Computers, Environment and Urban Systems 65 (2017) 150–161

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

journal homepage: www.elsevier.com/locate/ceus

Dynamic guidance tool for a safer earthquake pedestrian evacuation in urban systems

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A R T I C L E I N F O

Article history:
Received 12 October 2016
Received in revised form 29 June 2017
Accepted 1 July 2017
Available online xxxx

Keywords:
Earthquake emergency evacuation
Safe routes assessment
Non-invasive risk mitigation tool
Dynamic path navigation
Interactive systems for personal devices

A B S T R A C T

In earthquake disasters, the leading causes of death are directly related both to build collapses and fatalities during the following evacuation phase. Allowing people to autonomously gain safe areas and assembly points should be the basis for reducing human losses in urban systems. However, some important environmental and behavioural factors (e.g. vulnerability of buildings, compact urban fabric, cascade effects, presence of people unfamiliar with the urban layout, absence of information on evacuation paths) can hinder this 'self-help'-based evacuation process. This issue is really important in historical centres where evacuees suffer a combination of unfavourable conditions to safely escape.

This paper concerns a non-invasive solution for guiding people along probable safe evacuation routes in earthquake emergency. The proposed *Seismic Pedestrians' Evacuation Dynamic Guidance Expert System* (*SpeedGuides*) considers the influence of the main environmental and behavioural safety factors for evacuees (i.e. street vulnerability, street blockages probability, crowding conditions along paths, presence of mortal dangers, visibility conditions) and combines them in a safety index through the Multi-criteria techniques application. *SpeedGuides* dynamically collects safety factor data during the time and suggests the possible safest path to the nearest secure zone according to the Dijkstra's algorithm approach. *SpeedGuides* is an easy-to-use model proposed for application on personal devices (e.g. smartphone) that, taking advantage of different expert methods, allows evacuees to simple enhance their safety. A first effectiveness evaluation of *SpeedGuides* is provided through an earthquake pedestrians' evacuation simulator in a significant case study. The evacuee performances (with and without the proposed guidance tool) are compared and discussed. Results demonstrate how individuals' safety levels are increased when evacuees use *SpeedGuides*.

1. Introduction

Many studies in the last century have dealt with the reduction of the seismic risk in urban systems and the improvement of people's evacuation performances. Nevertheless, losses statistics[1] evidence how criticalities can be fatal for evacuees and thus can weaken the rescuers' efforts. Unfavourable environmental conditions for the escape can be especially found in historical city centres because of high building vulnerability (Santos, Ferreira, Vicente, & Mendes da Silva, 2013), complex geometric conformation of the urban fabric (D'Orazio, Spalazzi, Quagliarini, & Bernardini, 2014), high human densities, presence of people unfamiliar with spaces layout (e.g. tourists), individuals' risk perception and preparedness aspects (emergency plan and evacuation procedures (D'Orazio, Spalazzi et al., 2014; Sato, Izumi, & Nakatani, 2014)). Current main solutions to urban seismic risk reduction problem (Bernardini, D'Orazio, & Quagliarini, 2016) concern vulnerability *V* reduction, evacuation plans and wayfinding tools.

V reduction interventions on single buildings are often not enough to reach adequate safety levels and are sometimes strongly invasive (and expensive), especially for historical heritage, where cultural and artistic values need to be preserved (Santos et al., 2013). In addition, similar interventions require an urban-scale coordination (e.g. by local authorities) to be effective for a wide part of the city (Bernardini, D'Orazio, & Quagliarini, 2016).

Evacuation plans and rescuers' emergency activities' definition are aimed at reducing the exposure factor *E* through management strategies (Chen, Kwan, Li, & Chen, 2012). Evacuation plans' definition strictly depends on national and local regulations, which, over the decades, adopt this strategy as an important risk reduction tool (Federal Emergency Management Agency, 1996; Italian technical commission for seismic micro-zoning, 2014). Nevertheless, analyses of evacuation performances and adopted behaviours highlight that, especially in historical city centres, evacuees often do not follow (or do not know, as

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[1] www.protezionecivile.gov.it/jcms/it/descrizione_sismico.wp;jsessionid=F5D27C1681510C9963A14E7E05737C10?pagtab=3#pag-content (in Italian, last access 22/03/2016)

http://dx.doi.org/10.1016/j.compenvurbsys.2017.07.001

Table 1
Passive and active guidance systems for indoor and outdoor environments with main reference. Short descriptions highlight main advantages and limitations.

System	Description	Typology	Main existing application	Main reference examples
Traditional (reflective and electrically-illumined signs)	Effectiveness problems due to perception in bad visual condition; difficulty in interpretation and path memorisation; based on 'collective' signs; static routing.	Passive	Indoor/outdoor	Ishikawa et al. (2008), Xie, Filippidis, Galea, Blackshields, and Lawrence (2012)
Photoluminescent (signs, strips, tiles…)	Easy application and low maintenance; good perception for bad visual conditions; based on 'collective' signs; no power-supply needed; static routing.	Passive	Indoor	Tonikian, Proulx, Bénichou, and Reid (2006), D'Orazio, Bernardini, Tacconi, Arteconi, and Quagliarini (2016)
Others (laser, acoustic, …)	Generally combined with other systems; good perception for bad visual condition; visually impaired friendly; power supply generally needed; generally, static routing	Passive	Indoor	Ran et al. (2014), Liao and Shaw (2013)
Building Intelligent Modelling (BIM)	Real-time hazard monitoring; compatible with smart devices; mainly based on environmental conditions by themselves; dynamic routing;	Active	Indoor	Isikdag, Zlatanova, and Underwood (2013), Yenumula, Kolmer, Pan, and Su (2015)
Intelligent Evacuation Guidance System (IEGS)	Real-time hazard monitoring; dynamic routing; compatible with smart devices; human-behaviour aware.	Active	Indoor/outdoor	Ran et al. (2014), Shahabi and Wilson (2014), Kinugasa and Nakatani (2011)

for tourists) the evacuation plan (Quagliarini, Bernardini, Wazinski, Spalazzi, & D'Orazio, 2016). An effective implementation of similar strategies could be difficult because it should need a widespread communication of the emergency procedure to the population and/or a large number of rescuers during the disaster response phase (Ainuddin & Routray, 2012).

On the contrary, wayfinding tools can modify the evacuees' behaviours, thus improving the evacuation performances and leading population to gathering points (defined by the emergency plan) in a more efficient way. Wayfinding represents the process through which people orientate in the environment with the aim to move from an initial point to a different destination point. This process involves human sensorial mechanisms in relation to individuals' features (e.g. familiarity with the spaces and the surrounding environment conditions) (Car, Taylor, & Brunsdon, 2001). This issue is commonly applied to architecture and evacuation facilities (Carattin, Meneghetti, Tatano, & Pazzaglia, 2016) (including exit signs, evacuation instructions and maps (Carattin et al., 2016)).

To date, this solution is largely studied for fire emergency in indoor scenarios (Filippoupolitis & Gelenbe, 2012; Ran, Sun, & Gao, 2014; Vilar, Rebelo, Noriega, Teles, & Mayhorn, 2013). The related effectiveness during emergencies was investigated, especially in indoor conditions such as in complex and historical buildings (Ran et al., 2014). However, the benefits of its application could be extended to further different catastrophes and outdoor scenarios, especially by considering the smart cities perspective (Asimakopoulou & Bessis, 2011). Wayfinding tools based on behavioural design criteria can improve the effectiveness of 'self-help' (allowing people to autonomously move towards 'safe' paths and gain assembly areas) and look towards a performance-based approach (as for the fire safety case (Bernardini, Quagliarini, & D'Orazio, 2016; Kobes, Helsloot, de Vries, & Post, 2010)). During the initial emergence phases, the 'self-help' could have valuable benefits, especially because the public safety personnel may be not present in the scenario or may face some difficulty in reaching the damaged zones (Hashemi & Alesheikh, 2011; Moretti et al., 2013).

Table 1 summarises the different emergency guidance systems and approaches used for helping evacuees in wayfinding activities (in both indoor and outdoor scenarios) by outlining related main studies. According to the interaction level, they can be 'active' or 'passive' as their routing information does or does not depend on the environmental conditions (Bernardini, D'Orazio, & Quagliarini, 2016). Many studies demonstrate that their effectiveness varies with several factors such as typology (e.g. printed map; standard, electrical-illuminated or photoluminescent signs, interactive portable devices) (Ishikawa, Fujiwara, Imai, & Okabe, 2008; Onorati, Malizia, Diaz, & Aedo, 2014; Vilar, Rebelo, & Noriega, 2012); environmental conditions (e.g. low visibility level provoked by smoke, dusts or black-out conditions) (Carattin et al., 2016); and human features (e.g. panic, behavioural aspects, cognitive interdiction provoked by inhalation of smoke or toxic substance, physical and cognitive disabilities) (D'Orazio, Spalazzi et al., 2014).

Wayfinding systems are generally used to help people during fire emergencies. Although fire and earthquake produce different scenarios and have different time spread during the emergency, the involved wayfinding processes can be represented in a very similar way (Gelenbe & Wu, 2012; Onorati et al., 2014), especially from an ontological point of view (Taccari, Bernardini, Spalazzi, D'Orazio, & Smari, 2014).

Therefore, wayfinding solutions should be encouraged also for outdoor earthquake evacuation (Sato et al., 2014; Taccari et al., 2014). Because emergency wayfinding in outdoor scenario is a quite recent field and it is still being developed, only few studies involve this issue. Major studies apply wayfinding concepts to crisis management with the aim to design emergency plan (Bernardini, D'Orazio, & Quagliarini, 2016) and rescue operations (El-Gamily, Selim, & Hermas, 2010) by adopting the 'traditional' perspective. Evaluation techniques mainly take advantage of evacuation simulators (Kinugasa & Nakatani, 2011;