff distances for the scenarios were determined based on this hazard spread data. For the chlorine scenarios the distances were derived using a *Level of Concern* set equal to the AEGL-1 value was used (US EPA, 2025). The standoff distances for chlorine is shown in Fig. 8 and indicate the areas that need to be sequentially cleared of agents. For example, from 12 to 45 min the region shown in Fig. 8a will need to be cleared of agents. Conversely, the region shown in Fig. 8b needs to be cleared of agents from 45 to the end of the TTX (i.e., 90 min). An explanation of why these times were selected is provided in the next section that covers the response to the chlorine hazard during the TTX.

3.5. Emergency response to the hazard

As a response to the chlorine leakage, the authorities deemed it necessary that the area is evacuated. While in cases of chlorine leakage, it is more advisable to evacuate vertically (i.e., move to higher floors within the same building, if indoors, or to higher ground, if outdoors), in cases involving extreme chlorine concentrations horizontal evacuation is also a viable option. Nevertheless, during the TTX only horizontal evacuation was considered, as the requirements of the TTX included the provision of a training environment for managing horizontal evacuations.

For the purposes of the TTX a four-stage incident timeline was identified (see Table 10). The actual TTX only covered the response phase up to 90 min, after which the focus is expected to switch to the recovery of the hazard. By 90 min the chlorine hazard has been



(a) 15 Minutes (b) 45 minutes (c) 75 minutes

Fig. 7. Snapshots of chlorine hazardous gas spread at 15, 45, and 75 min past the start of the incident.

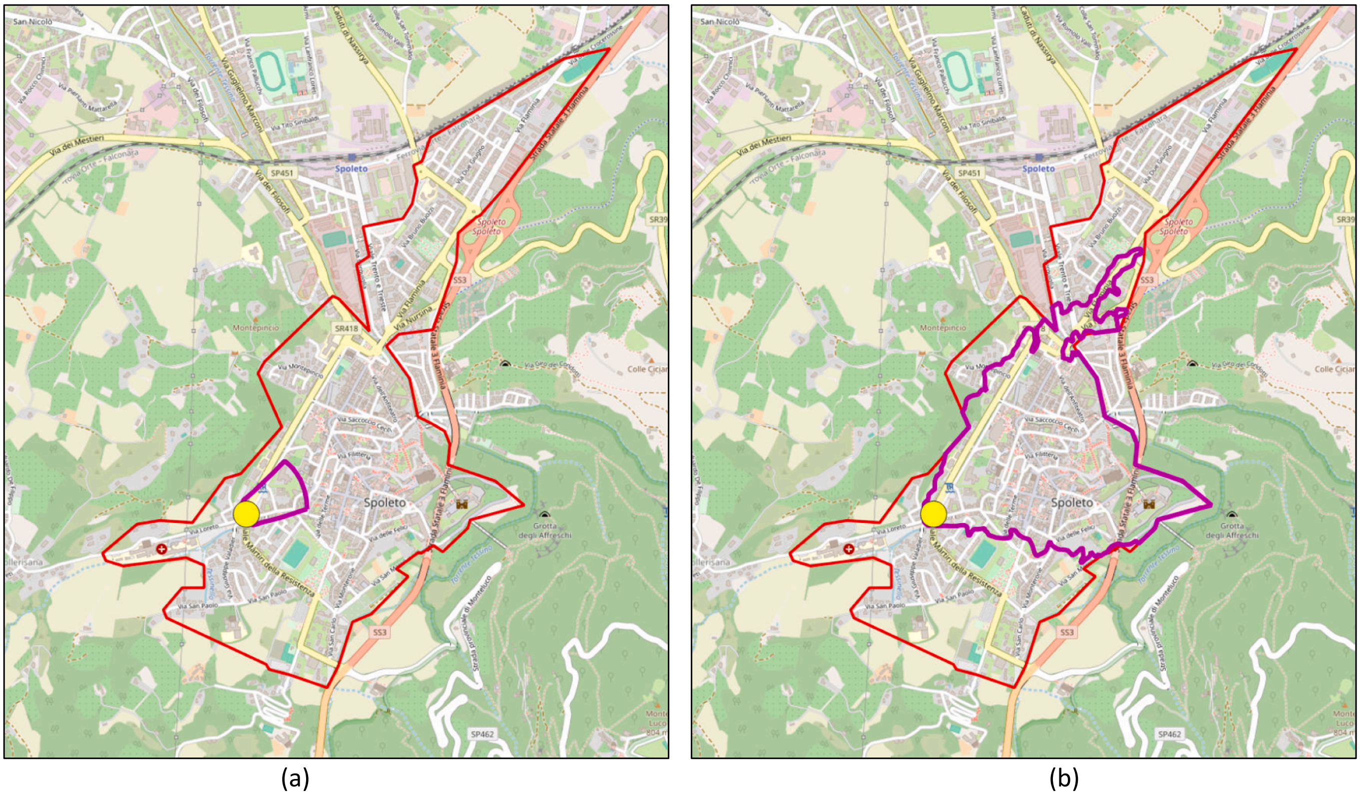


Fig. 8. Stand-off distances (a) from 12 to 45 min and (b) from 45 min till the end of the incident at 90 min. The yellow circle indicates the epicentre of the accident. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 10
Four phases of the TTX.

Stage	Time	Description
First	T0	Start of incident, no emergency service personnel are in place.
Second	T0 + 12 min	The first emergency service personnel arrive at the scene. One fire truck in place with five officers. It should be noted that only three of these officers will be responsible for notifying the public, while the other two will be in charge of maintaining the cordon.
Third	T0 + 70 min	Arrival of the CBRN team. CBRN fire truck from Perugia in place with four officers.
Fourth	T0 + 360 min	Hazmat is decanted into an emergency tank and cloud is dispersed.

contained, and the evacuation of Spoleto has been called off as no longer necessary. Hence during the TTX only 90 min are simulated by urbanEXODUS.

During these four-stages the emergency services utilised a range of methods to notify the local population that include *Ring the Intercom*, *Automatic Dialler* and *Spontaneous*. The specifics of each notification method that were utilised during the TTX are described in the next three sections.

3.6. Notification method: Ring the Intercom

For the first few moments, during the simulated incident, the only way to warn people residing within buildings is the most basic, i.e., ring the bell or intercom. However, before warning people in buildings the officers in place (i.e., first responders) are assumed to engage in several tasks. These tasks include establishing a virtual cordon to keep people and vehicles away from the accident, communicating with their control centres to report the situation, escalate the response, and request additional resources required. Thus, the process of notifying people in the surrounding buildings cannot start immediately.

From around 12 min the fire chief in place, having received situation from other officers in place via communication with the control centre, directs the evacuation. The fire chief provides instructions to the available officers, assigning them tasks to clear the buildings/area that are most exposed. Initially (i.e., at 12 min) three officers are assigned to notify the public. However, from 20 min onwards the number of officers on the scene increases, as detailed in Table 11. The 12 and 20 min are scenario injects (Filippidis et al., 2024) and were decided on the day by the TTX committee using their expert judgment and familiarity with the area.

The assumed notification process requires officers to receive confirmation from the notified citizen stating that they understood the alert message and instructions. The nature of this notification method requires that the households within buildings are notified in sequence and not concurrently to avoid confusion. The time to alert each family was determined by the experts and was deemed to vary throughout the simulation roughly in accordance with the number of officers available (see Table 11). The region notified by the officers also varies during the simulation. In total, two notification regions were defined corresponding to the stand-off distances (see Fig. 8). It is important to note that the action of the officers are modelled implicitly by the variation in both the notification regions and rates, in conjunction with a distance-based notification pattern. The distance-based notification pattern involves notifying residences within a specific notification region from the centre outwards.

3.7. Notification method: Automatic dialler

The second notification method employed during the TTX is the automatic calling system for landline telephones which can deliver massive pre-registered vocal messages to pre-defined zones. This system

Table 11
Summary of notification profiles and zones of notification methods used during the TTX.

Ring The Intercom
Notification Region: Varies depending on time, based on the stand-off distances (see Fig. 8).
Alerting order: Distance based starting from the centre of the area.
Coverage: Notifies all the residential locations in the area, together with people in the street network.
Start time: 12 min into the simulation.
Initial success rate: 90 %
Subsequent success rate/Interval: 90 % at a rate of 5 to 35 residencies, every 5 min.
This increases overtime as more emergency crew arrive, based on number of officers available at the scene of the incident.
Initial rate from 12 min is 5 residences/minute every 5 min: 3 officer available to notify.
Rate increase at 20 min to 11 residences/minute every 5 min: 7 officers available to notify.
Rate increase at 25 min to 13 residences/minute every 5 min: 11 officers available to notify.
Rate increase at 30 min to 15 residences/minute every 5 min: 13 officers available to notify.
Rate increase at 40 min to 17 residences/minute every 5 min: 15 officers available to notify.
Rate increase at 45 min to 25 residences/minute every 5 min: 23 officers available to notify.
Rate increase at 60 min to 32 residences/minute every 5 min: 26 officers available to notify.
Rate increase at 70 min to 35 residences/minute every 5 min: 29 officers available to notify.
Auto Dialler
Notification Region: The complete shaded area as shown in Fig. 4
Alerting order: randomly assigned within the area.
Coverage: Notifies 50 % of the residential locations in the area.
Start time: 30 min into the simulation.
Initial success rate: 15 %
Subsequent success rate/Interval: 15 % every 5 min
Spontaneous
Notification Region: The complete shaded area as shown in Fig. 4
Alerting order: randomly assigned within the area.
Coverage: Notifies all the residential locations in the area, together with people in the street network
Start time: 0 min into the simulation.
Initial success rate: 5 %
Subsequent success rate/Interval: 5 % every 5 min

takes 30 min on average to initiate. It is assumed that 50 % of the households can be notified by the system every 5 min. For this system, an initial success rate of 15 % is assumed, with a subsequent success rate of 15 % every 5 min (i.e., the success rate remains fixed). This low success rate was chosen as the best estimate by the TTX committee since it is expected that in most cases either the call will go unanswered or when answered, the message may be ignored as originating from an untrusted source. While the model is also capable of representing the impact that SMS messages (see Section *Voice and Text message Area Notification Systems*) have on the evacuation process this was not examined during the TTX.

For the TTX scenario, it is assumed that the system needs 30 min to complete the calls and then it starts again calling the ones that did not answer. The sequence in which locations (i.e., telephone numbers) within the notification region are called is selected at random. The message content was not specified during the TTX as the intention was only to represent the effect that the automatic dialler would have in notifying the population. Following the same format as the other notification methods, the transmission and receipt of voice messages are not simulated in the model. What is simulated is the effect that such a system is expected to have when notifying the recipient population.

3.8. Spontaneous self-evacuation

The Spontaneous notification method was included to account for people responding on their own, for example after observing incident cues or seeing others evacuating. A spontaneous evacuation profile was thus defined with a start time of zero minutes that covers the whole modelled area and therefore the entire population. The evacuation profile was defined in such a way because at any given time, any resident within the effect area may receive information or other cues, which could cause them to commence evacuation without being notified by the authorities. This may occur, for example, when seeing others evacuate. It is assumed that all agents within the evacuation area have a chance of spontaneously evacuating. Therefore, this method has a notification coverage of the entire population.

The TTX committee choose this method to have an initial success rate of 5 %, i.e. 5 % of the entire population would evacuate immediately, with a subsequent rate of 5 % every 5 min. This covers all people located within buildings and in the street network. A summary of the notification rates used for the stand-off distances at various times during the simulation is shown in Table 11.

3.9. Population response once notified

A population response time, representing the time between being notified and then starting to evacuate, was defined based on expert consensus from the IN-PREP expert panel.[1] Two response distributions were provided, both corresponding to a likely daytime response (7 am to 11 pm). These two response distributions corresponded to the response of people initially located within buildings, or within the streets.

The distribution for the day case response times as used in the TTX, is outlined in the first two columns of Table 12 that respectively list the

Table 12
Population specification and model allocation.

Building Residents' Response Times (Daytime Case)			
Response Time Ranges (minutes)	**Percentage Specified**	**Number Allocated in Model**	**Percentage Allocation in the Model**
0–1	1 %	47	1 %
1–4	9 %	423	9.01 %
5–10	55 %	2583	55 %
10–15	15 %	704	14.99 %
15–20	9 %	423	9.02 %
20–30	1 %	47	1.00 %
30–60	10 %	469	9.98 %
Street/Road Response Times (minutes)			
2–10	100 %	3495	100

[1] The expert panel consisted of members from Corpo Nazionale dei Vigili del Fuoco and the Civil Protection of Spoleto.

response time range in minutes and the percentage of people that will adopt a particular range. The second and third columns of Table 12 shows the actual number of people and their percentage of the overall population assigned a specific response time band for the actual TTX model. The difference between the specified percentage and the allocated percentage in the model is because it was assumed that all residences at the same address would respond at the same time, i.e., they would leave the building at the same time. Hence, this resulted in slight differences in model allocation in conjunction to rounding to the nearest person. The response time of those initially located on the roads (as pedestrians) are also shown in the same table (see Table 12). It is important to note that once individual people are randomly assigned to a given response time range, their individual response time is then in turn randomly determined within that range according to a random uniform distribution.

The building residents' response time values were used for all people initially located within residential buildings. All residents in a single occupancy unit (e.g., flat or house) are considered to respond at the same time. While this is a simplification, it is reasonable to suppose that once a member of a household becomes aware of the need to evacuate, they will notify other members of that dwelling. Furthermore, in strongly affiliated groups (i.e. family groups) it is common for the household to wait for all members to be ready prior to jointly commencing evacuation. Pedestrian agents that are initially located in the street/road network have their own individual response time. Group behaviour is not considered for either agents initially located within buildings or agents initially located in the streets.

In the model, an agent's personal response time is added to their time of notification. The resultant value represents the time that the agent starts purposefully moving towards either their nearest safe location (i.e., refuge area) or exit point from the affected area via the shortest available route. The overall response time for that agent is therefore relative to the start of the simulation. It is important to note that agents do not take into account the location of the hazard when determining the routes to take for their selected target location (i.e., agents will not attempt to reach their selected target via longer routes and will similarly not redirect to alternative refuge locations/exit point in order to avoid the hazard). Upon reaching a given exit point or refuge area the agents are assumed to be safe and hence are effectively removed from the simulation. As a result, agents can no longer be exposed to the toxic effects of the chlorine hazard.

3.10. TTX scenario results

One of the aims of the TTX was to fully test the participants' response to the assumed emergency conditions and their emergency procedures while utilising new technological tools. Therefore, it was deemed necessary to also assume a full evacuation of the affected area as indicated by the TTX scenario. During the TTX only one evacuation simulation was performed that represented the events unfolding during the selected TTX scenario. The simulation covered the period from the start of the incident till the time that the hazard was contained at 90 min. As the participants were following and responding to specific scenario related events and scenario injects it was necessary to have the pre-simulated evacuation results available when the TTX participants demanded them. Two snapshots of the evacuation simulation depicting the current location of the population at 30 and 60 min once the evacuation started are shown in Fig. 9. Once again, it is assumed that exit routes are not blocked due to the hazard and that the agents do not alter their path, in an attempt to avoid being exposed to chlorine. The agents are assumed to adopt the shortest routes to either an exit point or a refuge location, whichever is closer to them. All exit points and refuge locations are depicted in Fig. 5. When an agent reaches an exit point or a refuge location they are assumed to have reached safety. At that point they are effectively removed from the simulation while their experiences and exposure levels are recorded for further analysis.

The summary results produced from the single simulation that was run during the TTX can be seen in Fig. 10. These summary results were

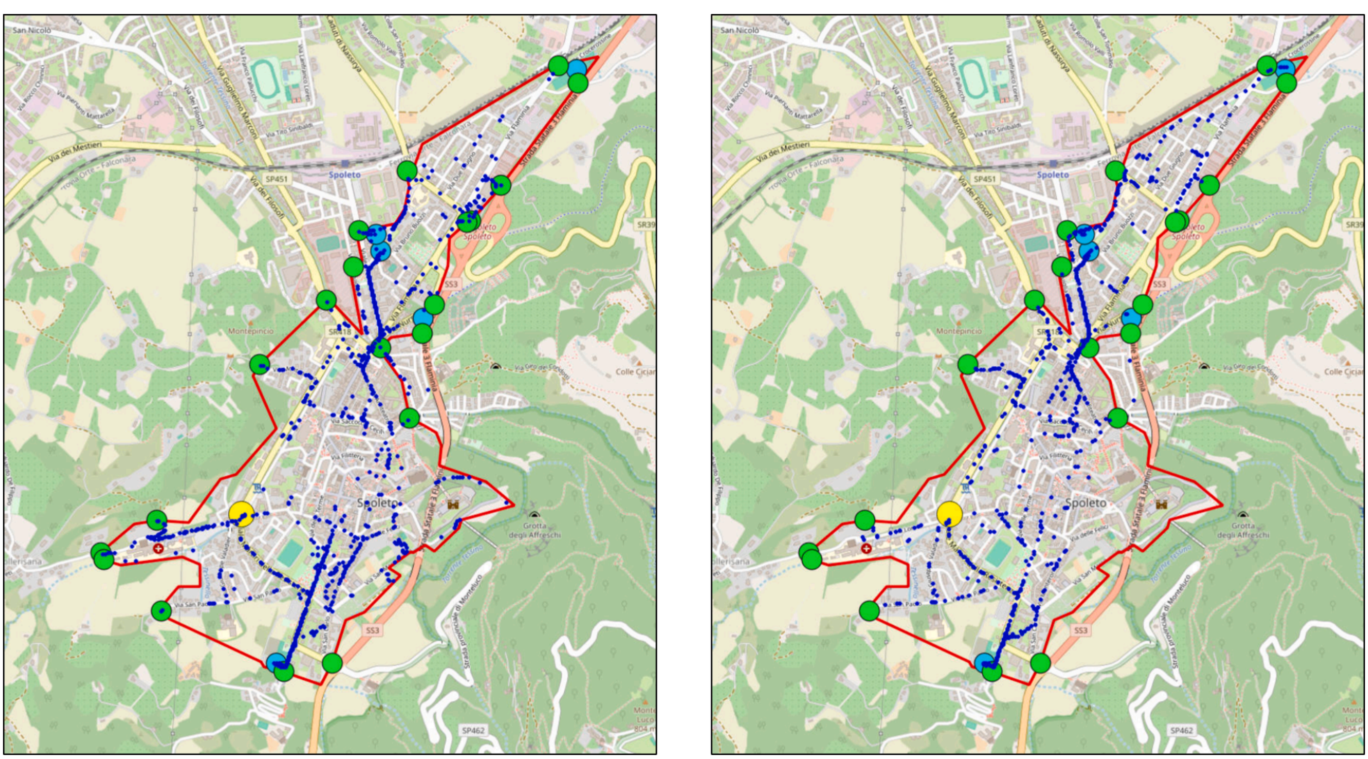


Fig. 9. Evacuation process at (a) 30 min and (b) 60 min depicting the location of the evacuees at those times. The yellow circle indicates the epicentre of the accident, green circles indicate exit locations from the area and light blue circles denote the gathering/refuge locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

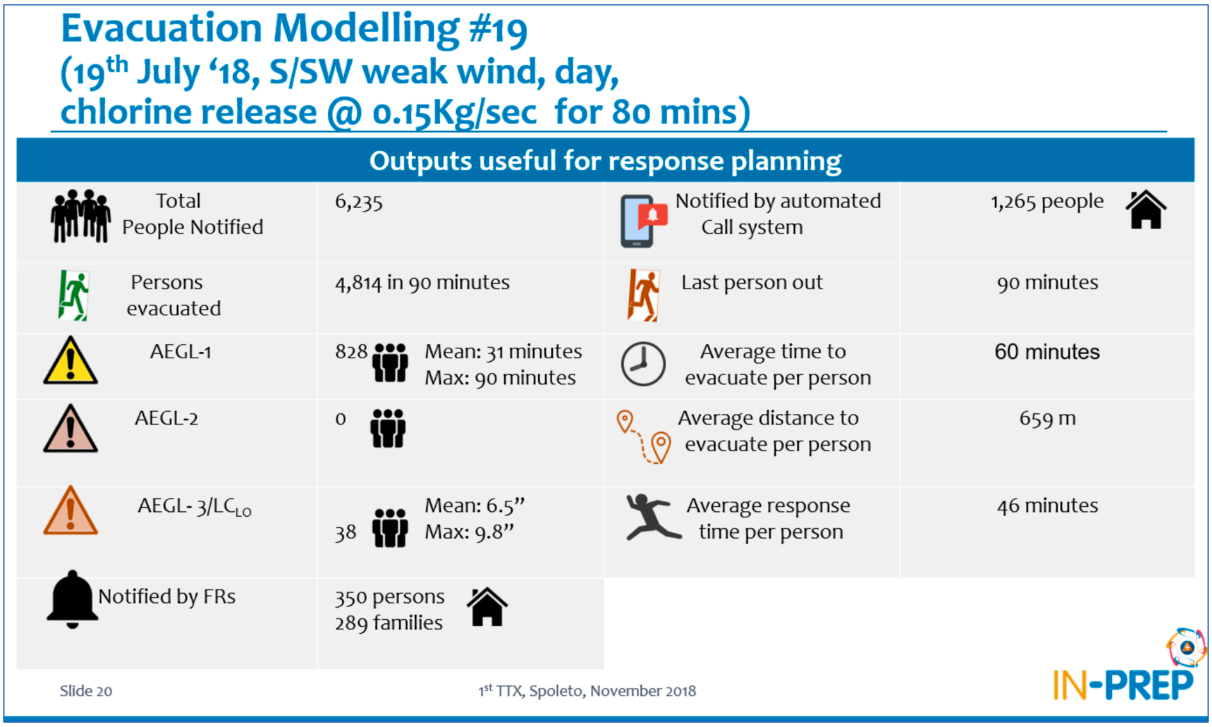


Fig. 10. Evacuation Simulation – Summery Information listing the main results of the simulated TTX scenario.

presented when the evacuation modelling results were requested during the TTX. As can be seen in Fig. 10, 38 people were exposed to a higher level of chlorine at AEGL-3, which would indicate that these people would need immediate attention by medical services. The lower level of AEGL-1 exposure, which impacted 828 agents, means that these people may need some minor medical assistance at the scene, before leaving the area (Chang et al., 2008; Gant et al., 2018; US EPA, 2025). It should be noted that the hazard isochrones generated for the TTX only included isochrones with two chlorine concentration values of 1.0E-6 kg/m^3 and 1.0E-4 kg/m^3 which correspond to the AEGL-1 and AEGL-3 exposure values respectively (see Table 9).

In Fig. 11 the evacuation process profile of the population is shown. This graph presents a novel way of displaying the evacuation process as it provides enhanced information over what is typically presented in the literature i.e., simply the number of agents that reached safety over time. This figure illustrates the impact that the various notification procedures have on the agents being notified, their subsequent response time, and eventually their evacuation time (i.e., moving outside the impacted area) or the time they reached a place of safety (i.e., reached a shelter within the impacted area). It thus links the time an agent is notified to the time they respond and then to the time they reach safety. Therefore, for each agent, there are three data points (i.e., dots on the graph) that correspond to that agent's evacuation process (see Fig. 11a). For each agent, the first, left most dot (coloured green) represents the time when that agent was notified, on its right, the second dot (coloured orange) represents that agent's response time, finally, the dot further to the right, i.e., the third dot (coloured blue) represents the time that that agent evacuated the area or reached safety. In Fig. 11b, a section of the graph shown in Fig. 11a is zoomed in, showing specifically the actions of the *Ring the Intercom* notification and the subsequent agents' response and evacuation times.

It is worth noting the unique characteristics of the data shown in Fig. 11. Firstly, the data presented is sorted by notification time. In essence, the notification time corresponds to a local *zero-time* for the notified agents as that is the time that the agents become aware of the danger. The *Automatic Phone Call* notification for each agent appears as a vertical line. This vertical line includes the *Spontaneous* notification process since it is assumed that the notification to multiple agents takes place concurrently at set times. However, the *Ring the Intercom* notification for multiple agents appears as a sloped line. This is because the *Ring the Intercom* notification is a sequential process, only one household can be notified at any one time by one emergency staff, and it takes time to notify a household. The slope of this line indicates the rate at which the emergency personnel can notify the residents. Finally, as the data is sorted by notification time the final evacuation graph is not continuous but is fragmented into smaller, sub-evacuation, graphs. Each fragment corresponds to the evacuation graph of the sub-population that was notified during a specific notification period. These sub-evacuation graphs appear to follow the S-curve shape that is typical of evacuation graphs. The graph depicted in Fig. 11 condenses a high volume of information that exceeds the conventional evacuation graph representations that are often utilised, that just show the number of agents reaching safety over time. When combined with summary information, such as that displayed in Fig. 10, crisis managers may better visualise the impact of their designed emergency procedures in terms of persons responding against the number of people reaching safety.

3.11. Further analysis

The TTX utilised a single simulation result corresponding to the executed scenario. However, additional analysis was performed post-TTX to gain further insights related to that specific scenario. This analysis reveals the variability that the selected TTX scenario could produce if simulated multiple times. For that purpose, a batch run of 50 simulations was performed. For reference, the average time it took to run one simulation was 241 s (5.9 SD) with an average memory usage of 50 GB (0.06 SD) on an i7-6950X CPU 3 GHz PC with a total memory of 64 GB running Windows 10. It was established that 50 simulations would exceed the number of simulations required to obtain a 95 % confidence interval with a 5 % accuracy (Winston, 2000; Grandison, 2020) for the key simulation outputs used during the TTX. These include the number of agents notified by the notification systems employed during the TTX, the average evacuation time, the average distance travelled by the agents, and the agents' average pre-evacuation time (see Table 13).

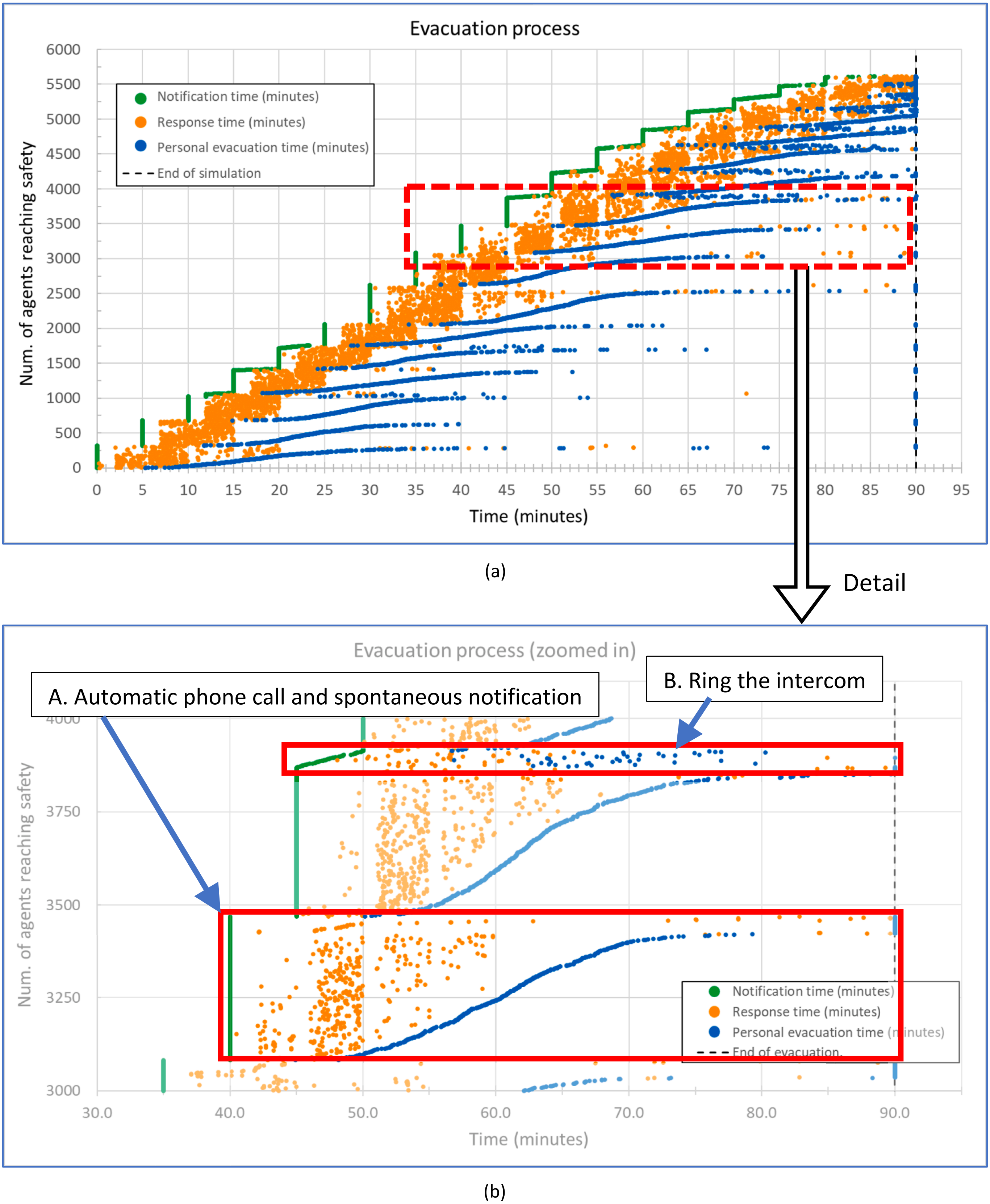


Fig. 11. (a) Evacuation process graph: **Green:** notification time, **Orange:** population response time, **Blue:** Evacuation time, (b) detail depicting a notification by the Automatic Dialler and Spontaneous, and a notification by Ring the Intercom. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 13
TTX Scenario simulation results.

	People Notified by Emergency Crews	People Notified by Automatic Dialler	People Notified Spontaneously	Average Pre-evacuation time (minutes)	Average Evacuation time (minutes)	Average Distance (m)
Mean (min – max)	1143.9 (1075 – 1274)	1317.7 (1262 – 1393)	3368.6 (3281 – 3471)	44.0 (43.6 – 44.5)	58.0 (57.6 – 58.5)	653.0 (648.9 – 657.2)
Standard Dev	31.6	28.4	46.1	0.2	0.2	2.0

Table 14
TTX scenario chlorine exposure data.

	Total People Notified	People Evacuated	AEGL-1 (People Exposed)	AEGL-2 (People Exposed)	AEGL-3 (People Exposed)	LC_{LO} (People Exposed)	Total People Exposed
Mean (min – max)	5830.2 (5758 – 5904)	4872.9 (4792 – 4962)	855.1 (813 – 898)	0	30.6 (22 – 40)	0	885.7 (844 – 924)
Standard Dev	34.5	34.8	17.9	0	4.2	0	16.5

Furthermore, the impact level that chlorine had on the simulated agents is also reported (see Table 14).

Furthermore, to assess the impact that the formal notification strategies had on the evacuation performance, additional analysis is undertaken. A new scenario was configured, and a further batch of simulations was conducted where the formal notification protocols (i.e., *Ring the Intercom* and *Automatic Dialler)* were not used. This is to remove the influence of such methods from the overall evacuation process and outcome and assess the effect of the *Spontaneous notification* method on its own. Secondly, considering the nature of the hazard, and the physical characteristics of how chlorine flows in the environment, the potential benefits of conducting a vertical evacuation strategy, compared to the full (horizontal) evacuation employed in the TTX, are investigated. These additional scenarios are intended to demonstrate how a comparison can be made between different strategies using the summary data and evacuation process graphs. In addition, these two scenarios are then compared with an alternative vertical evacuation strategy. In all the following scenarios the population starting locations will remain the same between simulations and scenarios. This is so that the impact of changing the notification methods can be compared across scenarios using the same population distribution.

3.12. TTX scenario variability

A summary of the variability for key simulation parameters is shown in Table 13. It is important to note that the average evacuation data (i.e., pre-evacuation time, evacuation time and distance travelled) are only for those who have left the evacuation area or reached a place of safety. As stated in the previous section, these results are based on 50 simulations, this was sufficient to achieve a 95 % confidence interval with a 5 % accuracy on the simulation outputs. It should be noted that the number of people notified by the emergency crews, shown in Table 13, is higher than the value shown in the summary results reported during the TTX (see Fig. 10) labelled as *Notified by FRs (First Responders)*. The difference arises because the TTX summary information reported only the number of residential locations notified by emergency crews (i.e., the first responders), while the analysis presented in Table 13 includes those individuals who were notified within residences and the street network. The variability of the hazard exposure levels is shown in Table 14.

As can be observed, the variability is low, since the route taken by first responders is identical between simulations, as they visit the same houses in the same order in every simulation (based on distance from the centre of the notification area). Therefore, the main source of variability comes from locations notified by the "automatic call system" and the *Spontaneous* notification methods. Also, the response time of individuals at each given location is derived from the same response time range, which does not vary between simulations. When a location is assigned a response time taken from one of the ranges listed in Table 12 for example, between 5 and 10 min, then for every repeat simulation a random value is chosen between those two extremes for that location. This reduces the response time variability. Furthermore, other factors that keep variability low include the relatively low population densities and therefore the low number of interactions between the agents, and the behaviour of the agents that are assumed to have good familiarity with the town and are thus aware of the shortest paths to refuge locations and exit points.

3.13. Impact of no formal notification method

To study the impact of the formal notification methods a base case is useful to establish the consequences if the authorities did not intervene and only relied on the spontaneous evacuation, which is modelled by the *Spontaneous* notification method. The results from 200 simulations where only the *Spontaneous* notification was utilised are shown in Tables 15 and 16. It is important to note that in this case 200 simulations were performed to achieve the required accuracy for all key parameters. This was due to the large size of the standard deviation of the AEGL-3 relative to its average value.

As can be seen when comparing Tables 14 (TTX) and 16 (no formal notification), there is a clear difference between AEGL exposures, with approximately 390 fewer people exposed to the hazard when no formal notification strategy is employed. This indicates that the formal notification methods, as utilised in the TTX, negatively impacted the

Table 15
No formal notification evacuation simulation results.

	People Notified Spontaneously	Average Pre-evacuation time (minutes)	Average Evacuation time (minutes)	Average Distance (m)
Mean (min – max)	3927.4 (3847 – 4000)	43.2 (10.5 – 44.3)	56.7 (55.7 – 57.8)	639.7 (628.1 – 653.5)
Standard Dev	28.8	0.4	0.4	21.7

Table 16
No formal notification *chlorine exposure data.*

	Total People Notified	People Evacuated	AEGL-1 (People Exposed)	AEGL-2 (People Exposed)	AEGL-3 (People Exposed)	LC_{LO} (People Exposed)	Total People Exposed
Mean (min – max)	4160.9 (3139 – 4233)	3221.7 (3139 – 3305)	479.4 (221 – 530)	0	15.8 (0 – 32)	0	495.2 (435 – 549)
Standard Dev	21.6	30.8	20.5	0	5.4	0	21.6

population. This is because approximately 1903 more people were notified to leave in the TTX case (see Tables 14 and 16), and hence approximately 390 more people passed through the hazardous plume.

Depicted in Fig. 12 is the notification/response graph for the spontaneous evacuation. This graph shows how the 5-minute time interval of the spontaneous notification method impacts the population and how they subsequently respond in the model. The groups of vertical green dots represent people simultaneously recognising the need to evacuate (i.e., being notified) and then subsequently responding (orange dots). Since it can be assumed that some people will respond the moment the incident occurs, this spontaneous notification method has an immediate effect from time zero. It is recognised that in reality, people self-responding to events would not be limited to a fixed time-step, and that the notification/response process would have a continuous profile, as mentioned previously in the Method Section. However, the TTX committee considered this approximation appropriate for the needs of the TTX.

3.14. *Vertical evacuation*

In the previous section, it was identified that the formal evacuation notification procedures prompting the population to evacuate from the area has a negative impact on the population as it exposes more people to the hazard compared to the scenario that inhibited the notifications. Therefore, this raises the question of what the authorities could have done differently.

As the hazard modelled in the TTX is chlorine, which is a heavy gas and tends to remain at ground level (Bauer, 2013), an alternative protective measure could have been to use a vertical evacuation strategy (Dou et al., 2019). This is where residents notified within a building are informed to move to a higher level within their residence, when possible. Such an evacuation strategy is implemented within urbanEXODUS. In this case when a person or group of people are successfully notified within a building, urbanEXODUS will assign the agents a response time associated with vertical evacuation. An assumed travel time to the higher floor is then added to the agent's response time indicating the arrival time to the higher floor. Once the agent's response time and travel time to the higher level has elapsed, they are assumed to have reached safety and are then subsequently removed from the simulation and added to the vertical simulation data list.

Tables 17 and 18 show the results from such a scenario, based on 50 simulations. In this scenario, the agents that are initially located within a building who are notified to evacuate are assumed to vertically evacuate, i.e., move to a higher floor. However, any agent which is initially located within the street network will evacuate in a similar fashion as in the TTX scenario (i.e., move to their nearest exit point or refuge area). Furthermore, it should be noted that the number of people notified by the emergency crews, shown in Table 17, includes both the individuals that were notified within residences and those located within the street network.

On examination of Tables 17 and 18, the use of a vertical evacuation procedure, reduces the overall exposure of the population to chlorine.

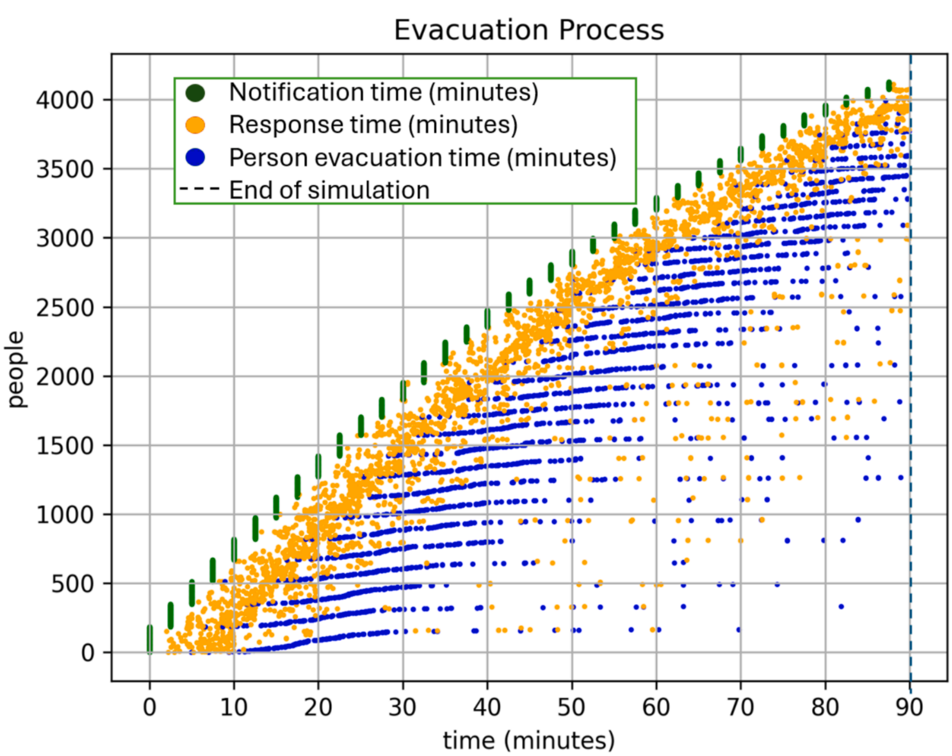


Fig. 12. Spontaneous only evacuation process.

Table 17
Vertical evacuation simulation results.

	People Notified by Emergency Crews	People Notified by Automatic call system	People Notified *Spontaneously*	People Vertical Evacuation	Average Pre-evacuation time (minutes)	Average Evacuation time (minutes)	Average Distance (m)
Mean (min – max)	1149..0 (1067 – 1204)	1312.9 (1251 – 1364)	3370.7 (3282 – 3453)	3722.8 (3637 – 3814)	46.0 (45.2 – 46.9)	51.9 (51.2 – 52.7)	259.3 (252.7 – 268.3)
Standard Dev	30.7	25.2	37.4	33.5	0.3	0.3	3.1

Table 18
Vertical evacuation chlorine exposure data.

	Total People Notified	People Evacuated	AEGL-1 (People Exposed)	AEGL-2 (People Exposed)	AEGL-3 (People Exposed)	LC_{LO} (People Exposed)	Total People Exposed
Mean (min – max)	5833.1 (5726 – 5897)	1796.0 (1756 – 1852)	342.7 (321 – 373)	0	24.5 (16 – 33)	0	367.1 (345–404)
Standard Dev	31.8	23.2	10.7	0	3.9	0	10.8

The number of agents exposed to the AEGL-1 level is lower in the vertical evacuation scenario (mean 342.7, SD 10.7) when compared to the no notification scenario (mean 479.4, SD 20.5) or the TTX scenario (mean 855.1, SD 17.9). However, the number of agents exposed to the AEGL-3 level is higher in the vertical evacuation scenario (mean 24.5, SD 3.9) when compared to the no notification scenario (mean 15.8, SD 5.37) but it is lower than the TTX scenario (mean 30.6, SD 4.2). Thus, approximately 31 people are predicted to incur life-threatening effects during the TTX scenario compared to 25 for the vertical evacuation and 16 for the no formal notification scenario. This is because in the Vertical Evacuation scenario, people in the street and within the stand-off distances are still responding to the emergency personnel and thus evacuating. Hence, more people are responding near the incident, compared to the no formal notification scenario, and therefore have a higher chance of being exposed to chlorine. However, there is a noticeable reduction in the AEGL-1 level exposure when compared to either the no formal notification or the TTX scenarios. This in turn means the total number of agents exposed to chlorine was on average 367.1 (SD 10.8) agents, compared to the no formal notification scenario mean of 495.2 (21.6 SD), and the TTX scenario mean of 885.7 (16.5 SD). In all examined scenarios, the simulations predicted exposure to chlorine at only AEGL-1 and AEGL-3 levels. The simulations did not predict any exposure to chlorine at AEGL-2, or more critically, at LC_{LO} levels.

3.15. Summary of results

To summarise, the key results of the TTX, the *No Formal Notification*, and the *Vertical Evacuation* scenarios are presented in Table 19. A key observation is, that in the absence of formal notification, awareness of the need to evacuate primarily relies only on the spontaneous notification method, leading to lower evacuation rates compared to the TTX and *Vertical Evacuation* scenarios. The *Vertical Evacuation* scenario has the lowest overall chlorine exposure. However, the no formal notification scenario presents the lowest exposure to high levels of chlorine. This is attributed to the fact that in the vertical evacuation scenario, individuals on the street are still notified to evacuate by emergency personnel, potentially directing them to areas with higher chlorine concentrations while on route to the assembly locations.

It should be noted that during the actual TTX, the project partners understood that a full horizontal evacuation was likely to cause higher exposure rates to the population as chlorine being a heavier than air gas, spreads near the surface or sinks to lower areas, increasing the risk of exposure. In those circumstances, a vertical evacuation may be more advisable as the population is instructed to move to a higher floor or higher ground. However, since one of the objectives of the TTX was to evaluate the full evacuation procedures, it was decided to proceed with a full horizontal evacuation as this would have been the most challenging scenario to manage. Furthermore, this was to ensure that all partner tools and capabilities were utilised to the maximum possible level at the time of the TTX. However, there is an additional educational element in the findings presented in this article. The authorities do not have to simply rely on expert opinion regarding the exposure level of a population, depending on the adopted evacuation procedure, but can obtain quantitative results based on simulation tools. The post-analysis performed here, confirms the opinions of the project partners stating that a vertical evacuation is overall the better option in the circumstances posed by the examined scenario.

Table 19
Summary information highlighting the key parameter differences between the scenarios.

	Total People Notified	People Evacuated	Average Evacuation time (minutes)	Average Distance (m)	AEGL-1 (People Exposed)	AEGL-3 (People Exposed)	Total People Exposed
TTX Case	5830.2	4872.9	44.0	653.0	855.1	30.6	885.7
Spontaneous Only	3927.4	3221.6	56.7	639.3	479.4	15.8	495.2
Vertical Evacuation	5833.1	1796.0	51.9	259.3	342.7	24.5	367.1

4. Discussion

The approach taken here was to focus on how a subject matter expert could provide estimates regarding details on a given notification strategy for an urban scale evacuation model, using parameters which are familiar to them. Therefore, the actual response profile for a given notification strategy is only based on their expert judgment. The approach used to implement the notification procedures does not require comprehensive data from a detailed data study, which is in general almost impossible to obtain and unlikely to be available. However, even if a detailed study was performed, its transferability to other locations and scenarios might be difficult to justify, as the results may not be generalisable. The 32 scenarios prepared for the TTX were selected to be representative of possible incidents that could occur in the Spoleto area, not of disasters in general. Nevertheless, by including a flexible method of specifying notification procedures, the proposed solution can be tailored to accommodate notification procedures based on empirical data provided by practitioners for a plethora of scenarios and regions.

The proposed technique for representing notification methods within urbanEXODUS, while promising, presents certain limitations as its notification success rates are based on expert judgment rather than empirical data. A key advantage of explicitly representing notification methods is the ability to directly assess and compare the impact of various notification strategies, along with generating data on their performance during the evacuation process. While other modelling tools might indirectly account for notification strategies by adjusting the pre-movement times, the proposed methodology demonstrates that the independent representation of the notification phase allows for multiple notification strategies to be factored into the model. This offers insights that allow emergency managers to assess the impact of various notification strategies that would otherwise be difficult to obtain if the notification phase was represented implicitly as part of the response phase. This is especially true when multiple notification methods are employed.

The inclusion of hazard exposure data into an urban-scale evacuation model enables a deeper understanding of the impact of a given evacuation notification procedure on the evacuation process and the affected population. The insights gained can provide exposure information for individuals and thus the potential need for follow-up medical care. For example, in the TTX case presented, further analysis showed that switching to a vertical evacuation/stay-put strategy significantly reduced the number of people exposed to the hazard, particularly within residential buildings. This finding supports the common knowledge among practitioners suggesting that a full horizontal evacuation is not the optimal course of action for the scenario examined during the TTX. The proposed methodology aids in the communication of the benefits of alternative evacuation strategies, depending on the scenario, as the simulation tool provides both qualitative and quantitative data. Complex ideas can be communicated to crisis management authorities or can be used to educate the wider public with regard to the best course of action, which can be hazard-specific. An additional educational value that can benefit both authorities and the public is how the public perceives the authorities' actions. Depending on the circumstances a reluctance to instruct for a full horizontal evacuation should not be seen as underacting as it may offer the safer option.

The vertical evacuation strategy resulted in a substantially lower number of exposed individuals compared to the TTX scenario. This reinforces the crucial concept that evacuation carries risks that need to be balanced against the dangers of remaining in place (Velotti et al., 2013). Therefore, integrating hazard exposure data into simulation tools is a critical factor for evaluating emergency response plans and ranking various notification procedures and scenarios. It should be noted that the flexibility that the simulation tools provide allow for a plethora of *what-if* scenarios to be examined. These scenarios can incorporate a variety of weather conditions that can affect the hazard propagations significantly and thus affect the chosen evacuation procedure. In the demonstration case, group behaviour, which is likely to have major implications on the outcome in a real situation (Drury, 2018) was not included. However, this kind of detail was not available at the time. Nevertheless, group behaviour was not completely ignored, since a simple assumption in the model was that once a household was notified successfully, all the residents would receive the same response time. Given these assumptions and limitations, the results are likely to be over-optimistic regarding travel distance and waiting for group members. However, the focus at the TTX was on the notification methods and subsequent analysis was then performed to see if a vertical evacuation strategy might be a better option, due to the nature of the hazard chlorine.

The model outputs two critical parameters for risk assessment: the individual's exposure to the hazard and the number of people exposed at each AEGL level. The TTX hazard data encompasses the type of chemical agent and prevailing weather conditions. The exposure duration and number of people that are impacted by the hazard is determined by the AEGL level classification data. The population vulnerability can then be assessed. For example, in the TTX case, people being outdoors and evacuating increased their exposure to the hazard, hence an alternative mitigation strategy should be adopted, such as a vertical evacuation, which was judged necessary to decrease exposure and harm to the population. The analysis performed in this paper showed that the proposed method for modelling notification procedures facilitates the evaluation of emergency crisis plans. This was illustrated in the TTX where the model was used during an actual TTX which was designed to represent, as close as possible, a plausible situation that is relevant to the area of Spoleto. In addition, further analyses were performed confirming that a vertical evacuation strategy was the best option for minimising the population's exposure to chlorine. In this example, the AEGL levels aided in determining the most optimal scenario, as well as providing information regarding the expected level of additional support that would be necessary to assist potential casualties, such as the possible number of people exposed to the hazard who may need further medical assistance. Thus, enabling the development and testing of crisis management protocols with key stakeholders during an actual TTX and possibly assess resource allocation.

By simulating potential incidents, that include the population notification procedures, valuable insights into evacuation performance and overall management strategies are provided. A deeper understanding of the overall evacuation process could aid in fostering continuous improvement in crisis preparedness, ultimately leading to more effective responses and safer communities. Consequently, planners are empowered to prioritize the well-being of those affected by a crisis by considering the potential impact of their response and notification procedures beforehand. Furthermore, the summary information as presented in Fig. 10, together with any simulation playback should aid in communicating and demonstrating emergency plans to affected communities.

The notification model described in this paper has not been validated yet, only functional verification was performed during the IN-PREP project (IN-PREP, 2021). The focus of this study was to explore how to represent notification procedures within a large-scale pedestrian model, focusing on defining a format that can easily incorporate notification time and rate estimates by a subject matter expert. The notification model's strength lies in its ability to simulate and compare the impact of different notification methods. This capability was demonstrated in the case study presented here. To perform validation, the model requires further refinement and calibration using real-world data from relevant studies (Vaiciulyte et al., 2021, 2022; Hulse et al., 2020; Gallego et al., 2019; Veeraswamy et al., 2020). Therefore, additional work is being performed to identify possible notification and response profiles on which this technique and others, such as social cue-based models (Zhang et al., 2024), could be developed and potentially validated.

5. Conclusions

Uncertainties surrounding major incidents regarding how people are notified and then react, is a major challenge for the emergency services. For evacuation modelling, it is well known that pre-evacuation/response times are an important factor since they can have a significant impact on evacuation results (Lovreglio et al., 2019). However, response and notification time data and profiles are typically scarce, partial and presented in a form which can be difficult to use as input into an evacuation model (Lovreglio et al., 2019). A method to address this issue has been presented that defines a notification specification and a model which can be used to approximate or estimate the impact of a given notification strategy, based on expert judgement.

It should be noted that basing a notification model on values obtained mainly on expert consensus comes with many caveats. However, utilising models, based on the available data, even when imperfect or incomplete, provides a means to explore and compare available options. Thus, enabling the identification of robust plans that can adapt to and accommodate uncertainties related to actual evolving emergency situations. In the work presented here it was demonstrated that the evacuation model could estimate the impact of a given notification strategy, or a combination of notification strategies, on the evacuation process. A novel evacuation process graph and summary table were developed to compare the impact of different notification methods and enhance understanding of their influence on evacuation. This method, featuring a combined notification/evacuation graph, goes beyond the more traditional and simple time-based evacuation graph.

The presented case study, even though it does not provide validation, demonstrated that altering the notification and evacuation strategy utilised during the TTX to a vertical evacuation, which is the standard practice for the given hazard, reduced the predicted harm to the evacuated population. Hence, the model provides insights that fit with expectation and allow experts to compare evacuation viability based on a measure of possible hazard exposure or harm to the population, which could be used to aid the decision to evacuate or not.

Further development, will focus on how the model can be adapted to accept different notification profiles, going beyond an initial and subsequent success rate. For example, include user defined distributions such as log normal, Weibull, Gamma, and Logistics. Also, further sensitivity analysis is required related to the impact of varying the time steps between notification periods, i.e., at what intervals subsequent sets of people are notified. This would be performed in conjunction with additional model calibration, as and when data becomes available regarding the effectiveness of various emergency notification procedures, since a model is only as good as the data it is based on.

CRediT authorship contribution statement

Peter J. Lawrence: Writing – original draft, Visualization, Software, Formal analysis, Conceptualization. **Lazaros Filippidis (Λάζαρος Φιλιππίδης):** Writing – review & editing, Visualization, Investigation, Formal analysis. **Anand Veeraswamy:** Writing – review & editing, Methodology, Investigation. **Darren Blackshields:** Writing – review & editing, Software. **Marcello Marzoli:** Writing – review & editing, Methodology. **Stefano Marsella:** Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

AL-Fazari, S., Kasimm, N., 2019. Role of Stakeholders in Mitigating Disaster Prevalence: Theoretical Perspective, International Conference on Built Environment and Engineering 2018, MATEC Web Conf, Volume 266, https://doi.org/10.1051/matecconf/201926603008.

Bauer, T.J., 2013. Comparison of chlorine and ammonia concentration field trial data with calculated results from a Gaussian atmospheric transport and dispersion model. J. Hazardous Materials 254–255, 325–335. https://doi.org/10.1016/j.jhazmat.2013.04.002.

Bayram, V., 2016. Optimization models for large scale network evacuation planning and management: A literature review. Surveys in Operations Research and Management Science 21 (2), 63–84.

Bernardini, G., Lovreglio, R., Quagliarini, E., 2019. Proposing behavior-oriented strategies for earthquake emergency evacuation: A behavioral data analysis from New Zealand. Italy and Japan. Safety Science 116, 295–309. https://doi.org/10.1016/j.ssci.2019.03.023.

Chang, Y.S., Samsa, M.E., Folga, S.M., Hartmann, H.M., 2008. Probabilistic consequence model of accidental or intentional chemical releases Probabilistic consequence model of accidental or intentional chemical releases. United States. https://doi.org/10.2172/937013.

Chen, A., Chen, N., Li, J., 2012. During-incident process assessment in emergency management: concept and strategy. Safety Science 50 (1), 90–102. https://doi.org/10.1016/j.ssci.2011.07.006.

Chilcott, R.P., 2014. Managing mass casualties and decontamination. Environ. Int. 72. https://doi.org/10.1016/j.envint.2014.02.006.

Chooramun, N., Lawrence, P.J., Galea, E.R., 2018. Investigating the application of a hybrid space discretisation for urban scale evacuation simulation. Fire Technol. https://doi.org/10.1007/s10694-018-0742-y.

CNVVF, 2011. Corpo Nazionale dei Vigili del Fuoco, Il soccorso, https://www.vigilfuoco.it/chi-siamo/il-soccorso, Accessed September 2024.

Decreto Legislativo n. 139, 2006. Gazzetta ufficiale, Decreto Legislativo 8 March 2006, n. 139, https://www.gazzettaufficiale.it/eli/gu/2006/04/05/80/so/83/sg/pdf, Accessed March 2025.

Dou, Z., Mebarki, A., Cheng, Y., Zheng, X., Jiang, J., Wang, Y., Li, Y., Li, J., 2019. Review on the emergency evacuation in chemicals-concentrated areas. J. Loss Prev. Process Ind. 60, 35–45. https://doi.org/10.1016/j.jlp.2019.03.008.

Drury, J., 2018. The role of social identity processes in mass emergency behaviour: An integrative review. Eur. Rev. Soc. Psychol. 29 (1), 38–81. https://doi.org/10.1080/10463283.2018.1471948.

Filippidis, L., Lawrence, P.J., Blackshields, D., Ewer, J., 2023. Trapped on the seashore, seaborne evacuation, impact of exposure to PM2.5: demonstration of the urbanEXODUS evacuation model. Nova Science Publishers, pp. 439–457. https://doi.org/10.52305/QURT7964.

Filippidis, L., Lawrence, P.J., Blackshields, D., Cooney, D., Galea, E.R., 2024. Evacuation modelling for rapid multi-hazard tabletop exercise deployment. Safety Science 173, 106438. https://doi.org/10.1016/j.ssci.2024.106438.

M.A. Finney, 2004. FARSITE: Fire Area Simulator, model development and evaluation, USDA Research Paper RMRS-RP-4 Revised, 2004.

Galea E.R., Perez Galparsoro J.M., 1993. EXODUS: An Evacuation Model for Mass Transport Vehicles. UK CAA Paper 93 006 ISBN 0 86039 543X.

Galea, E., Sharp, G., Filippidis, L., Deere, S., Sauter, M., 2013. Investigating the Impact of Culture on Evacuation Behaviour – A UK Data-Sey, Proceedings of the 13th International Fire Science & Engineering Conference, Interflam 2013 24-26th June, Royal Holloway College, London, UK, Volume 2, pp. 893-906, 2013, ISBN 978 0 9556548-9-3.

Galea, E.R., Lawrence, P.J., Gwynne, S.V., Filippidis, L., Blackshields, D., Cooney, D., 2017. buildingEXODUS v6.3 theory manual Fire Safety Engineering. Group, University of Greenwich, London, UK.

Gallego D.M., Veeraswamy A., Galea E.R., (2019). Analysis report on specific requirements of large-scale evacuations in case of wildfires, GEO-SAFE H2020 project 691161, final D2.4 report, https://fseg.gre.ac.uk/fire/geo-safe_files/D2_4.pdf.

Gant, S., Weil, J., Monache, L.D., McKenna, B., Garcia, M.M., Tickle, G., Tucker, H., Stewart, J., Kelsey, A., McGillivray, A., Batt, R., Witlox, H., Wardman, M., 2018. Dense gas dispersion model development and testing for the Jack Rabbit II phase 1

chlorine release experiments. Atmos. Environ. 192. https://doi.org/10.1016/j.atmosenv.2018.08.009.
Grandison, A., 2020. Determining Confidence Intervals, and Convergence, for Parameters in Stochastic Evacuation Models. Fire Technology 56 (6). https://doi.org/10.1007/s10694-020-00968-0.
GSCP, 2020. 1st Edition of the General Emergency Response Plan for Accidents during the Road and Railway Transport of Dangerous Goods according to the ADR/RID Regulations, General Secretariat for Civil Protection, Hellenic Republic, https://civilprotection.gov.gr/sxedia-politikis-prostasias/1i-ekdosi-toy-genikoy-shedioy-antimetopisis-ektakton-anagkon-exaitias, Accessed 02 Oct 2024.
Haghani, M., Kuligowski, E., Rajabifard, A., Kolden, C.A., 2022. The state of wildfire and bushfire science: Temporal trends, research divisions and knowledge gaps. Saf. Sci. 153, 105797. https://doi.org/10.1016/j.ssci.2022.105797.
Harris, A., Roebber, P., Morss, R., 2022. An agent-based modeling framework for examining the dynamics of the hurricane-forecast-evacuation system. Int. J. Disaster Risk Reduction 67, 102669. https://doi.org/10.1016/j.ijdrr.2021.102669.
Hobeika, A.G., Kim, C., 1998. Comparison of traffic assignments in evacuation modeling. IEEE Trans. Eng. Manag. 45 (2), 192–198.
Hou, J., Gai, W., Cheng, W., Deng, Y., 2020. Statistical analysis of evacuation warning diffusion in major chemical accidents based on real evacuation cases. Process Safety and Environmental Protection 138, 90–98. https://doi.org/10.1016/j.psep.2020.02.028.
Hou, J., Gai, W., Cheng, W., Shuran, L., 2024. Are emergency warnings received? A model for estimating communication effectiveness during emergencies. Journal of Loss Prevention in the Process Industries 90, 105359. https://doi.org/10.1016/j.jlp.2024.105359.
Hulse L.M., Veeraswamy A., Galea E.R., 2020. Report on wildfire large-scale evacuations - behavioural responses, GEO-SAFE H2020 project 691161, final D2.5 report, https://fseg.gre.ac.uk/fire/geo-safe_files/D2_5_final.pdf.
IESC, 2018. Intelligence for Environment & Security - IES Consulting SRL. Italy. Accessed 21 October 2022 https://ies.solutions/en/.
IN-PREP, 2021. An INtegrated next generation PREParedness programme for improving effective interorganisational response capacity in complex environments of disasters and causes of crises, EU Horizon 2020 Innovative Action Project 2017, https://doi.org/10.3030/740627.
Intini, P., Ronchi, E., Gwynne, S., Pel, A., 2019. Traffic modeling for wildland–urban interface fire evacuation. J. Trans. Eng., Part A: Systems 145 (3), 040190.
Jones J.M., Ng P., Wood N.J., 2002. Geographic Information Systems Software for Modeling Hazard Evacuation Potential Chapter 9 of Section C, Geographic Information Systems Tools and Applications Book 11, Collection and Delineation of Spatial Data.
Jullien, Q., Dréan, V., Wyzgolik, A., Ntoung, J.Z., Blouin, M., Kabalan, B., Gwynne, S., Ganiyu, A., Collin, A., Pianet, G., Dong, H., Bourlet, N., Trevisan, N., Faure, S., Maury, B., Pinsard, E., Paillat, J., Hourqueig, R. Nejjar, M., 2020. Evacuation modelling–application to an office building using several simulation tools, Fire and Evacuation Modeling Technical Conference 15.
Katzilieris, E.I., Vlahogianni, H. Wang, 2022. Evacuation behavior of affected individuals and households in response to the 2018 Attica wildfires: From empirical data to models. Safety Science 153, 105799. https://doi.org/10.1016/j.ssci.2022.105799.
Kinateder, M.T., Kuligowski, E.D., Reneke, P.A., Peacoak, R.D., 2015. Risk perception in fire evacuation behavior revisited: definitions, related concepts, and empirical evidence. Fire Sci. Review 4, 1. https://doi.org/10.1186/s40038-014-0005-z.
Könnecke, R., Schneider, V., 2011. Risk Management at Major Events - Study of Behavioral Aspects and Implementation into the ASERI Microscopic Evacuation Mode. In: Peacock, R., Kuligowski, E., Averill, J. (Eds.), Pedestrian and Evacuation Dynamics. Springer, Boston, MA. https://doi.org/10.1007/978-1-4419-9725-8_65.
Kuligowski, E., 2020. Evacuation decision-making and behavior in wildfires: Past research, current challenges and a future research agenda. Fire Saf. J., 103129 https://doi.org/10.1016/j.firesaf.2020.103129.
Kuligowski, E.D., Zhao, X., Lovreglio, R., Xu, N., Yang, K., Westbury, A., Nilsson, D., Brown, N., 2022. Modeling evacuation decisions in the 2019 Kincade fire in California. Saf. Sci. 146, 105541. https://doi.org/10.1016/j.ssci.2021.105541.
Labhiri, A., Vaiciulyte, S., Kuligowski, E., Ronchi, E., 2024. Evacuation decisions of tourists in wildfire scenarios. International Journal of Disaster Risk Reduction 113, 104836. https://doi.org/10.1016/j.ijdrr.2024.104836.
Lämmel, G., Grether, D., Nagel, K., 2010. The representation and implementation of time-dependent inundation in large-scale microscopic evacuation simulations. Transport. Res. Part C: Emerging Technology 18 (1), 84–98.
Lawrence P.J., Filippidis L., Veeraswamy A., Galea E.R., 2016. Utilising OpenStreetMap for Urban Evacuation Analysis. The 24th GIS Research UK (GISRUK) conference. London, UK.
Lindell, M.K., Kang, J.E., Prater, C.S., 2011. The logistics of household hurricane evacuation. Nat. Hazards 58 (3), 1093–1109. https://doi.org/10.1007/s11069-011-9715-x.
Lovreglio, R., Ronchi, E., Nilsson, D., 2015. A model of the decision-making process during pre-evacuation. Fire Saf. J. 78, 168–179. https://doi.org/10.1016/j.firesaf.2015.07.001.
Lovreglio, R., Ronchi, E., Nilsson, D., 2016. An Evacuation Decision Model based on perceived risk, social influence and behavioural uncertainty. Simul. Model. Pract. Theory 66, 226–242. https://doi.org/10.1016/j.simpat.2016.03.006.
Lovreglio, R., Kuligowski, E., Gwynne, S., Boyce, K., 2019. A pre-evacuation database for use in egress simulations. Fire Saf. J. 105, 107–128. https://doi.org/10.1016/j.firesaf.2018.12.009.
Marsella, S., Pozzi, D., Marzoli, M., dell'Interno, M., del Fuoco, C.N.D.V., Ferrucci, F., Filippidis, L., Lawrence, P., Veeraswamy, A., Garibaldi, C., 2019. Evacuation Planning as a Key Factor in Disaster Management: the contribution of the H2020 IN-PREP Action. In: Proceedings of the 10th International Multi-Conference on Complexity, Informatics and Cybernetics, (IMCIC 2019).
Mas, E., Suppasri, A.F.I., Koshimura, K., 2012. Agent-based simulation of the 2011 great east Japan earthquake/tsunami evacuation: an integrated model of tsunami inudation and evacuation. J. Nat. Dis. Sci. 34, 41–57. https://doi.org/10.2328/jnds.34.41.
Mileti, D.S., Sorensen, J.H., 1990. Communication of emergency public warnings: A social science perspective and state-of-the-art assessment, technical report for the federal emergency management agency. Washington. D.C. https://doi.org/10.2172/6137387.
Miller, C., Hilton, J., Sullivan, A., Prakash, M., 2015. SPARK–A bushfire spread prediction tool. In: International Symposium on Environmental Software Systems. Springer, Cham, pp. 262–271. https://doi.org/10.1007/978-3-319-15994-2_26.
Monedero, S., Ramirez, J., Cardil, A., 2019. Predicting fire spread and behaviour on the fireline, Wildfire analyst pocket: A mobile app for wildland fire prediction. Ecological Modelling 392, 103–107. https://doi.org/10.1016/j.ecolmodel.2018.11.016.
Needham, J., Fields, W., Lehman, W., 2016. The US Army Corps of Engineers scalable approach to estimating loss of life from flooding, FLOODrisk 2016, 3rd European Conference on Flood Risk Management. https://doi.org/10.1051/e3sconf/20160706003.
NFPA, 1616, 2020. Standard on mass evacuation, sheltering, and re-entry programs. National Fire Protection Association, ISBN: 9781455925216.
Oliveira, S., Rocha, J., Sa, A., 2021. Wildfire risk modeling. Current Opinion in Environmental Science & Health 23, 100274. https://doi.org/10.1016/j.coesh.2021.100274.
Purser, D.A., Bensilum, M., 2001. Quantification of behaviour for engineering design standards and escape time calculations. Saf. Sci. 38 (2), 157–182. https://doi.org/10.1016/S0925-7535(00)00066-7.
Ronchi, E., 2020. Developing and validating evacuation models for fire safety engineering. Fire Saf. J., 103020 https://doi.org/10.1016/j.firesaf.2020.103020.
Ronchi, E., Nilsson, D., 2016. Basic Concepts and Modelling Methods. In: Cuesta, A., Abreu, O., Alvear, D. (Eds.), Evacuation Modeling Trends. Springer International Publishing, pp. 1–23. http://link.springer.com/10.1007/978-3-319-20708-7_1.
Ronchi, E., Reneke, P.A., Peacock, R.D., 2014. A method for the analysis of behavioural uncertainty in evacuation modelling. Fire Technol 50 (6), 1545–1571. https://doi.org/10.1007/s10694-013-0352-7.
Ronchi, E., Gwynne, S.M., Rein, G., Wadhwani, R., Intini, P., Bergstedt, A., 2017. Open multi-physics framework for modelling wildfire urban evacuation. Fire Protection Research Foundation, Quincy, MA.
Ronchi, E., Gwynne, S.M.V., Rein, G., Intini, P., Wadhwani, R., 2019. An open multi-physics framework for modelling wildland-urban interface fire evacuations. Saf. Sci. 118, 868–880. https://doi.org/10.1016/j.ssci.2019.06.009.
Ronchi, E., Wahlqvist, J., Ardinge, A., Gwynne, S., Rein, G., Mitchell, H., Kalogeropulos, N., Kinateder, M., Bénichou, N., Kuligowski, E., Kimball, A., 2023. The verification of wildland–urban interface fire evacuation models. Nat. Hazards 117, 1493–1519. https://doi.org/10.1007/s11069-023-05913-2.
Ryan, B., 2018. Establishing information seeking pathways in slow and flash floods. Int. J. Disaster Risk Reduct. 31, 9–19. https://doi.org/10.1016/j.ijdrr.2018.04.005.
Senanayake, G., Kieu, M., Zou, Y., Dirks, K., 2024. Agent-based simulation for pedestrian evacuation: A systematic literature review ISSN 2212–4209. Int. J. Disaster Risk Reduction 111, 104705. https://doi.org/10.1016/j.ijdrr.2024.104705.
Smedberg, E., Kinsey, M., Ronchi, E., 2021. Multifactor variance assessment for determining the number of repeat simulation runs in evacuation modelling. Fire Technology 57 (5), 2615–2641. https://doi.org/10.1007/s10694-021-01134-w.
Solís, I.A., Gazmuri, P., 2017. Evaluation of the risk and the evacuation policy in the case of a tsunami in the city of Iquique, Chile. National Hazards 88, 503–532.
Sorensen, J.H., 2000. Hazard warning systems: review of 20 years of progress. Nat. Hazard. Rev. 1 (2), 120–125.
Takabatake, T., Shibayama, T., Esteban, M., Ishii, H., Hamano, G., 2017. Simulated tsunami evacuation behavior of local residents and visitors in kamakura Japan. Int. J. Disaster Risk Reduction 23, 1–14. https://doi.org/10.1016/j.ijdrr.2017.04.003.
Tolhurst, K., Shields, B., Chong, D., 2008. Phoenix: development and application of a bushfire risk management tool. The Australian J. Emergency Management 23, 47–54.
Tymstra, C., Bryce, R.W., Wotton, B.M., Taylor, S.W., Armitage, O.B., 2010. Development and structure of Prometheus: The Canadian Wildland Fire Growth Simulation Model, Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Information Report NOR-X-417.
US EPA, 2025. Acute Exposure Guideline Levels for Airborne Chemicals, Retrieved from https://www.epa.gov/aegl, Accessed March 2025.
Vaiciulyte, S., Hulse, L.M., Veeraswamy, A., Galea, E.R., 2021. Cross-cultural comparison of behavioural itinerary actions and times in wildfire evacuations. Safety Science 135, 105122. https://doi.org/10.1016/j.ssci.2020.105122.
Vaiciulyte, S., Hulse, L.M., Galea, E.R., Veeraswamy, A., 2022. Exploring 'wait and see' responses in French and Australian WUI wildfire emergencies. Saf. Sci. 155, 105866. https://doi.org/10.1016/j.ssci.2022.105866.
Veeraswamy, A., Galea, E.R., Filippidis, L., Lawrence, P.J., Gazzard, R, 2015. The Simulation of Urban-Scale Evacuation Scenarios: Swinley Forest Fire. 6th International Human Behaviour in Fire symposium. UK, London, pp. 221–232. https://doi.org/10.1016/j.ssci.2017.07.015.
Veeraswamy, A., Galea, E.R., Lawrence, P.J., Gallego, D.M., Blackshields, D., 2020. Global wildfire large-scale evacuation model, GEO-SAFE H2020 project 691161, final D2.6 report, https://fseg.gre.ac.uk/fire/geo-safe_files/D2.6_final.pdf.

Velotti, L., Trainor, J.E., Engel, K., Torres, M., Myamoto, T., 2013. Beyond vertical evacuation: Research considerations for a comprehensive "vertical protection strategy". Int. J. Mass Emerg. Disasters 31 (1), 60–77.
Wahlqvist, J., Ronchi, E., Gwynne, S.M.V., Kinateder, M., Rein, G., Mitchell, H., Bénichou, N., Ma, C., Kimball, A., Kuligowski, E., 2021. The simulation of wildland-urban interface fire evacuation: The WUI-NITY platform. Saf. Sci. 136. https://doi.org/10.1016/j.ssci.2020.105145.
Wahlqvist, J., Ronchi, E., Gwynne, S., Kinateder, M., Rein, G., Mitchell, H., Benichou, N., Chunyun, M., Kimball, A., Kuligowski, E., 2021. The simulation of wildland-urban interface fire evacuation: the WUI-NITY platform. Safety Science 136, 105145. https://doi.org/10.1016/j.ssci.2020.105145.
Winston, W.L., 2000. How many trials do we need? Simulation Modeling Using @RISK. Duxbury Press, 978-0534380595.
Zhang, R., Liu, D., Du, E., Xiong, L., Chen, J., Chen, H., 2024. An agent-based model to simulate human responses to flash flood warnings for improving evacuation performance. Journal of Hydrology 628, 130452. https://doi.org/10.1016/j.jhydrol.2023.130452.