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A discrete choice model based on random utilities for exit choice in emergency evacuations

Ruggiero Lovreglio [a], Dino Borri [a], Luigi dell'Olio [b,*], Angel Ibeas [b]

[a] Department of Civil and Environmental Engineering, Technical University of Bari, Italy
[b] Department of Transport and Logistic, University of Cantabria, Santander, Spain

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ABSTRACT

This work presents a behavioural model based on discrete choice models (DCMs) in order to simulate decision maker behaviour during an emergency situation. The proposed model is a probabilistic exit choice model that allows understanding the heterogeneity of the different decision maker's tastes. A stated preference survey was designed and realized with a sample of decision makers in order to achieve this objective. Thus, the obtained data was used to model the optimal mixed logit model. The use of DCMs allows to know the behaviour of different decision maker types during an evacuation process. The case study highlights the importance of the influence of other decision makers on the decision-making process. This work could be used as the starting point in the development of behavioural models which could be implemented in the current tools for the simulation of emergency evacuation.

1. Introduction

Over the last few decades, Performance Based Design (PBD) has been introduced into the different codes of several countries in order to give designers a flexible and effective method of evaluating safety levels in structures and infrastructures during emergency situations (Meacham et al., 1998; Hadjisophocleous and Bénichou, 2000; Lo et al., 2004; Tavares, 2009; Ronchi et al., 2013; Lovreglio et al., 2013). In fire engineering terms, PBD consists of the comparison between two different times: required safe egress time (RSET) and available safe egress time (ASET) (Nelson et al., 2002; Purser, 2003).

PBD allows designers to use predictive evacuation models, which are able to reproduce real evacuation processes and therefore, provide insights into human behaviour under different emergency situations (Kuligowski et al., 2010; Bensilum, 2003).

Ebacuation behaviour is complex because it is characterized by both physical factors, such as the user's movements towards a safe space, and psycho-social factors (Santos and Aguirre, 2004). Ronchi et al. (2012a,b) splits these factors into internal and external, the relevant literature shows that the most important external factors are social interaction (Nilsson, 2009; Kuligowski et al., 2011; Purser and Bensilum, 2001; Frantzich et al., 2001; Sime, 1985) and the prevailing environmental conditions (such as warning systems, and visibility) (Nilsson, 2009; Norén and Winér, 2003).

The main social interaction, which has a fundamental role during evacuation, is the *social influence* (Latané and Darley, 1968; Nilsson and Johansson, 2009; Nilsson, 2009). According to the literature, social influence can be divided into normative and informational influence. The first influence leads people to behave in accordance with their expectations of other individuals. The second influence occurs when people's understanding of a situation is influenced by the action or inaction of others (Deutsch and Gerard, 1955; Nilsson and Johansson, 2009; Kinateder, 2012).

A number of internal factors can be used to characterize human behaviour, such as: physical abilities (which may depend on age or health) and socio-psychological characteristics (direct or indirect risk perception, emotional states, cultural background or training, past experiences, familiarity with the environment and *affiliation* behaviour (Ronchi et al., 2012a,b; Fridolf et al., 2011; Galea et al., 2010; Gandit et al., 2008; Worm et al., 2006; Wilde, 2001; Sime, 1985). In particular, *affiliation* behaviour occurs when people are attracted to and move towards familiar persons and places (Sime, 1985).

The complexity of human behaviour during emergencies led to the development of a variety of evacuation models (Kuligowski et al., 2010; Johnson, 2005; Gwynne et al.,1999). Those models usually calculate the aforementioned RSET in accordance with the simplified time line model (BS PD7974, 2004; Purser et al., 2007; Candy et al., 2006).

One of the most important issues of these models is route choice modelling and exit selection (Ronchi et al., 2012a,b).

The literature agrees that the exit choice is not only influenced by the perceived time required to evacuate from a specific exit

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* Corresponding author. Tel.: +34 942202262; fax: +34 942201703.
E-mail address: delloliol@unican.es (L. dell'Olio).

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from those available. In fact, familiarity with the exit according to *affiliation theory* (Sime, 1985; Proulx, 1993; Pan, 2006), herding behaviour (Helbing et al., 2002; Pan, 2006; Low, 2000) and the effect of cooperative or selfish behaviour according to *social influence* (Cirillo and Muntean, 2012; Heliövaara et al., 2012; McLean et al., 1996; Muir et al., 1995), and environmental conditions (Nilsson, 2009; Ronchi et al., 2012a,b) can also influence the choice process. A multiplicity of models are available in the literature for the study of this process (Kuligowski et al., 2012). In some models the agent selects the nearest exit without any consideration of other factors, while in other models the agent selects the exit on the basis of optimal decision (shortest amount of time) or consideration of an environmental condition (other occupants' behaviours, fire, etc.) (Kuligowski et al., 2012, Heliövaara et al. 2012).

Random Utility Models (RUMs) make an important contribution to the modelling process and allow predicting the behaviour of individuals in choice situations (Ben-Akiva and Lerman, 1985). In fact they allow the uncertainty of human behaviour to be embedded in one or more random components (McFadden and Train, 2000). Another advantage of these models is that choices are also influenced by the decision maker's characteristics (Greene, 2000). To cite specific applications, RUM modelling of pedestrians walking has addressed the 'short range' (walking) behaviour of individuals (Antonini et al., 2005; Robin et al., 2011): these works are based on a decision making framework initially proposed by Hoogendoorn et al. (2002) and Daamen et al. (2004), which shows the hierarchical structuring of choices. According to this view, decision making can be split by cascade into a *strategic* level (the users choose the strategy to be performed), a *tactical* level (the users choose the tactical actions to be performed on the basis of the strategic level and schedule their actions accordingly), and an *operational* level (the users take snap decisions in order to instantiate the choices made in the two previous levels) (Hoogendoorn et al., 2002; Daamen et al., 2004; Hoogendoorn and Bovy, 2004). In an evacuation context the first and highest level coincides with the decision to go towards a safe place, which is the fundamental choice made during the *pre-movement time* (Purser et al., 2007), the second level coincides with the process of route and exit selection and affects the *movement time* (Candy et al., 2006), in the end, the third level embeds the typical short range choices which characterize the evacuation process and also affects the *movement time* (Antonini et al., 2005; Robin et al., 2011).

The present work focuses on the tactical level and in particular on the modelling of the exit choice process during emergency evacuation situations. We investigate the exit choice processes which are seen as fundamental elements in emergency evacuation routing.

Among all the factors listed above, this work focuses on how the following defined factors influence exit choice: the decision maker's proximity to an exit, the crowds near exits, herding behaviour and the effect of cooperative or selfish behaviour.

The main contributions made by this work are: firstly, the development of an exit choice model for emergency evacuation behaviour based on the RUMs approach; secondly, the consideration of human factors in order to achieve more detailed modelling of human behaviour based on the inclusion of the systematic and random tastes of different decision makers.

The first part of the paper analyses the evolution of RUMs and stated preferences survey techniques, in the light of the advantages they offer compared with the current simplified mainstream models. The second part describes a case study. The third part involves a discussion of the pros and cons coming from the results. The paper ends with some suggestions about future work that is needed to overcome the persistent limitations of our approach in challenging the complexity of emergency evacuation behaviour (EEBs).

2. State of the art

RUMs belong to the DCM (Discrete Choice Models) class of models which are used to model choices taken by decision makers when they are put in front of a finite set of alternatives (Train, 1986).

This theory was introduced in the scientific literature by Thurstone (1927), who considered the usefulness perceived by the "q" decision maker about the "i" alternative represented by the following sum:

$$U_{iq} = V_{iq} + \varepsilon_{iq} \tag{1}$$

This equation highlights that the utility function comes from the sum of two terms. The first one (V_{iq}) is a systematic quantity, meaning the main or expected value of the perceived utility. The second term (ε_{iq}), called the *random residual*, represents the deviation of the average utility from the real value. In this way all the factors that make the decision-making model deviate from pure rationality are embedded in the random residual. The scientific literature provides various models of random utility which differ from each other because of the different probability distributions chosen by different authors for modelling the random residual (Cascetta, 1998).

The Mixed Logit Models (MLMs) used in this paper (Boyd and Mellman, 1980; Cardell et al., 1980) are based on the hypothesis that the random residues (ε_{iq}) are independent and identically distributed (IID) according to a Gumbel random distribution with a mean equal to zero and a λ parameter (McFadden, 1974). MLMs are highly flexible and can approximate any random utility model (McFadden and Train, 2000) overcoming the limitations of standard Logit models (Train, 2009). In fact, MLMs can model the decision maker's varying tastes by the use of random distributions for the θ_{ik} coefficients and the probability of choosing a certain alternative can be provided by the following integral:

$$\mathrm{MLP}_{jq} = \int P_{jq}(\boldsymbol{\theta}) f(\boldsymbol{\theta}|\boldsymbol{\beta}) d\boldsymbol{\theta} \tag{2}$$

where P_{jq} has the expression of Multinomial Logit probability, while $\boldsymbol{\theta}$ is the vector of the generic values that are assumed by the θ_{ik} coefficients and have $f(\boldsymbol{\theta}|\boldsymbol{\beta})$ probability. Finally, $\boldsymbol{\beta}$ is the vector of the parameters characterizing the probability distribution f. Unlike Multinomial Logit and Nested Logit Models, MLM do not have closed solutions (see Eq. (2)). Nevertheless, solutions can be achieved both by numerical integration and by using Monte Carlo draws $\boldsymbol{\vartheta i}$ ($i = 1 - R$) from $f(\boldsymbol{\vartheta}|\boldsymbol{\beta})$ based on the Halton sequence and the following equation (Hensher, 2001; Hensher et al., 2005):

$$\mathrm{MLP}_{jq} = \frac{1}{R}\sum_{i=1}^{R} P_{jq}(\theta) \tag{3}$$

To date, RUMs have been widely used in econometrics and have had many useful applications in a diverse range of fields: marketing, finance, etc. These models have also been used by different authors to solve transportation issues (Ben-Akiva and Lerman, 1985; Cascetta et al., 1992; Antonini et al., 2005). Their fields of application have been various, for example, they have been used to model transport demand (dell'Olio et al., 2009) and to evaluate the public's perception of quality in a public transport service (dell'Olio et al., 2011).

This paper demonstrates the utility of RUMs in modelling the process of choosing an emergency exit during emergency conditions. In the literature, the modelling of exit choice has been addressed in different ways (Kuligowski et al., 2012, Heliövaara et al. 2012). For example Lo et al. (2006) and Ehtamo et al. (2010) use game theory, while other authors such as Heliövaara (2007) used deterministic models based on utility maximization by decision makers. A deterministic approach to the problem has