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Evacuation modelling for rapid multi-hazard tabletop exercise deployment

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ABSTRACT

To prepare for large-scale emergencies and crisis affecting communities, authorities, and emergency commanders use several types of training methods ranging from seminars to full-scale exercises. Within this continuum of exercise types, tabletop exercises (TTXs) are habitually used to familiarise participants with mitigation strategies, population management and evacuation procedures conducted as a response to natural or technological hazards. Commonly, TTXs are paper-based, and if computerised, use basic electronic maps, tend to be scripted and have a linear nature. Information flow is unidirectional as the script dictates how the exercise unfolds. These exercises have little capacity for producing qualitative or quantitative feedback related to the impact that the received scenario injects (i.e., incoming messages including scripted events and hazard locations), the authorities' decisions, and the impact of hazards have on the wellbeing of the community and the evacuation process. While informative during training, this type of feedback may prove vital in assessing the likely impact of real incident. In this work an evacuation simulation model is proposed to augment the TTX experience in real time, offering feedback and insights on the impact that such injects, decisions and hazards have on the simulated community.

The proposed methodology is utilised in an actual TTX co-organised and executed by the Municipality of Rhodes, Greece, where the evacuation model is used to (a) develop the standard, non-incident specific evacuation procedures for the Medieval City of Rhodes (MCR), (b) to adapt these procedures based on the injects (generated on-site or telecommunicated, emulating receipt from the field), producing the TTX scenario and (c) to provide information on the impact that the TTX hazards have on the evacuation process. The integration of evacuation modelling into the TTX process demonstrated that it is possible to gain a deeper understanding of the complexities related to route choices in response to path closures, the assembly and evacuation performance, as well as the management of the simulated incident by analysing qualitative and quantitative simulation results.

1. Introduction

Preparing for emergencies that involve large-scale evacuations requires that authorities and emergency commanders use several types of training methods ranging from seminars to full-scale exercises. Within this continuum of exercise types (Edzén, 2014; US Department of Homeland Security, 2006, 2020), tabletop exercises (TTXs) are habitually used to familiarise participants with mitigation strategies, evacuation procedures and population management.

TTXs are particularly suitable for assessing emergency plans. Their main goal is to identify and determine various weaknesses, problems, oversights, or overlaps associated with the roles and responsibilities of the involved stakeholders or organisations. TTXs can also be used to determine the adequacy of guidelines, the systems and methodologies used during an incident, with a focus mainly on coordination and collaboration issues (US Department of Homeland Security, 2006, 2020; ISO Copyright, 2013).

Commonly, TTXs are typically paper-based and follow a script written as a narrative of simulated events (ISO Copyright, 2013) that may include injects assumed to be received from the field (US Department of Homeland Security, 2006, 2020). These injects correspond to scripted events, simulated information such as issues and problems and

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have the form of incoming messages (e.g., simulated text messages, phone calls, social media posts, etc.). These injects may steer the scenario beyond its initial script. When computerised, TTXs, typically use basic electronic maps, weather, or hazard model data, but still remain scripted. However, the information flow is mainly unidirectional, as the script or injects (that augment the scenario), dictate how the exercise will ultimately unfold. These exercises have little capacity for determining or producing feedback to the participants related to the impact that the received scenario injects, the effect of decisions taken, and the effect hazards have on the evacuation process. Currently there is a lack of tools that can be readily used for accommodating scenario injects and assessing the impact that hazards have on large populations, how large-scale evacuations are likely to be affected and how they are likely to unfold.

In this work an evacuation simulation model (Lawrence et al., 2016, 2020; Filippidis et al., 2020; Chooramun et al., 2019, 2012; Veeraswamy et al., 2015, 2018; Galea et al., 2017; Grandison et al., 2017) is proposed to augment the TTX experience during its execution. The evacuation model offers feedback to the exercise participants regarding the consequences that the TTX injects have on the simulated community (e.g., scenario specific events and the occurrence and location of hazards), or the decisions made by crisis managements (e.g., enforcing closure of exit routes) or the impact that hazards have on the wellbeing of the simulated community. The feedback provided by the evacuation model includes both qualitative and quantitative information such as the population's travel rates, congestion levels, the assembly and evacuation times, the exit route usage, and the level of injury or number of fatalities due to hazard exposure (Razzetti, 2019; Araz et al., 2012).

The purpose of the work presented in this paper is two-fold, namely (a) to demonstrate the use of the urbanEXODUS evacuation simulation tool in representing existing, non-incident specific evacuation plans for the Medieval City of Rhodes (MCR), Greece (Medieval City of Rhodes, 1988; Medieval Town of Rhodes., 2012), and (b) the use of urbanEXODUS as a rapidly deployed tool, during the TTX, to represent the incident's conditions. The model accommodates the necessary modifications to pre-existing emergency base plans, as a response to injects generated on-site or assumed to be received from the field. Thus, producing the simulated TTX scenario and demonstrating the benefits that such models provide to crisis managers (Razzetti, 2019; Araz et al., 2012; Marsella et al., 2019). It is anticipated that modelling the evacuation aspect of the TTX will help improve the participant's training as they will gain a deeper understanding of the intrinsic complexities of the TTX scenario. The likely evolution and quantification of the evacuation process will help to improve the preparedness and response capabilities of the participants, which may enhance their decision processes during real incidents (Lawrence et al., 2020; Razzetti, 2019; Marsella et al., 2019).

Furthermore, as the evacuation model quantifies central aspects of the evacuation process, it facilitates in meeting the exercise performance objectives mentioned in ISO 22398 (ISO Copyright, 2013). These objectives include increasing awareness of vulnerabilities, highlight the importance of effective crisis plans, the enhancement of situational awareness and acquisition of incident-specific knowledge, examination and evaluation of new strategies and evacuation procedures (ISO Copyright, 2013; Shari et al., 2012). Furthermore, it aids in the planning of full-scale exercises (FSXs) as it can provide necessary quantifiable information for the design of full-scale exercises (e.g., estimating the required resources to provide medical care for survivors, allowing enough space for the assembly process to complete, etc.). This will enable the FSXs to adapt representative requirements, better reflect reality and contribution to the improvement of interoperability between crisis management agencies (ISO Copyright, 2013).

Given its location, the MCR, is potentially vulnerable to a variety of hazards including earthquakes and tsunamis. Mitigating these risks requires preparedness which should include evacuation strategies and procedures that allow, when necessary, for the efficient and safe movement and transfer of people to safety. The proposed solution provides insights and feedback from the rapidly deployed evacuation simulation. The simulation determines the impact that procedural adaptations (due to fear of tsunami and subsequent unavailability of exit gates), building collapses (due to an earthquake), blocked escape paths (due to debris from collapsed buildings), and the presence of fire at one of the gates, have on evacuation movement, and performance. Without the use of simulation tools quantifying important aspects of the TTX scenario it would be difficult for incident managers to evaluate the combined effect produced by the characteristics of the urban layout, the population, the evacuation procedures, the hazards and the injects generated on-site or assumed to be received from the field, on the overall evacuation performance.

2. Background

Incident managers are expected to be able to deal with any probable incident caused by a natural or technological hazard in their area of jurisdiction. For example, in a flood-prone area they need to be prepared and be able to deal with the intricacies of flooding incidents. In a wildfire prone area, they need to be prepared and be able to deal with wildfire incidents. Additionally, they need to be prepared and demonstrate resilience not only to single events but also to cascading events, as well as to the event complexity during disasters (Shari et al., 2012).

To better prepare for these eventualities, key personnel involved in mitigation measures such as local authorities, incident and emergency commanders, and first responders, may resort to several types of training exercises (Edzén, 2014; US Department of Homeland Security, 2006, 2020). These exercises allow the players to familiarise themselves with the roles and responsibilities that they will have to assume and fulfil in a multi-agency and collaborative manner during an actual incident. Furthermore, exercises are used to identify shortfalls and flaws in existing policies and procedures and amend and update operational procedures.

Training exercises fall within two broad categories (US Department of Homeland Security, 2020); *discussion-based* and *operational-based* exercises (see Fig. 1). For large-scale incidents that involve the management and evacuation of large populations it is practically and ethically not possible to conduct drills or full-scale exercises that involve large numbers of civilians. Thus, in this case, discussion-based approaches are more common.

Tabletop exercises (TTXs), the main theme of this work, fall within the discussion-based category. A TTX provides a safe environment in which participants are engaged in the process of mitigating a hypothetical but plausible hazardous scenario and timeline. Participants review, discuss, identify flaws, and provide solutions to problems as they arise, and act as they would be expected to act, during a real incident. Overall, a TTX helps visualise and comprehend the flow of events and actions taken as a response to a crisis (Austere et al., 2022). Traditionally, TTXs were not conducted with time pressure (i.e., were not run at real time) and were fully paper-based. However, this approach has been enhanced through developments that allow for GIS and hazard models to augment traditional TTXs. As a result, the fidelity and realism of the TTXs is increased. Furthermore, these enhancements enable the TTXs to be conducted in a near real time environment thus adopting a hybrid approach utilising features of operations-based and game exercises too (ISO Copyright, 2013). In this approach the simulation models that are used offer estimations on the outcomes and duration of events and processes that are emulated during a TTX (e.g., flood or wildfire evolution) (ISO Copyright, 2013; Filippidis et al., 2020; Veeraswamy et al., 2018; Marsella et al., 2019; Austere et al., 2022). While this approach increases the complexity of the exercise it still offers a safe training environment while increasing fidelity (US Department of Homeland Security, 2020; Razzetti, 2019; Araz et al., 2012), realism and emulating the time pressures of real incidents. However, the duration of processes that involve the population movement and behaviours, such as the

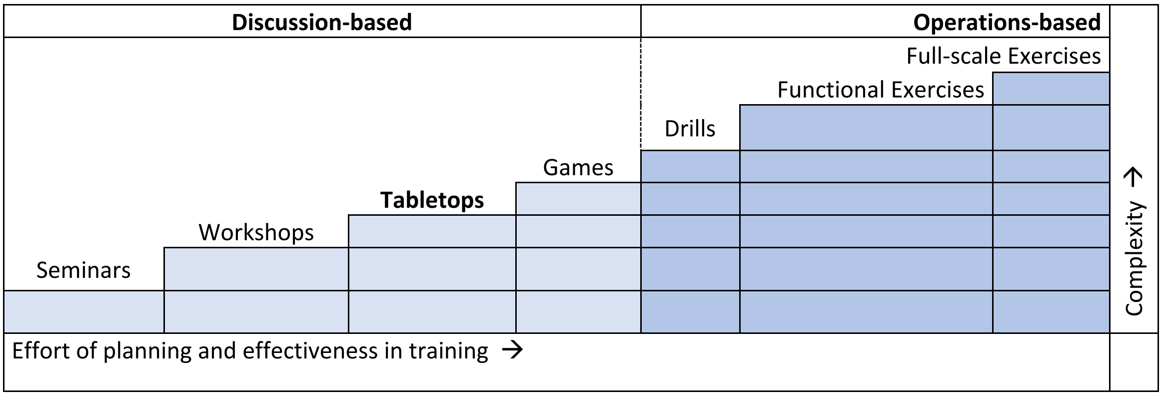


Fig. 1. Exercise types indicating effort of planning, effectiveness in training and their corresponding complexity (image adapted from US Homeland Security Exercise and Evaluation Program, Volume 1: Overview and Exercise Program Management, Revised March 2006 (US Department of Homeland Security, 2006).

assembly or evacuation process, or the impact of hazards on the population, are currently only based on the TTX coordinator's subjective estimates (if considered at all). Estimating the duration of these processes when not based on engineering tools, may therefore include subjective errors resulting from the participants' knowledge or past experiences that may be scenario or region specific. These miscalculations can lead to cumulative discrepancies in the temporal dimension of the TTX.

In this paper a further enhancement of TTX deployment is proposed by augmenting the current TTX paradigms to incorporate an evacuation simulation model to address the lack of information regarding how people behave during emergency situations and how the assembly and evacuation processes are likely to unfold. By adding the human element into the TTX environment, and in conjunction with other modelling tools that are habitually used (e.g., weather predictions, hazard spread models), estimates on hazard impact, vulnerability, and population management can be forecasted. This offers insights that traditionally are not available in paper-based TTXs (US Department of Homeland Security, 2020; Razzetti, 2019; Araz et al., 2012). Modelling tools offer advantages over paper-based methods in terms of, results obtained, number of scenarios examined, access to calculated forecast data, the estimation of the temporal dimension of TTX processes, and the ability to aid incident managers in making informed decisions (Marsella et al., 2019). As the TTX processes are estimated more accurately the projected time when these processes start or end can be incorporated into the TTXs timeline, thus, the TTX's events can take place at a more representative timeframe.

Furthermore, the modelling results can greatly contribute to the evaluation of a TTX, i.e., during debriefing (for facilitators and controllers) or during the hotwash meeting (US Department of Homeland Security, 2020; Razzetti, 2019) between the exercise players where practitioners discuss weaknesses or strengths of the exercise. This evaluation process becomes even more important when complex scenarios and cascading effects are addressed (US Department of Homeland Security, 2006, 2020; ISO Copyright, 2013). More specifically as the evacuation simulation results quantifies critical aspects of the TTX, including for example, assembly location usage, exit route usage, number of casualties, assembly times, evacuation times, congestion levels, etc., these results can aid in the overall evaluation of the TTX.

3. Methodology

The evacuation simulation model used for this study is urbanEXODUS (Lawrence et al., 2016, 2020; Filippidis et al., 2020; Chooramun et al., 2016, 2019; IDIRA, 2015; Fraunhofer, 2015; Gallego et al., 2019; Hulse et al., 2020; Veeraswamy et al., 2020), a variant of the EXODUS Agent Based Model (ABM) (Chooramun et al., 2019, 2012; Veeraswamy et al., 2018; Galea et al., 2017; Grandison et al., 2017) that has been specifically modified to allow for large-scale, multi-modal, and multi-hazard rural and urban scale evacuation simulations (Lawrence et al., 2016; Filippidis et al., 2020, 2023; Veeraswamy et al., 2015, 2018). The software takes into consideration people-people, people-hazard, and people-outdoor environment interactions. The model tracs the trajectory of each individual agent from their current location to a location of safety unless they become trapped or overcome by a hazard (e.g., building collapse, wildfire, chemical spill, etc.). The behaviour and movement of each agent is determined using set of rules. These rules are grouped into several submodels including the *Agent*, *Movement*, *Behaviour*, *Hazard*, and *Toxicity* submodels. These submodels operate on a region of space defined by the *Geometry* submodel that is responsible for representing the layout of the studied area that includes the space that the agents can freely walk on, and the road network. Within urbanEXODUS the population is represented as a collection of individual agents where each agent is defined by a set of physical (e.g., age, gender, walking speed, agility, mobility), psychological (e.g., response time, patience, drive, disorientation due to fire hazards), physiological (e.g., respiratory rate, resilience to hazards, impact of narcotic and irritant gasses, impact of heat) and experiential (e.g., distance travelled, travelling time, time wasted in congestion) attributes.

When a population is generated, each agent's attributes are assigned values that are randomly selected from within pre-set ranges. Each agent can have their own evacuation agenda (e.g., forming groups with relatives, communicating with other agents, or following itineraries before commencing the evacuation) or follow the currently defined evacuation procedure. Spatial representation is based on OpenStreetMap data (Lawrence et al., 2016) that is used to generate a fine grid of nodes that the pedestrians can use to move on and navigate. The road and foot-path network are meshed using this fine grid of nodes while the structures present within the area are represented as coarse nodes with only the occupancy and flow out of the structure being represented. If hazard data (e.g., fire data) has been included into the model then the software determines the physiological response to the hazard based on each agent's attributes. The simulated scenario can be modified during runtime (e.g., assigning new itineraries to a group of agents, closing of exits, blocking of exit routes or regions, etc.) 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.).

The urbanEXODUS software is stochastic in nature, meaning that variation in the output results can be observed as multiple simulations are run. This stochastic nature is inherited from the core EXODUS model and is due to two main aspects of the model (a) the population generation where each agent is assigned their own unique set of attributes, and (b) the decisions that the individuals take during their movement and egress from an area especially when encountering congestion. During the simulation, the agents do not perform the same actions every time they interact with other agents or with their surrounding environment. For example, when agents that are equally driven to evacuate compete for the same location a stochastic decision is made to resolve this conflict. Also, in situations when two or more moves provide an equal benefit to the agent then the selected option is randomly selected.

The urbanEXODUS tool can simulate the evacuation of large populations (measured in the tens or hundreds of thousands) from large-scale environments (measuring many square kilometres).

In terms of output results, urbanEXODUS produces a plethora of output data including both quantitative (e.g., number of agents evacuated) and qualitative data (e.g., evacuation graphs). This data is generated in several formats. It produces visual representations including depictions of the entire evacuation process showing the movement of the agents towards the assembly and exit locations, population density contours or regions that have reached critical densities during the evacuation. It produces numerical data including, but not limited to, the time required for pedestrians to reach refuge locations or exit points, the usage of assembly locations and exit routes, the average distance travelled, the time that agents remained stationary due to congestion, the distance travelled, the impact that hazards have on the pedestrians and the number of agents that were trapped due to the presence of hazards. It can also generate GIS data such as shapefiles representing the movement of the population that can be displayed on web-based GIS applications. This feature allows urbanEXODUS to be integrated with mixed reality training platforms and C2 systems for training, preparedness and incident management tasks as demonstrated during the EU Horizon 2020 project IN-PREP (Marsella et al., 2019; IN-PREP, 2021). In this work urbanEXODUS is used prior to a TTX to simulate the standard evacuation procedures for the Medieval City of Rhodes, and thereafter during the TTX to adapt these procedures based on the received injects (i.e., information generated on-site or assumed to be received from the field) to simulate and demonstrate the actual TTX scenario.

The software can be used during the pre-incident planning phase by allowing the user to examine numerous *what-if* evacuation scenarios (Marsella et al., 2019). The incident managers can thus make decisions based on forecasts and information that is difficult, if not impossible to obtain using any other means. The national emergency management plans for seismic risk developed by the Hellenic Ministry of Civil Protection (General Secretariat for Civil Protection et al., 2020), states that the country's Municipalities' services and first responder organizations (e.g., the Hellenic Fire Service) place, as expected, human life as their top priority. Additionally, these organizations have the responsibility of assessing both the extent of human injuries or losses and the needs of individuals requiring medical care during a disaster. The quantification of evacuation performance and hazard impact through modelling can facilitate this requirement and can furthermore be used to assess and take appropriate actions to maintain an organisation's response structure during disruptive incidents (ISO Copyright, 2019).

4. Demonstration case

On 15 November 2019, an advanced tabletop exercise (TTX) (US Department of Homeland Security, 2006), part of Rhodes Project 2019 co-organised by Rhodes Municipality and the Postgraduate Program "Environmental, Disasters, and Crisis Management Strategies" (Postgraduate Program: Environmental, Disasters, and Crisis Management Strategies., 2023) of the National and Kapodistrian University of Athens, was held at the *Inn of the Tongue of Spain*. The participants consisted of local authorities including, first responders, civil protection organisations, the fire service, and the emergency and medical response services.[2]

The main theme of the TTX was *Major intensity earthquake and the management of emergency conditions*. The TTX involved events that were assumed to be taking place all over the island of Rhodes, however, for this paper, only those events that supposedly took place within the fortifications, and therefore those that affected the Medieval City of Rhodes and its population, are considered.

The Medieval City of Rhodes (MCR) is located at the northern part of the modern city of Rhodes, which in turn is located at the northern tip of the Rhodes Island in Greece. It has a history spanning several millennia during which it has transformed significantly in terms of population, strategic importance, size, layout, and defensive fortifications. Fortifications were being built up to the 16th century forming the current walls of the city. These fortifications completely surround the city, while nine gates provide access to and from the newer capital of the island that surrounds the MCR.

The main events of the TTX that affected the Medieval City are (a) a 6.8R earthquake with an epicentre 25 km north-northeast of the city, (b) the collapse of two historical buildings at 8 and 12 min after the earthquake, (c) an official warning for possible tsunami reaching the MCR, and (d) a fire at one of the gates along the fortifications at 36 min after the earthquake blocking the evacuation from that location. The timeline of these events is depicted in Fig. 2.

For the purposes of this TTX the urbanEXODUS evacuation simulation software was used to develop the necessary evacuation scenarios for the MCR. The urbanEXODUS software was used in two ways. First, prior to the TTX to computerise the existing paper-based, non-incident specific evacuation procedures. The resultant simulated scenario was demonstrated prior to the execution of the TTX. The purpose of this demonstration was to offer insights to the participants on how the emergency procedures would likely work as if a basic full-scale drill was run. Secondly, urbanEXODUS was used during the TTX to rapidly deploy the incident-specific evacuation procedures and processes accommodating the injects, events and incidents, which took place during the TTX. The aim was to add realism to the TTX, examine the consequences that the intrinsic characteristics of the TTX had on the simulated population and the evacuation process, to receive feedback from the simulation in terms of population movement and behaviour, and to assess the viability of the tool in representing existing and incident-specific, *what-if* scenarios.

The area that is of interest and therefore modelled corresponds to what exists within the city's fortification walls, with all its footpaths, roads, open spaces, and structures. The spatial information that is used to create the city's layout, within the software, is retrieved from OpenStreetMap (OSM) (see Fig. 3). The map of the MCR is imported into urbanEXODUS and the model is prepared (i.e., meshed with a fine nodal grid) to allow the evacuation simulation to be conducted. The approximate area of the MCR covers 0.48 km^2 with a perimeter of approximately 3.1 km.

Due to the nature of OSM data (i.e., its primary use is for displaying maps, data on maps, navigation) it does not represent the most dependable or complete map data for evacuation modelling purposes. However, it is readily available and has an open access license and therefore it is free for use and suitable for demonstrating concepts (Lawrence et al., 2016). However, a significant amount of data required

[2] The full list of participants included the Independent Civil Protection Office of Rhodes Municipality, the local Authorities of Hellenic Fire Brigade, Hellenic Coast Guard, Hellenic Police, Hellenic National Emergency Centre, and Hellenic Civil Aviation. It also included the British Consulate in Rhodes, the Ephorate of Antiquities of Dodecanese, the Earthquake Planning and Protection Organization of Greece and local Voluntary Organizations.

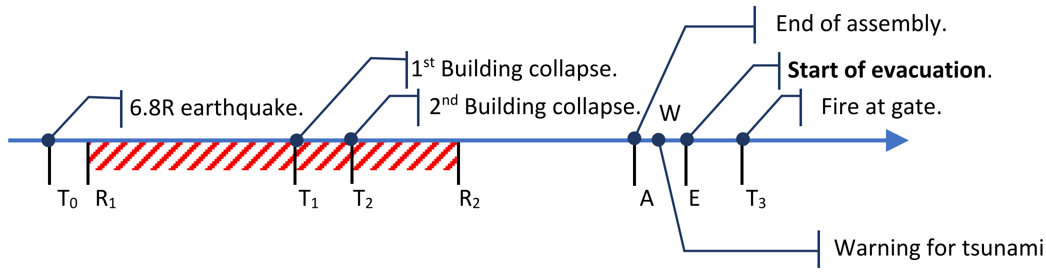


Fig. 2. Timeline of events T0 is 10:30, T1 and T2 are at + 8 and + 12 min respectively, T3 is at + 36 min. The hatched area bounded by R1 and R2 at + 1 and + 15 min indicate the response time of the agent prior to commencing the assembly process and then the evacuation (Timeline not in scale).

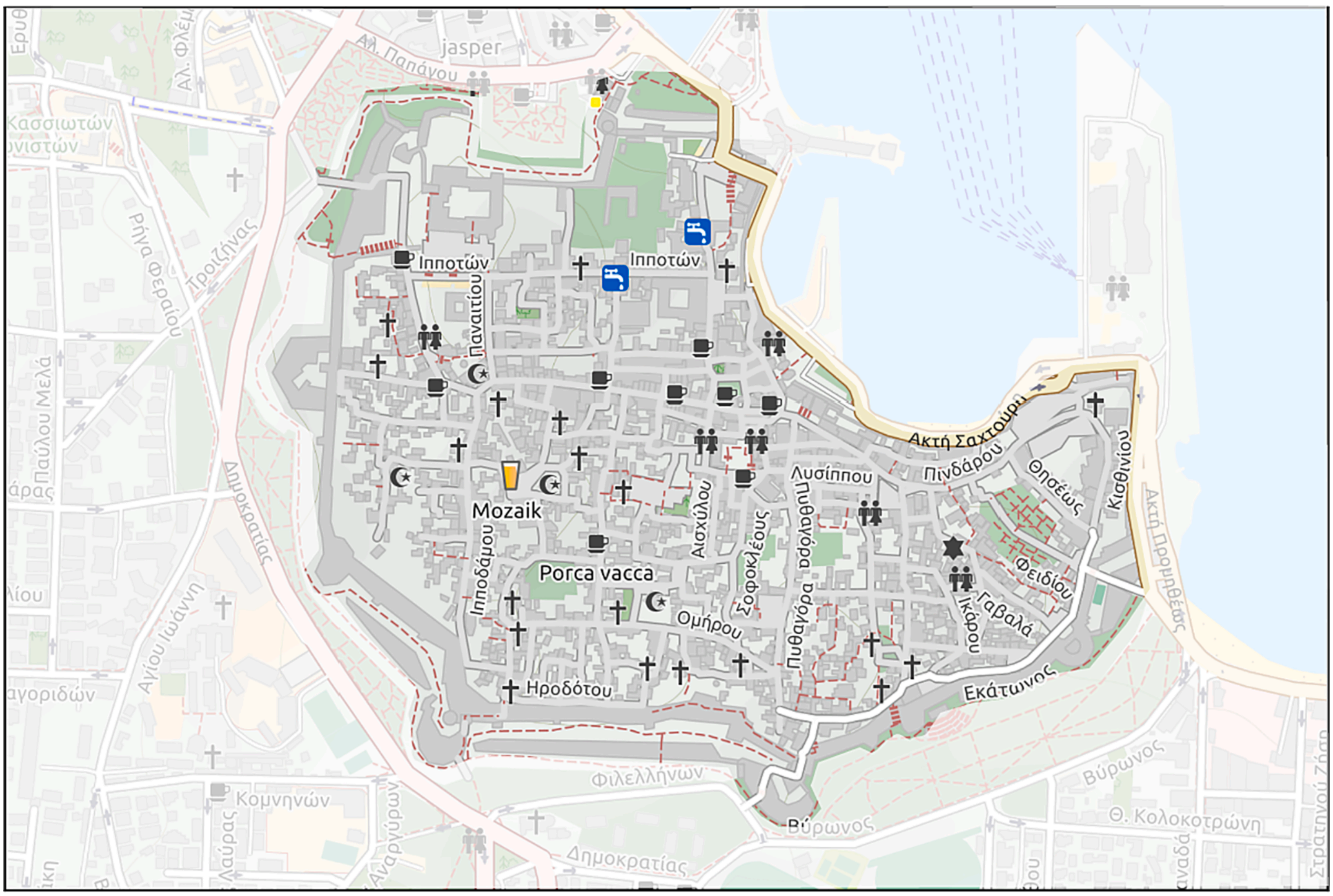


Fig. 3. Map of Medieval City of Rhodes as represented by OpenStreetMaps November 2019.

by evacuation models is missing from OSM data. The missing data includes the location of pavements, width of roads, location of exits from buildings, connectivity of open spaces with roads and paths, etc. In essence, what is missing is the continuous and unobstructed spatial information regarding the available space that pedestrians can occupy, navigate on, and use to leave the area. Wherever possible this information is manually incorporated into the imported map using publicly available satellite imagery as an aid (e.g., Google maps and Google Earth). However, in the case of the MCR, the space is mainly pedestrian and the OSM road network completely represents this area (i.e., the area that the agents can use to navigate). Furthermore, all buildings are well defined within the OSM dataset. This is because OSM data is generally more detailed for major touristic locations or world heritage sites. Therefore, minimal editing was required to construct the spatial model for the MCR. This work involved mainly the connection of large open spaces such as town squares and car parks to the road network.

The population of the MCR varies significantly depending on the season. The date and time of the TTX incident is assumed to be during the off-peak, early winter, season. The total population of the city at this period was assumed to be 6000 people (which corresponds approximately to the actual population of the area during the month of November). Given that no information was provided regarding the actual population distribution by the Municipality it was assumed that this population was uniformly distributed across the city (Argyris, 2019; Lekkas, 2019). It was also assumed that 30 % of the population would occupy the buildings while 70 % would be located on the paths, roads, or open spaces (Argyris, 2019; Lekkas, 2019). However, the software can import accurate population data with granularity to the level of each structure (i.e., number of occupants and demographic information) (Marsella et al., 2019).

As mentioned earlier the city is completely enclosed by fortifications. Nine gates allow for movement in and out of the city. The locations of the gates that allow the population to leave the area are shown in Fig. 4. Most gates are located near the sea front. Furthermore, nine assembly locations have been identified (Argyris, 2019; Lekkas, 2019) within the MCR. The locations of the assembly points are shown in Fig. 4, along with the catchment area that corresponds to each assembly location. It is assumed that in the case of an emergency, safety marshals will be deployed throughout the city providing guidance to the public regarding the location of the assembly locations and the gates to use if and when an evacuation is deemed necessary. These marshals are primarily responsible to accommodate those that are not familiar with the evacuation procedures or the layout of the city, for example tourists. It is also assumed that the evacuation plans are known to the population via announcements, signs, and other means.

5. Scenarios

In this work two scenarios are examined, the first, the base-case scenario, constitutes the generic, non-incident specific protocol that should be adhered to in the case of an emergency. The synopsis of the base-case scenario can be stated as follows: *in case of emergency first assemble and then, if deemed necessary, evacuate the MCR using your nearest gate*. The second, an adaptation of the base-case scenario, represents the incident-specific scenario as it unfolded during the TTX.

Implementing the emergency protocol using the evacuation model required some assumptions to be made and agreed with the organisers of the TTX. These assumptions are listed in Table 1. The assumed agents' knowledge, movement and behaviour is listed in Table 2. These assumptions include physical abilities, familiarity with MCR and the evacuation procedures, as well as social behavioural aspects adopted by

Table 1
The demographic characteristics of the populations used in the examined scenarios.

Total population [Males/ Females]	**Age** Average [min – max]	**Travel speeds** (m/s) Average [min – max]	**Response Time** (min.) Average [min – max]	**Mobility**
6000 3600/2400	46 [17–80]	0.92 [0.85–1.5]	8 [1–15]	All able bodied

Table 2
Agents' knowledge of the layout of the Medieval City of Rhodes (MCR), their familiarity of the emergency procedures and their implications to the agent's movement and behaviour.

Agent knowledge and agent behaviour	**Familiarity**	**Implication**
Emergency procedures	Full	Agents observe the emergency procedures.
Navigation routes	Full	Agents adopt shortest routes during navigation within the MCR.
Assembly locations	Full	Agents aware of nearest assembly location and shortest paths to reach it.
Location of Gates	Full	Agents aware of all gates and shortest paths to reach their nearest available gate.
Social behaviour	No group behaviour	Each agent evacuates as an individual. Social or familial groups are not formed before the evacuation commences.

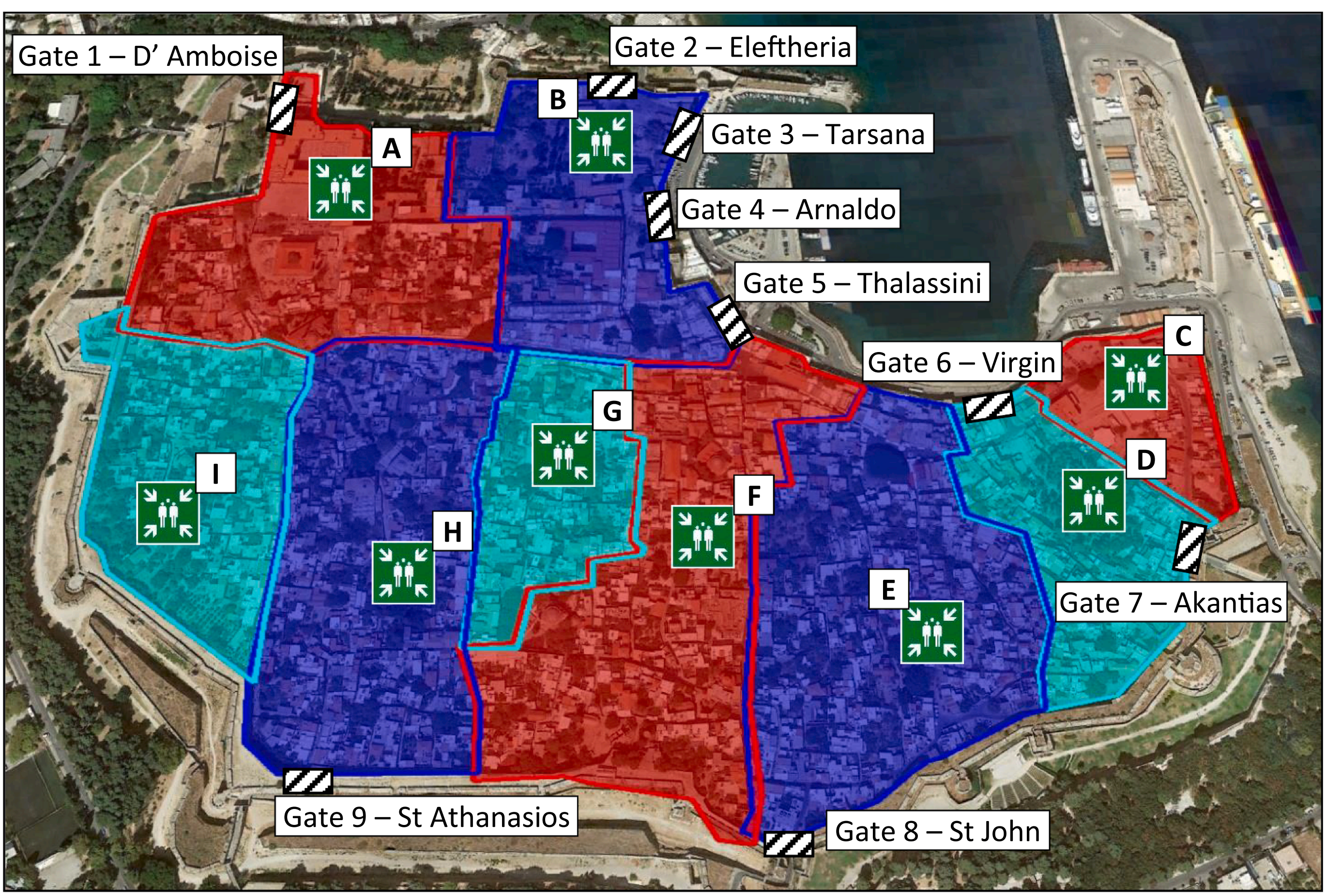


Fig. 4. Assembly locations within the Medieval City of Rhodes (MCR). The polygons denote the catchment areas of each assembly location. The location of the nine gates leading out of the MCR are also shown on the map.

the agents. These assumptions are also mentioned in the following sections where the simulated scenarios are examined more closely (i.e., sections 5.1 and 5.2).

5.1. Base-case scenario: non-incident specific evacuation procedures

A set of generic, non-incident specific evacuation procedures exist for the MCR that are employed in the case of an emergency and when an evacuation is deemed necessary. Those emergency procedures dictate that the population, upon notification or instruction, should first move to their designated assembly locations and await there for further instructions. For some hazards, the hazard event constitutes the notification. For example, in the case of a significant earthquake, it is assumed that the earthquake is the notification event, and that the population will start moving towards the assembly locations once the earthquake is over. If the authorities deem that the city needs to be fully evacuated then, once the assembly process has been completed, they instruct the population to move towards their nearest available gate by which they can leave the area (see Fig. 4). This non-incident specific scenario forms the base protocol upon which updated, incident-specific, procedures are employed during an actual emergency as the authorities consider the peculiarities of the incident and hazard. For example, the effects of a hazard may result in some routes, assembly locations or gates becoming blocked or unavailable preventing the residents from using them. In such circumstances, the evacuation procedure needs to be adapted to the new developments and requirements.

5.2. TTX scenario: earthquake

The purpose of the TTX was to allow the stakeholders to engage in a multi-hazard disaster response activity and to manage and mitigate a hypothetical and simulated disaster scenario affecting the entire island of Rhodes. Both the response plan and the actions of the participants would be assessed for their effectiveness in mitigating the effects of the hazards. However, this assessment and its result are beyond the scope of this work. Due to the objectives of this research, as stated in the introduction, only the events that affect the population and structures within the Medieval City are considered.

The TTX organisers assumed that on the day of the incident a major earthquake took place at 10:30am with an intensity of 6.8 on the Richter scale. The epicentre was located in the sea region 25 km north-northeast of the Medieval City of Rhodes (MCR). The time of day that the

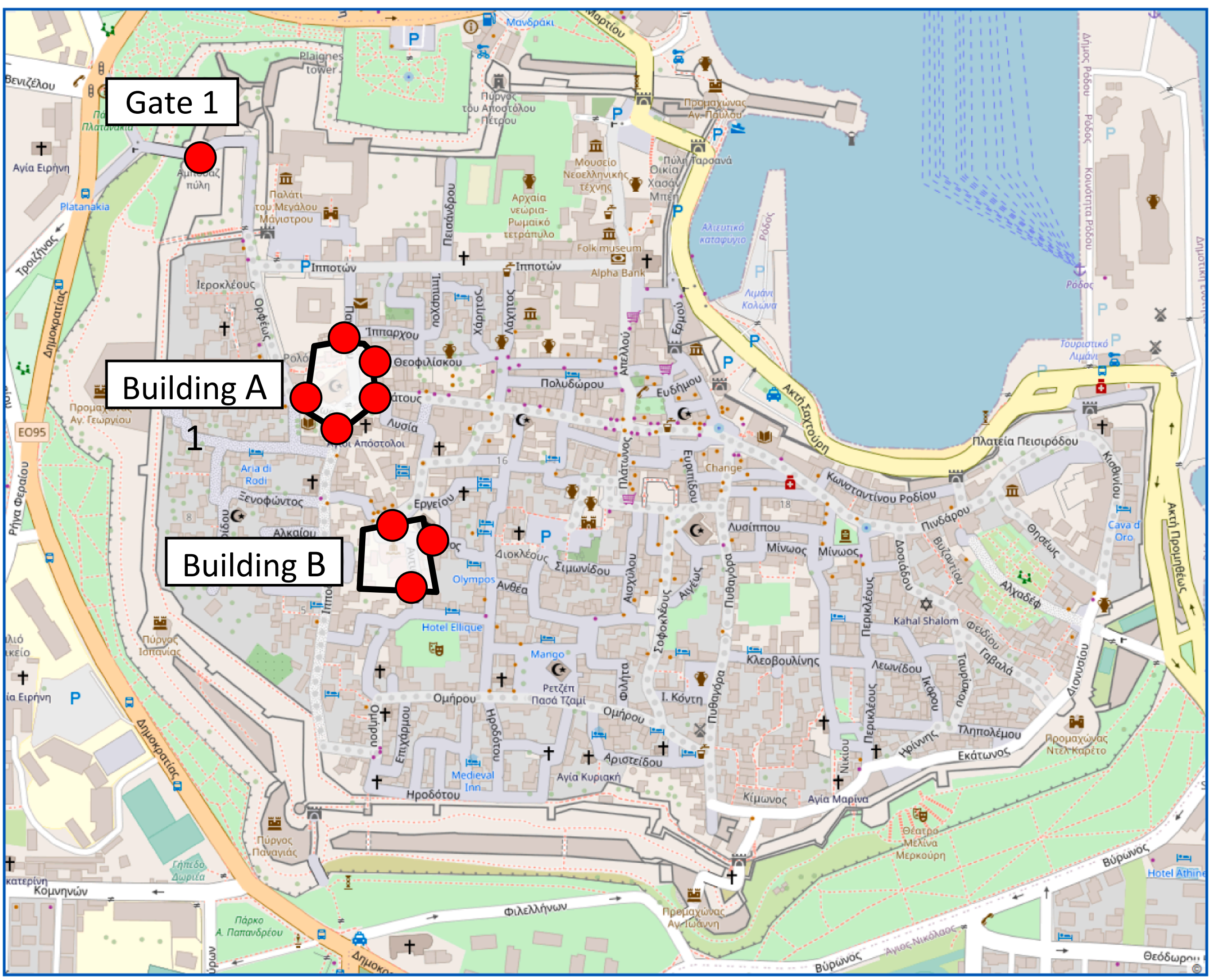


Fig. 5. Building A collapsed at 8 min after the earthquake, Building B collapsed at 12 min after the earthquake, Gate 1 became blocked due to fire at 36 min into the scenario. The red dots indicate the blocked routes that occurred at those times. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

earthquake strikes means that the population became fully aware of the hazard. The earthquake acts as the notification event to commence the protective measures by adopting the evacuation procedures. It is also assumed that the population is aware that after a significant earthquake strike, they need to move to their designated assembly location. This is not an unreasonable assumption, as Greece is an earthquake prone zone and seismic education takes place from an early stage (i.e., starting at nursery and primary school). Nevertheless, the model is flexible enough to simulate specific notification methods to be employed, such as door-to-door notification, phone and SMS, radio, and television, social media, etc (Edzén, 2014). The response time of the agents is assumed to range from 1 to 15 min from the time the population becomes aware of the earthquake (Argyris, 2019; Lekkas, 2019). The evacuation process is assumed to commence after the earthquake ends and once the response time of each individual agent elapses. While vehicles are allowed within the MCR the evacuation procedure states that vehicles should not be used during an emergency as their use my cause significant traffic blockages hindering the evacuation process. Thus, the population moves, by foot, towards their designated assembly locations and waits there for further instructions. However, the earthquake also affected the city by causing damage to historical buildings at various levels.

Two historical buildings are reported to have collapsed, the first at 10:38am and the second at 10:42am (see Fig. 5) trapping several residents inside them as well as in the adjacent paths. The foot paths in the vicinity of the collapsed buildings are thus assumed to be inaccessible and therefore blocked for access. The non-trapped pedestrians need to navigate around these areas to assemble and thereafter leave the city. A command to fully evacuate the city is issued at 11:00am. By this time, the assembly process is complete. Given the location and proximity of the epicentre, a tsunami warning is also issued at this time. The gates facing the waterfront are deemed unsuitable for evacuation purposes and cannot be used due to the posed risk. This means that gates Gate 2 to Gate 7 cannot be used for evacuation. Consequently, only three of the nine gates are available for leaving the MCR, those are Gates 1, 8, and 9.

At 11:06am the presence of fire is reported in the vicinity of Gate 1 deeming it unavailable from that point onwards (see Fig. 5). While a number of pedestrians would have managed to escape by this time from that gate any further arrivals at that gate are redirected to their nearest alternative gate, which is Gate 9, located approximately 800 m away, at the South part of the city. For the purposes of the TTX it is assumed that the population is aware of their nearest assembly location, nearest gate, and nearest alternative gate if their assigned gate becomes blocked. These are assumptions that are true for the paper-based TTX too, however, the evacuation model is flexible to allow the representation of reduced familiarity with the layout of the town and thus allows for agents to take non-optimal paths and evacuate through a gate that is not the closest to them.

The specifics of the TTX scenario (i.e., hazard types, locations and intensities, event times, building collapses, etc.) were dictated by the TTX organisers. The authors of this work had no input or control over this aspect of the TTX as they did not want to influence the organisers tailoring their decisions to better suit the evacuation model.

6. Results

The results of the two scenarios are described and presented in the following two sections.

6.1. Base-case scenario results

In order to obtain a good estimate of the evacuation time an arbitrary number of simulations were initially run, 50 in this case. After conducting statistical testing, it was determined that this number was more than enough to obtain a 95 % confidence interval on the mean value of Total Evacuation Time (TET) with a 5 % margin of error (Grandison, 2020; Winston, 2000). Therefore, no additional simulations had to be run. As this case represents only a base scenario that will be modified to follow the TTX scenario, a detailed sensitivity analysis is not required. The variability that is introduced at each simulation run is attributed to the population generated within the Medieval City of Rhodes (MCR). For each simulation run a new population is generated, with the population's attributes randomly generated from within set ranges. Thus, the location of the agents and the demographic characteristics of the population differs for each simulation run. A single simulation run took on average 6.6 min to finish [6.2–7.2], the set of 50 simulations took approximately 5.5 h to complete.[3]

Two snapshots of the assembly process at 10 and 15 min into the simulation are shown in Fig. 6. In the figure the agents are represented as red, dark blue and cyan dots. The agents move from their initial location and congregate to the assembly locations. Once assembled, the agents will await there for further instruction.

Once the assembly process completes the emergency protocol states that, if necessary, the evacuation can commence. This is assumed to happen at 30 min at which time the population is instructed to move towards their nearest Gate. Two snapshots of the evacuation process at 31 and 35 min into the simulation are shown in Fig. 7 Figure. Long queues of agents are formed as they move and reach the Gates.

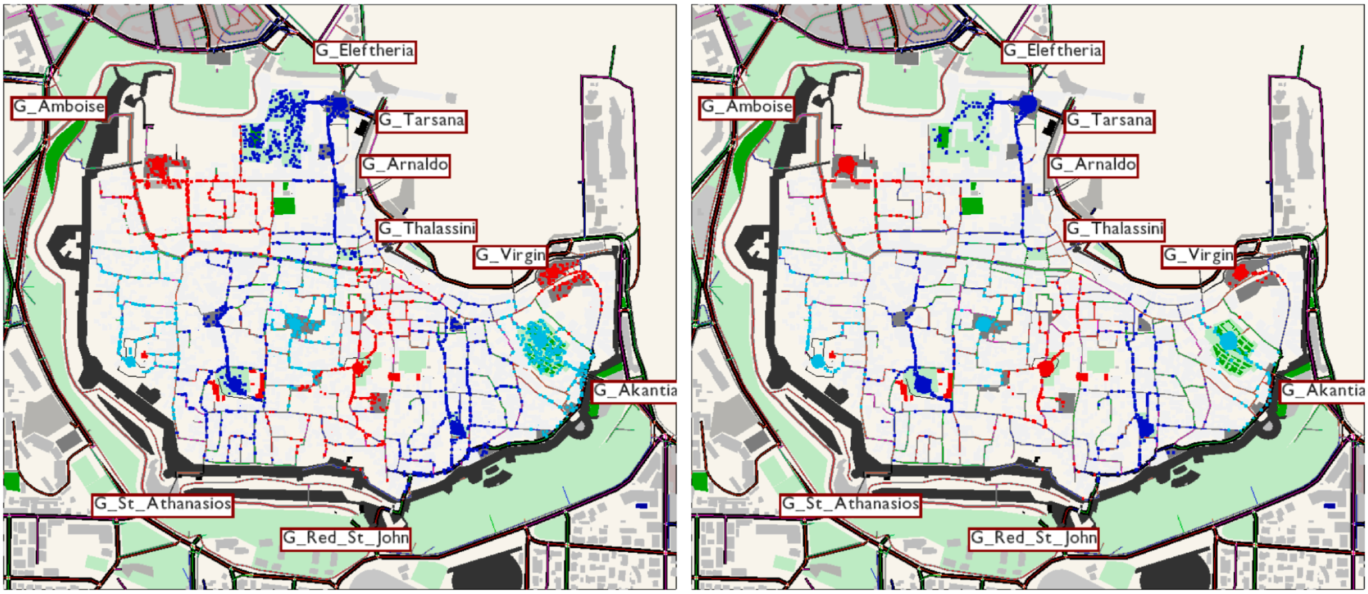
In Fig. 8a, the assembly process as agents reach the assembly location B (see Fig. 4) is depicted as a population density contour. In this image the hotter the colour the higher the population density, with blue indicating $1p/m^2$ and red $4p/m^2$. Fig. 8b depicts in dark blue the route contours of the agents that moved from their initial locations to the assembly locations and thereafter to their nearest Gate.

The summary evacuation performance results are presented in Table 3. The gate usage, i.e., the number of agents that used each gate, is reported in Table 4. Furthermore, Fig. 9 depicts the average gate usage along with an indication for the minimum and maximum usages of each gate.

Given the assumptions relating to the full familiarity of the agents with the layout of the city and the fact that the agents would use optimal paths when moving towards their nearest gate, the variability of the results is relatively small in terms of the evacuation performance parameters (see Table 3). This is evident by examining the magnitude of the mean performance values (e.g., average Total Evacuation Time, average distance travelled, etc) and comparing them with their corresponding standard deviations. The variability observed in those parameters, and also in the gate usage (see Table 4) data, is mainly due to the generation of a new population for each simulation run. It should be noted that due to the proximity of gates 3, 4 and 5 and the location of the assembly locations that were closer to gates 3 and 5 there were no agents using gate 4. The assembly process completes between 20.7 and 24.0 min after the earthquake. At 30 min the instruction to evacuate the city is given. The most significant agent attributes in this setup that would drive their assembly and evacuation performance is their response time and their travel speeds.

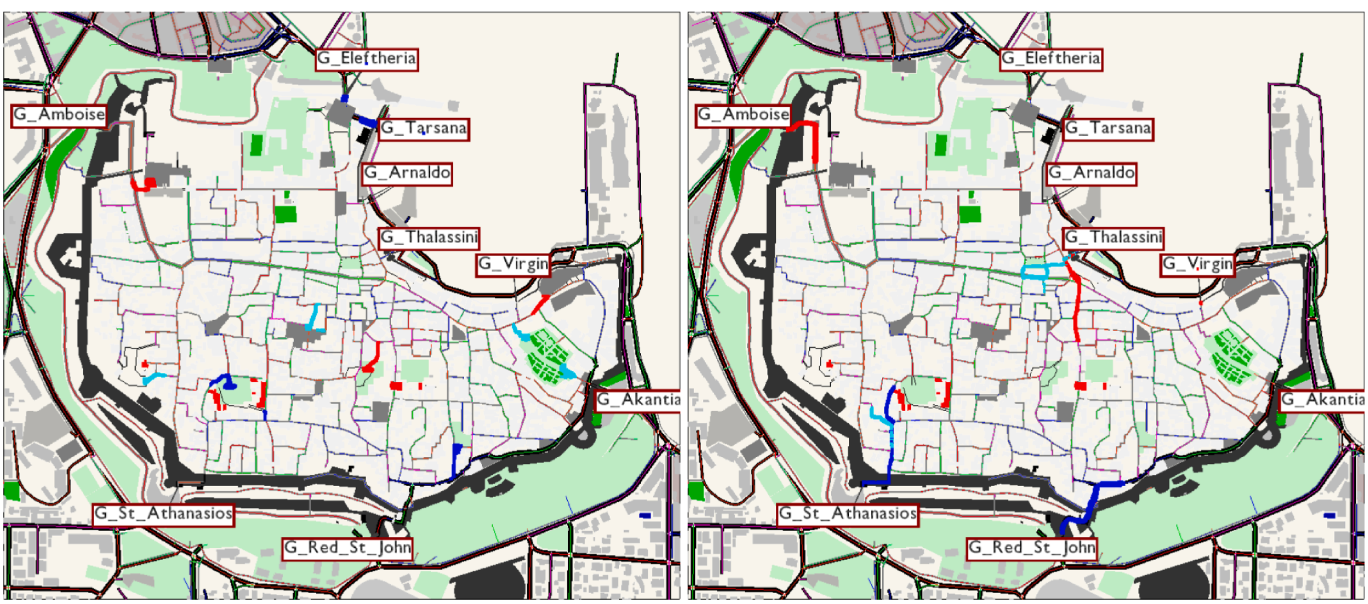
The average time for the first person to leave the city is 30.2 min moving from assembly location B to Gate 2. The average Total Evacuation Time (TET) is 41.5 min. The average Personal Evacuation Time (PET) is 35.4 min, and the average distance travelled is 391 m. In terms of congestion, the agents experienced very low levels of congestion with an average cumulative time remaining stationary due to congestion of approximately 1 min. The exit usage (see Table 4) is determined by the size of the catchment area assigned to each assembly location (see Fig. 4) and the proximity of the assembly locations to the gates. Therefore, some gates will be used by significantly more agents compared to others e.g., on average 417 agents used Gate 7 compared with an average of 1141 using Gate 5.

[3] The simulations were run on a custom-made PC running Windows 10 with an i7 6700K CPU running at 4GHz with 32GB of DDR4 RAM, and an Nvidia 1080 graphics card.



(a) Simulation at 10 minutes *(b) Simulation at 15 minutes*

Fig. 6. (a) Assembly process at 10 min, (b) assembly process at 15 min. The agents are depicted as red, dark blue and cyan dots. The time at which the images were taken was arbitrary selected. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



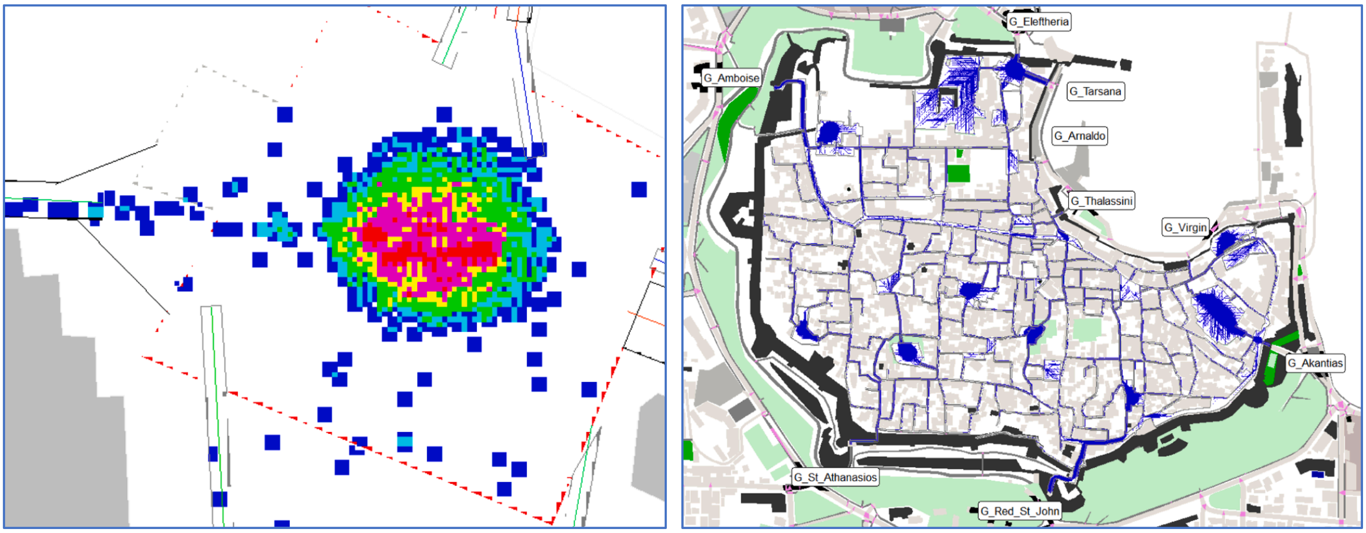
(a) Simulation at 31 minutes *(b) Simulation at 35 minutes*

Fig. 7. (a) Evacuation process at 31 min, (b) evacuation process 35 min. The time at which the images were taken was arbitrary selected.

During the TTX, and prior to the execution of the exercise, a single simulation of the base-case was demonstrated to the participants. The purpose of this demonstration was for the participants to observe the likely movement of the population as if a basic full-scale drill was run, i.e., when following the base emergency procedures where the population would first assemble and then evacuate without being threatened by any hazard. The entire process is depicted in Fig. 10 that shows the number of agents assembled and evacuated over time. The evacuation performance results for this particular simulation are listed in in Table 5.

6.2. TTX scenario results

During the actual TTX the evacuation simulation scenario was run live only once to provide insights to incident managers regarding the evacuation performance and to accommodate the events of the TTX scenario. Given the modelling assumptions, the insights offered include the time it would take the population to reach the assembly locations, the time it would take to evacuate the MCR once the command to evacuate was given, the distances that the population would need to travel, the overall evacuation time, the amount of time the evacuees would wait in congestion while unable to move, the gate usage, the impact of any hazard present. In contrast, a paper-based TTX, cannot



(a) Population density contours *(b) Agent trajectories*

Fig. 8. (a) Example of population density contours as agents move towards assembly location B. Each square represents a single agent, the hotter the colour the greater the population density with red representing 4p/m^2, (b) in dark blue, the route contours of all agents as they moved from their initial locations to the assembly regions and thereafter to their nearest gates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Evacuation performance results for the base-case scenario.

	Travel speed (m/s)	Total evacuation time (minutes, SD in sec)	First out (minutes)	Average personal evacuation time (minutes, SD in sec)	Average distance (m)	Average congestion (sec)
Min	0.85	41.3	30.2	35.3	387	58.2
Avg	**0.92**	**41.5**	**30.2**	**35.4**	**391**	**59.8**
Max	1.50	41.7	30.3	35.5	393	61.6
SD	N/A	5.4	N/A	2.1	1.4	0.78

Table 4
Number of agents that used each gate for the base-case scenario.

Gate	1	2	3	4	5	6	7	8	9
Min	634	764	419	0	1075	587	382	761	1032
Avg	**689**	**798**	**440**	**0**	**1141**	**617**	**417**	**815**	**1083**
Max	737	834	478	0	1198	643	460	856	1144
SD	22.1	15.3	11.3	0	24.9	13.8	16.2	23.9	21.5

produce all this information.

For better comparison with the base-case, in the work presented here, the TTX case scenario was also run 50 times. As with the base-case it was determined that this number was more than enough to obtain a 95 % confidence interval on the mean value of Total Evacuation Time (TET) with a 5 % margin of error (Grandison, 2020; Winston, 2000). Therefore, no additional simulations had to be run. A single simulation run took on average 20.2 min to finish [18.1 – 42.6], the set of 50 simulations took approximately 16.9 h to complete.

Two snapshots of the assembly process at 8 and 12 min into the simulation are shown in Fig. 11. These times correspond to the times when two building A and B collapsed respectively. The affected area that includes the collapsed buildings and the blocked routes in their vicinity are highlighted. Agents that happen to be within these regions are assumed to be trapped. The number of trapped agents for this scenario is reported in Table 6.

Once the assembly process has been completed the population is instructed to leave the city via their nearest available Gates. This instruction is issued at 30 min after the start of the assembly process. Two example snapshots of the evacuation process are shown in Fig. 12 focusing on the population that was using Gate 1. Fig. 12a depicts the status of the evacuation process at 36 min when Gate 1 becomes unavailable due to fire that broke out at that location. The agents will be required to redirect and move to their next nearest available exit which is Gate 9. Fig. 12b depicts the status of the evacuation process at 42 min showing the remainder population moving towards Gate 9.

The route contours for the TTX scenario are depicted in Fig. 13 in dark blue. The image shows the paths that all agents took from their initial location towards the assembly locations and thereafter their paths towards their nearest available exits. In this image only the footpaths and the agents' paths are shown, all other map details have been removed.

The summary results are presented in Table 6 and the utilisation of the gates, i.e., the number of agents that used each exit, is reported in Table 7. Furthermore, Fig. 14 depicts the average gate usage along with an indication for the minimum and maximum usages of each gate.

Similarly, to the base-case scenario, the agents in the TTX scenario are assumed to have full familiarity with the layout of the city and would use optimal (i.e., shortest available) paths when moving towards their assigned assembly location and gates. Furthermore, in this scenario

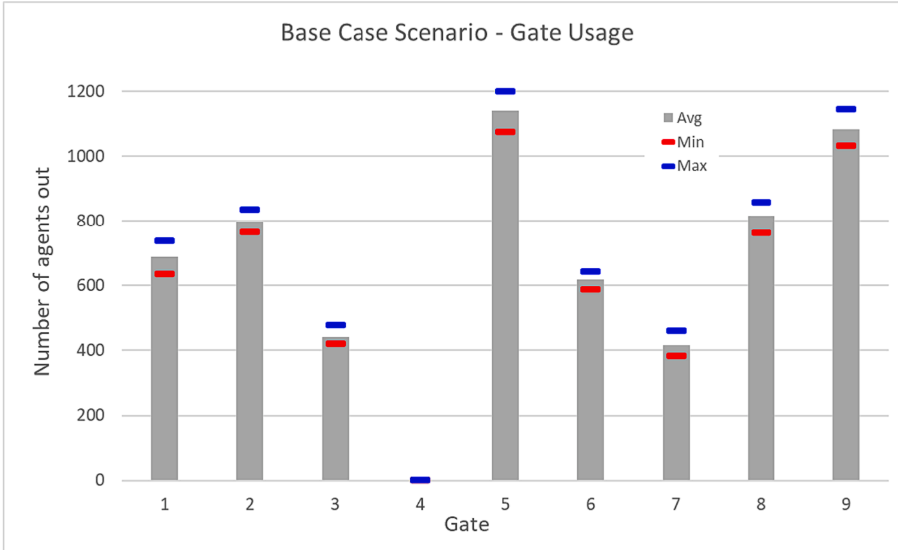


Fig. 9. Gate usage for the base-case scenario.

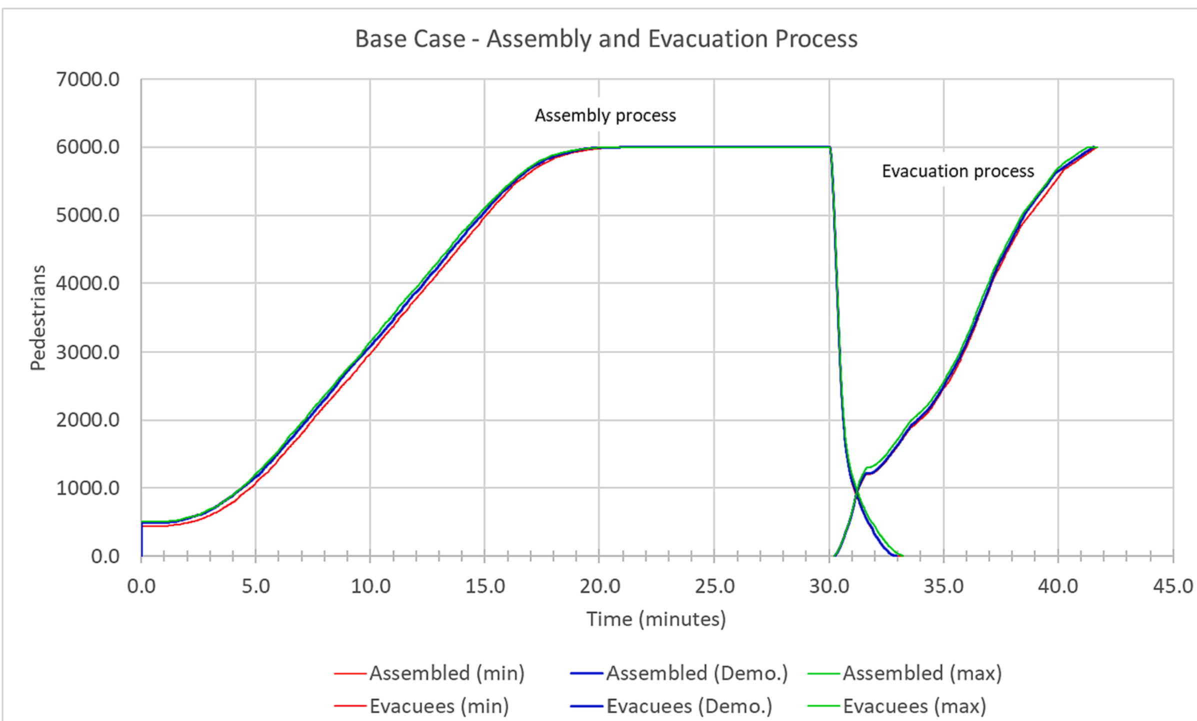
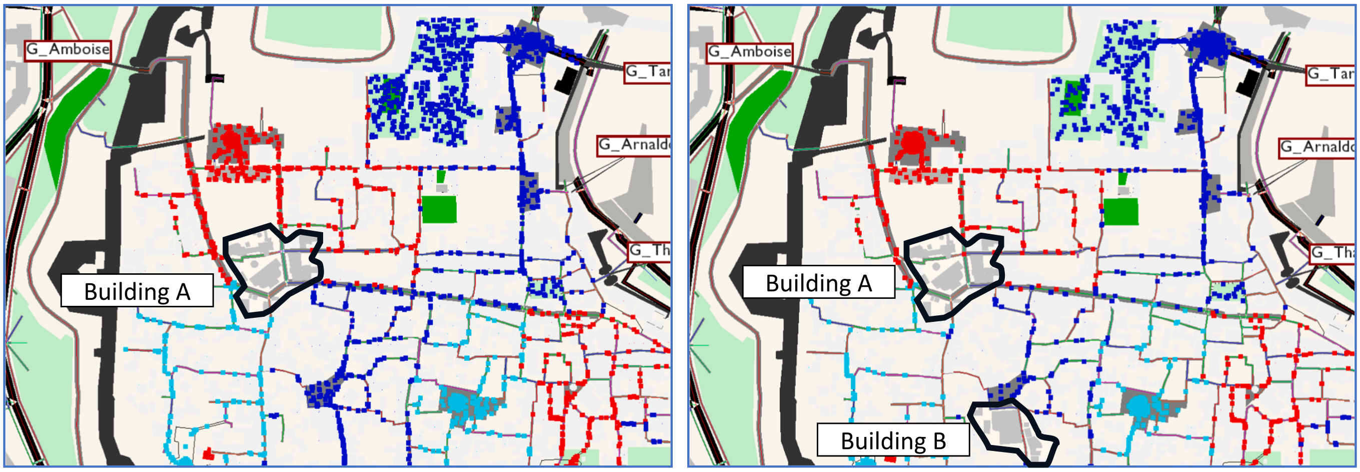


Fig. 10. The assembly and evacuation process for the base-case scenario showing the number of agents that assembled and evacuated from the MCR over time.

Table 5
Basic evacuation performance parameters of the base-case scenario simulation that was demonstrated prior to the start of the TTX.

Total evacuation time (minutes)	First out (minutes)	Average personal evacuation time (minutes)	Average distance (m)	Average congestion (sec)
41.6	30.2	35.4	390	60

Gates 2 to 7 are assumed to be unavailable from the start of the scenario due to fear of tsunami. At 8 min and 12 min after the earthquake, two historical buildings collapsed causing a large number of people to get trapped in the affected area with an average number of trapped people at around 90. The assembly process completes between 22.6 and 23.4 min after the earthquake. At 30 min the instruction to evacuate the city is given. Gate 1 becomes unavailable 36 min into the scenario due to the presence of fire in its vicinity at that time. The variability of the results is relatively small in terms of the evacuation performance parameters (see Table 6). This is evident by examining the magnitude of the mean performance values (e.g., average Total Evacuation Time, average distance travelled, etc.) and comparing them with their corresponding standard deviations. The variability observed in those parameters, and also in the gate usage (see Table 7) data, is mainly due to the generation of a new population for each simulation run. The most significant agent attributes in this setup that would drive their assembly and evacuation



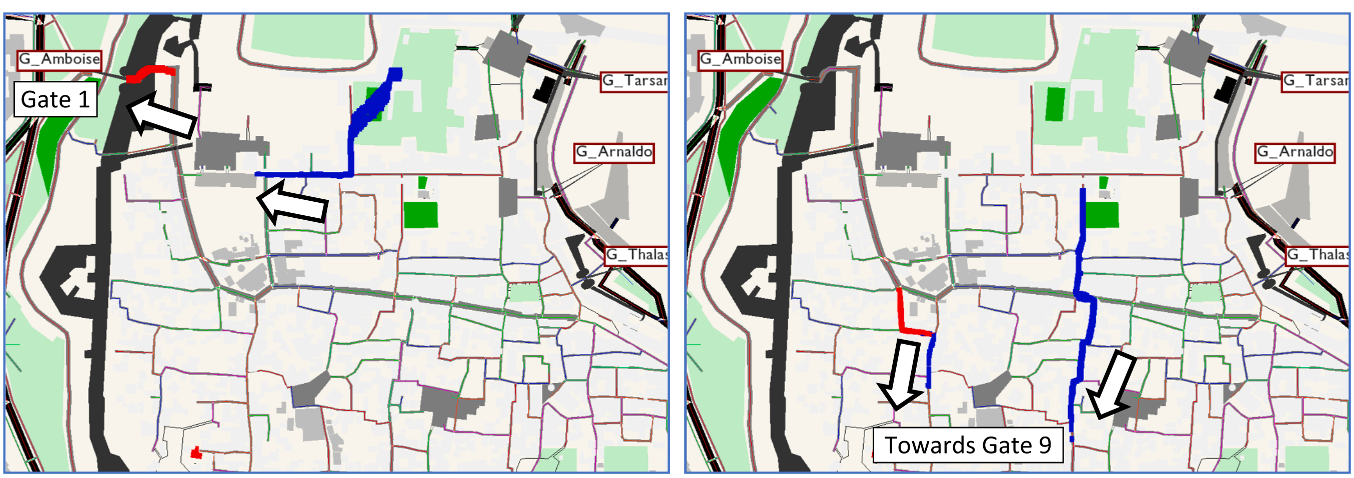
(a) Simulation at 8 minutes

(b) Simulation at 12 minutes

Fig. 11. (a) Building A collapse at 8 min, (b) building B collapses at 12 min. The agents are depicted in red, dark blue and cyan dots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
Evacuation performance results for the TTX scenario.

	Travel speed (m/s)	Total evacuation time (minutes, SD in sec)	First out (minutes)	Average personal evacuation time (minutes, SD in sec)	Average distance (m)	Average congestion (sec)	Trapped
Min	0.85	57.9	33.4	43.0	787	87.6	69
Avg	**0.93**	**58.3**	**35.5**	**43.2**	**795**	**91.1**	**90.4**
Max	1.49	58.6	33.7	43.3	801	95.6	111
SD	N/A	9.0	N/A	4.4	3.8	1.63	10.4



(a) Simulation at 36 minutes

(b) Simulation at 42 minutes

Fig. 12. (a) The state of the evacuation process as Gate 1 becomes unavailable at 36 min at which point the agents redirect towards the next nearest available exit, i. e., Gate 9 (b) the state of the evacuation process at 42 min showing the agents that redirected away from Gate 1 moving towards Gate 9 located at the south end of the Medieval City.

performance is their response time and their travel speeds.

The average time for the first person to leave the city is 35.5 min, while the average Total Evacuation Time (TET) is 58.3 min. The average Personal Evacuation Time (PET) is 43.2 min and the average distance travelled is 795 m. In terms of congestion, the agents experienced very low levels of congestion with an average of approximately 1.5 min remaining stationary due to congestion.

A single simulation run was demonstrated live after the execution of the TTX as the base-case scenario was modified to accommodate the exercises peculiarities and injects. The assembly and evacuation process of this simulation is depicted in Fig. 15 that shows the number of agents assembled and evacuated over time. The evacuation performance results for this particular simulation are also listed in Table 8.

6.3. Comparison of base case and TTX case

A representation of the entire assembly and evacuation performance for the base-case and the TTX case scenarios is depicted in Fig. 16. The

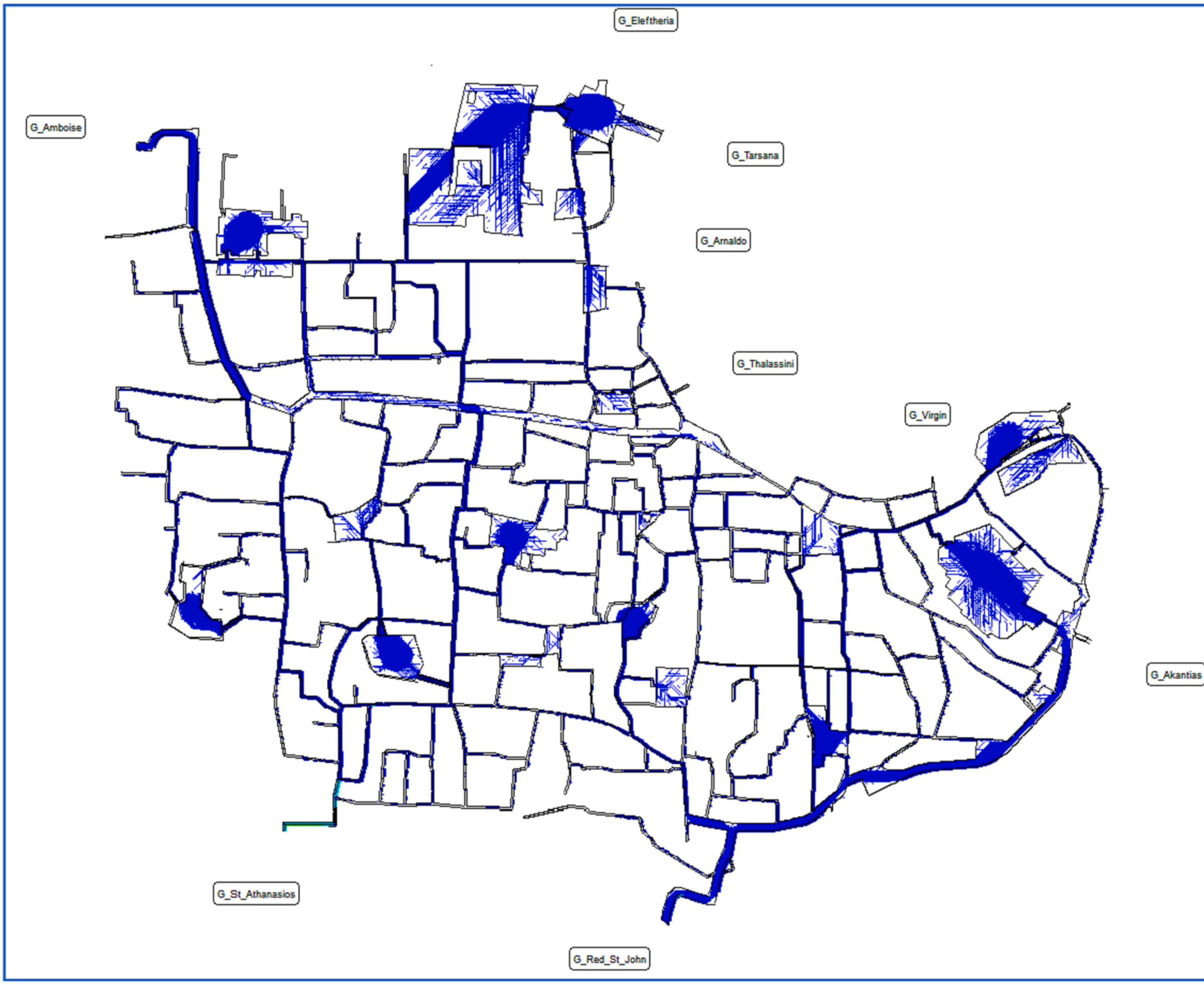


Fig. 13. The image shows only the free space available to the agents to walk on and the paths that all agents took to reach the assembly areas and then to reach the gates.

Table 7
Total number of agents that used each gate for the TTX scenario.

Gate	1	2	3	4	5	6	7	8	9
Min	374	0	0	0	0	0	0	2525	2849
Avg	**389**	0	0	0	0	0	0	**2601**	**2919**
Max	401	0	0	0	0	0	0	2671	2997
SD	5.4	0	0	0	0	0	0	33.4	34.2

graph represents, over time, the number of pedestrians arriving, waiting, and departing from the assembly locations (dashed lines) and thereafter evacuating via their nearest available gate (solid lines). The blue curve corresponds to the base-case scenario while the red curve corresponds to the TTX scenario. The figure also includes the time-markers for the three main events that took place during the TTX scenario. That is, at 8 min and 12 min, the collapse of two historical buildings, and at 36 min the blocking of Gate 1 due to the presence of fire in its vicinity.

Comparing the two processes it is evident that the TTX scenario leads to a significantly slower evacuation averaging at 58.3 min [57.9–58.6, SD 9.0 sec], compared to the base-case scenario that averages at 41.5 min [41.3–41.7, SD 5.4 sec]. This is because in the base-case scenario the full complement of gates is available for use by the evacuees and there are no hazards that impact the evacuation process. However, in the TTX scenario the hazards impacted the emergency evacuation in three ways:

(1) The fear of tsunami meant that all gates facing the seafront were not allowed to be used (i.e., Gates 2–7),
(2) The collapse of two historical buildings at 8 and 12 min respectively, meant that on average 90 people got trapped in the ruins. Furthermore, those not directly affected by the building collapses had to use alternative escape routes to reach the gates,
(3) A fire outside Gate 1 at 36 min after the earthquake meant that the agents that were trying to use that gate to leave the MCR had to redirect to the alternative exit Gate 9.

The graph indicates that at the start of the simulations the average number of people that were already located at the nine assembly locations was approximately 480 people. This is due to the assembly locations being within open spaces (i.e., the city's squares) that naturally draw large number of people. The assembly curve has the typical S shape indicating a generally unobstructed assembly process.

The impact of the building collapses at 8 and 12 min after the earthquake on the assembly curve is not immediately evident at those

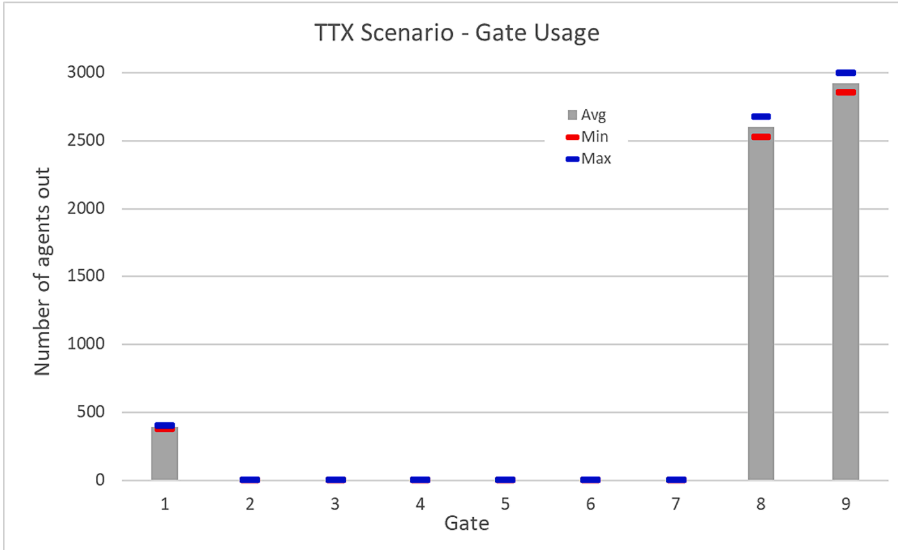


Fig. 14. Gate usage for the base-case scenario.

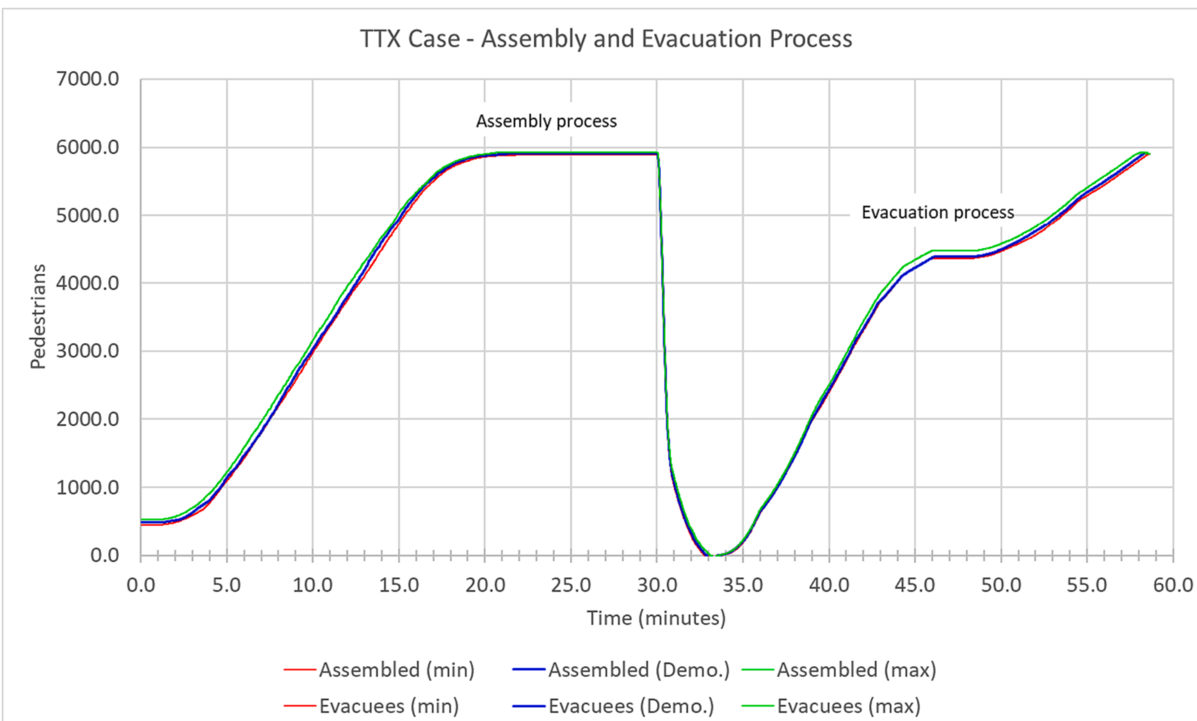


Fig. 15. The assembly and evacuation process for the TTX scenario showing the number of agents that assembled and evacuated from the MCR over time.

Table 8
Basic evacuation performance parameters for the TTX scenario simulation that was demonstrated after the execution of the exercise.

Total evacuation time (minutes)	First out (minutes)	Average personal evacuation time (minutes)	Average distance (m)	Average congestion (sec)
58.3	33.5	43.3	800	92

times (i.e., the slope does not change significantly). This is because the number of people directly affected is relatively small in comparison to the overall population (i.e., on average 1.5 % of the population becomes trapped). Also, the travel distance of the population near the collapsed buildings does not increase significantly as they move around the collapsed areas to reach the assembly locations. The impact of the collapses however is evident in the horizontal part of the assembly process. The vertical distance between the two curves represents the average number of people trapped in the collapsed buildings. The horizontal part of the assembly curves includes both the time when agents arrived at the assembly locations and the time that the agents had to wait there before the evacuation command was issued. The graph also highlights the spread of assembly completion times for both the base-case (blue band in Fig. 16) and the TTX scenarios (red band in Fig. 16).

Once the evacuation starts at 30 min the number of people in the assembly locations drops dramatically for both scenarios. At the same

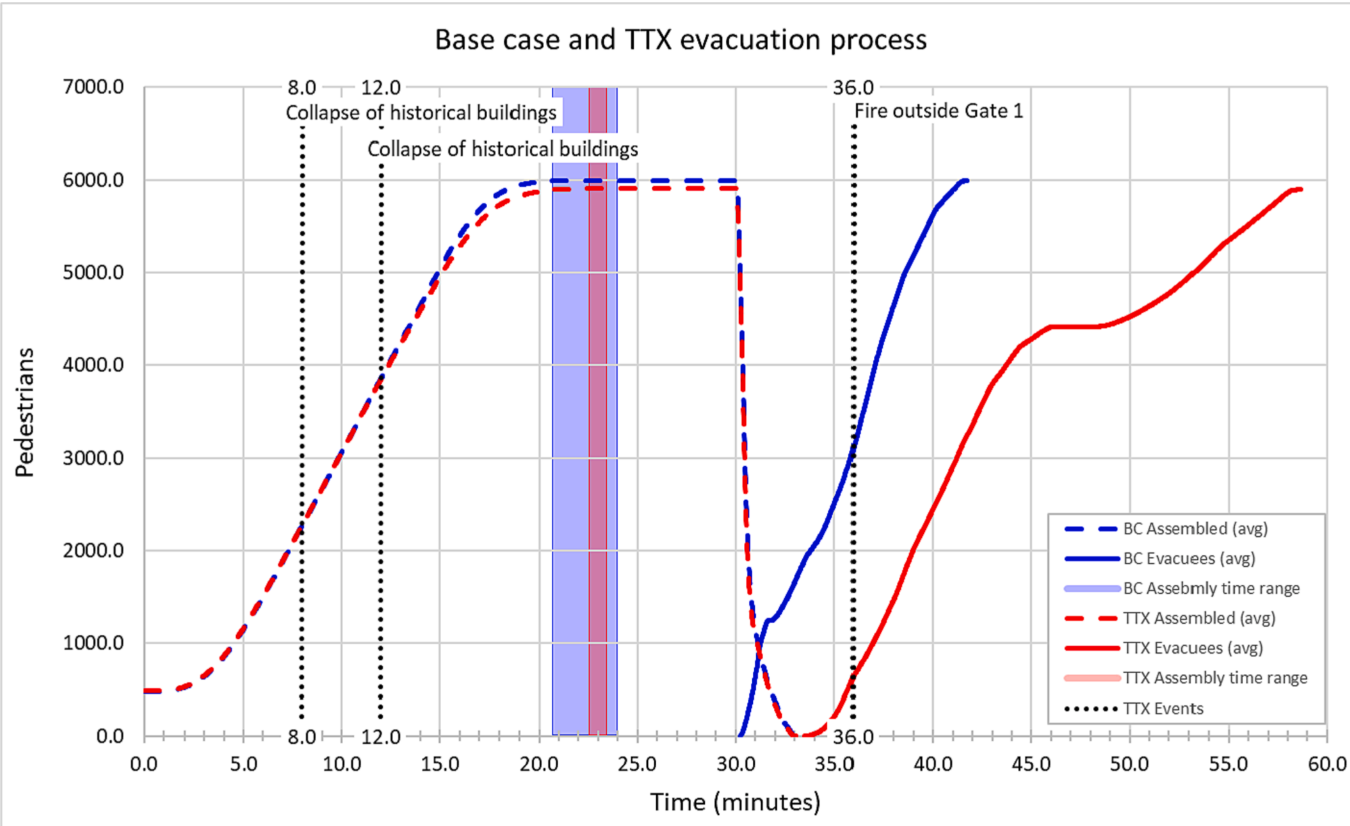


Fig. 16. Whole evacuation process for the base-case (blue lines) and the TTX case (red lines). The dashed lines represent the assembly process and occupancy of the assembly areas over time as the total number of agents reaching the assembly areas, while the solid lines represent the evacuation process as the total number of people leaving the Medieval City of Rhodes over time. The dotted lines represent the events that took place during the TTX. The wide bands represent the range within which the assembly process completes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

time the evacuation process starts. For the base-case scenario the first person to evacuate from the MCR does so on average at 30.2 min taking the first person approximately 14 s to reach Gate 2 from the nearby assembly area B. The steepness of the base-case curve up to approximately 31.5 min represents the use of Gates 2 and 3 that are very close to the assembly location B. The kink of the curve at 31.5 min indicates that the evacuation slowed down at that point as the agents from the other assembly locations were still trying to reach their corresponding gates and did so at a slower rate as the gates were further away. From that point onwards the evacuation process for the base-case was mainly unhindered up to its conclusion, on average at 41.5 min. The picture for the TTX scenario is however quite different. The first person to evacuate from the MCR originates from assembly location A and evacuates via Gate 1. This is because the assembly location A is the closest to any of the available gates. On average the fire evacuee leaves the city at 33.5 min, 3.5 min after the command to evacuate is given. This delay is caused by the fact that the gates facing the seafront are not available (i.e., Gates 2 to 7) thus having to use Gates 1, 8 and 9. At 36 min a fire in the vicinity of Gate 1 deems that gate unavailable. All agents using or heading towards Gate 1 must now redirect and use the nearest available exit which is Gate 9. At about 45 min the evacuation slows down as the use of the gates dries up. The plateau between 46 and 49 min indicates that no agent evacuated during this period. The agents that redirected from Gate 1 have not reached any gate yet. However, at approximately 49 min the first agents have started to arrive which continue until the conclusion of the evacuation which happens on average at 58.3 min.

In both scenarios, the change of slope of the evacuation part of the process (solid lines) is a side effect of the proximity of the evacuees to the gates. In the TTX scenario case this proximity is significantly skewed given that from the start, six out of the nine gates are not used and from 36 min onwards Gate 1 becomes unavailable too. The unavailability of Gate 1 causes a large number of agents (on average 300 agents) to redirect away from that gate and seek egress through the next closer available exit which is Gate 9. Given the collapse of historical buildings at 8 min and 12 min there are, on average, 90 [69–111, SD 10] people that become trapped and are unable to evacuate. Furthermore, the collapse of the historical buildings block paths in their vicinity causing nearby agents to use alternative paths to reach their target gates.

Examining the results in more detail, it is evident that all measured parameters including the time of the first person out of the MCR, the Personal Evacuation Time (PET), the distance travelled, and the congestion, increased in the TTX-scenario when compared to the base-case scenario. The first person to evacuate the MCR, in the base-case scenario, did so, on average, at 30.2 min while in the TTX scenario this increased to an average of 35.5 min, representing an increase of 17.6 %. The personal evacuation time also increased in the TTX scenario, from an average of 35.4 min to an average of 43.2 min, an increase of 22 %. In terms of the distance travelled, in the base-case scenario the agents travelled on average 391 m while on the TTX they travelled on average 795 m, an increase of 103 %. The amount of time that the agent in the base-case scenario that had to remain stationary or travel at a reduced speed due to congestion was on average 60 sec, while in the TTX scenario case it was on average 91 sec, an increase of 52 %. This deterioration of all evacuation performance parameters is a direct result of the reduced evacuation options in the TTX scenario compared to the base-case scenario. These reductions were caused by the unavailability of six gates facing the seafront, from the start of the scenario (Gates 2–7), the collapse of two historical buildings at 8 min and 12 min, blocking the paths in their vicinity, and the blocking of Gate 1 at the 36 min of the scenario. The combined effect of these factors caused the simulated agents to travel longer distance before they can leave the MCR.

In terms of gate usage, while in both scenarios the agents were assumed to have perfect knowledge of the gates and moved towards their nearest gate, in the TTX scenario Gates 8 and 9 were utilised by 93 % of the entire population as gates 2 to 7 were unavailable and Gate 1 was available for only the first 36 min.

7. Limitations

Several assumptions for the base-case and the TTX scenarios are made. These assumptions mainly involve the population characteristics, familiarity with emergency procedures and the layout of the Medieval City of Rhodes (MCR). It is assumed that the simulated agents are uniformly distributed across the MCR, that they are fully aware of the evacuation procedures, that they are compliant to the instructions they receive, that they are aware of the shortest paths towards the assembly locations and thereafter the nearest available gates. Furthermore, it is assumed that when a part of the MCR becomes inaccessible (e.g., a gate or a block of buildings) the simulated agents are immediately aware that they need to redirect and use an alternative route or gate (i.e., even though they may not be able to directly see the obstruction). These are assumptions that could deem both examined scenarios as best-case scenarios given the assumed full familiarity of the agents to both the layout of the MCR and the means of escape from the city. However, the purpose of this study was to demonstrate the added value of utilizing an evacuation modelling tool to recreate non-incident specific evacuation procedures and thereafter its ability to modify these procedures as the user would take into account for events and incidents that took place during the TTX. Without the use of a simulation modelling tool, it is practically impossible to accurately predict, study, and assess the likely evacuation performance of a population from an area.

While the aforementioned assumptions are a limitation, the model is flexible enough to allow the user to setup the population so that it is distributed based on actual population survey information for the city. Also, the model is flexible enough to allow for a reduced familiarity with the city's layout and location of gates. Using these features would allow for a more thorough study as well as the evaluation of more representative evacuation processes. A more detailed study of the evacuation processes for the MCR should include the definition of appropriate response times and an element of unfamiliarity with the layout of the town and the evacuation procedures.

Furthermore, while it is assumed that the population that evacuated via the gates has reached safety, it is rather simplistic to assume that this would be the case in reality. The evacuation procedures must consider what happens outside the walls too, as events that may be unfolding outside the walls may have implications limiting the available options and the ability of the population to truly reach safety (Lawrence et al., 2020). For example, the area between the sea and the city's walls is quite confined and spatially restricted so an evacuation towards that side, especially during peak season, may prove problematic as the capacity of the seaside road is limited and thus the ability of the population to further move on will be significantly hindered.

The use of simulation tools in tabletop exercises has been acknowledged in previous research (Razzetti, 2019; Araz et al., 2012). In addition, the use of simulation tools in tabletop exercises has also been supported by previous work that funded the development of urban-EXODUS (IDIRA, 2015; IN-PREP, 2021). However, further evaluation of the proposed methodology is still required to be performed to ensure that it meets the crisis-managers requirements and prove that it can constitute a valuable tool for preparedness and planning when responding to natural or technological hazards.

8. Discussion

A tabletop exercise offers the opportunity for actors that hold emergency management roles and responsibilities, to engage in a non-threatening environment, through various simulated emergency scenarios, in crisis mitigation training activities. Such exercises focus on communications, resource allocation, organisational aspects of the exercise, and population management. During a paper-based exercise the actors can specify the key events that are assumed to take place during the simulated scenario (see Fig. 16, vertical TTX Event lines). However, in such traditional TTXs, it is difficult to consider the common element of all socio-natural disasters that is, the human element and how the community is affected by the effect that the scenario's simulated hazards. A paper-based TTX cannot consider how the affected community is impacted in any meaningful (i.e., quantifiable) manner, for example, the way it may respond to or is affected by a hazard, or how it could be managed effectively to reduce assembly and evacuation times. A paper-based TTX cannot quantify the assembly or evacuation times, the usage of escape routes or refuge locations, the congestion experienced by the population during the evacuation or provide an overview of the evacuation performance (see Section 6 for a demonstration of qualitative and quantitative data produced by the evacuation model). The use of engineering evacuation simulation models during tabletop exercises can provide this information adding realism and fidelity to the exercise. Given that incident managers can determine the population's assembly time, they can estimate the earliest point in time that they can call the evacuation (if deemed necessary). In the presented example the agents were notified to start the assembly process by the earthquake event. Commencement of the evacuation however was assumed to be decided by the authorities at an arbitrary time (i.e., 30 min after the earthquake) ignoring the temporal dimension of the processes or arrival of the hazard. Knowing the number of people that will use the available escape routes the authorities can form contingency plans for organising the crowd and managing the congestion that will develop outside the city's walls (i.e., dealing with post-evacuation issues) (Lawrence et al., 2020). Appropriate number of first responders and resources may need to be redirected towards these locations (Shari et al., 2012) to accommodate for the population that will congregate outside the gates (i.e., once they are assumed to have reached safety). Knowing the location of the collapsed buildings the authorities can examine the capacity of the alternative routes that will need to be used following the formation of blocked areas. All this information produced by the evacuation model helps to meet most of the exercise performance objectives of ISO 22398 (ISO Copyright, 2013). These objectives include increasing awareness of vulnerabilities, the enhancement of situational awareness, the acquisition of incident-specific knowledge, allowing for the examination and evaluation of new strategies and evacuation procedures (ISO Copyright, 2013; Shari et al., 2012). Furthermore, the insights offered by evacuation modelling can assist organisations that design full-scale exercises to better capture and define the exercise's requirements (ISO Copyright, 2013) that include responsibilities and tasks far beyond those evident in TTXs.

Given the assumptions and limitations of the model it is evident that the results are over-optimistic as the agents follow, by default, the most optimal paths to their desired destinations (i.e., assembly locations and gates). However, to simulate scenarios that more closely match the likely evacuation behaviours and performances the input data and modelling capabilities are required to be more representative. For example, these should include the ability of simulated agents or group of agents (e.g., familial groups) to select routes based on criteria such as local knowledge, physical fitness, congestion levels and signage. Therefore, covering factors related to familiarity with the layout of the area, terrain, health, information received from the surroundings and communication between the simulated agents.

Furthermore, for any emergency procedures to be effective it is necessary that (a) the residents of the Medieval City of Rhodes (MCR) need to be informed and trained on those procedures (Edzén, 2014; US Department of Homeland Security, 2006, 2020; ISO Copyright, 2013), and (b) for both residents and tourists appropriate information and signage should be provided across the MCR to facilitate the assembly and evacuation process (e.g., signs pointing towards the assembly locations, painted paths that indicate the paths to the assembly locations and to the gates, intelligent/dynamic signs etc) (ISO Copyright Office, 2022; Wang and Jia, 2022). However, this aspect of disaster management is beyond the scope of this work. Additionally, the emergency procedures should be adapted according to the hazard that may affect the city. A single procedure may not be able to address all types of hazards. The main hazard that threatened the city during the TTX scenario, that also instigated the evacuation, was the fear of tsunami. The manner in which the TTX was executed assumed that the tsunami would arrive well after the assembly process would complete. However, given the distance of the epicentre to the MCR (25 km) and the approximate depth profile (Navionics, n.d.) of the sea between these two points the tsunami speed and therefore the time of arrival can be calculated. The tsunami wave speed calculation is expressed by the formula $s = \sqrt{gd}$, where g is the acceleration due to gravity and d is the average depth of the sea (Ghasemi, 2011). Using this formula, the likely arrival time of the tsunami at the city's harbour was calculated to be approximately 10 min. This value is less than half the time that the assembly process takes to complete. Therefore, in this case the existing emergency procedures seem to be inadequate to address this hazard and should be modified to dictate that the population immediately evacuates towards higher grounds without first assembling.

9. Conclusions

Tabletop exercises that aim to familiarise participants with mitigation strategies and population management procedures as a response to an emergency typically lack information on how the population will respond, how it will reach safe locations or how it will be affected by the presence of hazards and the crisis managers' control. The methodology presented in this study demonstrated that the urbanEXODUS model is flexible enough and able to recreate existing, non-incident specific, as well as incident-specific, emergency procedures and scenarios that are steered by the manifestation of hazards. The qualitative and quantitative information and insights produced by the evacuation model are difficult or perhaps impossible to obtain without the use of such tools. Typically, in standard TTXs the effect of hazards or crisis manager's control over the population is just informative, providing scenario-based steering information. However, the evacuation model provides feedback regarding the consequences of the presence of hazards or actions taken by crisis mangers. Receiving this type of feedback from the TTX can offer unique and enhanced training opportunities to incident managers as the development of the TTX may become dynamic, when the likely evacuation behaviour of the population, and likely impact of the hazard upon this population, are considered. This enhances the training experience of the participants and improves preparedness and planning for a future crisis.

The results generated by the model provide a more complete overview of events, identifying congestion, assembly location usage, assembly and evacuation times, along with the possible impact that the hazards have on the evacuation process. Evacuation performance is demonstrated by the use of visual representations of people's movement, performance curves depicting the assembly and evacuation process (see Fig. 16), and several performance indicators (see Tables 3, 4, 6 and 7). This is a step change from paper-based TTXs where only events on a timeline are considered that drive the scenario, and simple hand-calculation could be used at best to determine evacuation times, which cannot consider the interactions between the various components represented in an agent-based microscopic model. Further work will focus on expanding the emergency procedures being represented by the evacuation model, to include emergency notificaion methods to the public, and the actions of emergency crews on the ground (e.g., automatic telephone emergency alerts, door-to-door notification, establishment of stand-off distances) to better represent their effect on the evacuation process and to estimate their temporal dimension during future TTXs. Work is also currently underway to allow the model to be used during the response phase of an emergency which involves even more time critical operation compared to its use during a TTX.

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CRediT authorship contribution statement

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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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