Risk Reduction in Urban Areas by Means of Evacuation: Survey Design on Use of Emerging Information and Communication Technologies

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Abstract. The issue of risk from man-made or natural events has become increasingly important. The disasters caused by hurricane Katrina and the tsunami that hit Fukushima have forced an increase in attention to all components that can reduce the risk. Considering the overall formalization, the component on which it is possible to act independently of what is done for the reduction of the occurrence and vulnerability, is exposure.

The development of the application of Information and Communication Technologies (ICTs) in the urban road systems can give a contribution to exposure reduction.

It is important to develop a methodology to analyze how a survey should be structured, as risk analysis must include both Revealed Preference (RP) and Stated Preference (SP) information. This is necessary because the investigation is not conducted during a real emergency event, as it simulates a realistic but hypothetical scenario. The proposed methodology is designed to examine the dynamic evolution of citizens' behavior in terms of trip choices, offering deeper insights into their decision-making processes in emergency situations especially considering the presence of ICT. To validate its effectiveness, the methodology has been tested on a prototype sample.

The result of this methodology is particularly important because the established structure allows an ex-ante analysis of the questions to be asked by the respondents and permits the insertion of SP demand also for urban areas where, to date, there is no ICT. The innovative aspect lies in the possibility of analyzing dynamic route choices, taking into account the presence or absence of information provided to the user.

Keywords: Risk analysis · Exposure · Evacuation · Stated Preference (SP) · Survey · Demand analysis · Updated choice · Information and Communication Technologies (ICTs)

1 Introduction

According to the UN Global Assessment Report on Disaster Risk Reduction (GAR) [1], the last 50 years have been characterized by an increased trend in the number of disaster events worldwide due to climate change, which has led to an increase in extreme weather

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events even in parts of the world not typically affected by these events. Current trends are coupled with the future prospect of increasing global conflicts.

In this context, Sustainable Development Goals 1, 11 and 13 of the Agenda 2030 [2–4] and the Sendai Framework for Disaster Risk Reduction 2015–2030 [5] emphasize the need for shared global strategies to improve community resilience through the planning of common evacuation procedures for all countries. The evacuation plan plays a crucial role as the primary strategy for risk reduction. Its importance is recognized in several targets and relative indicators, where it is integrated into national and local policies to promote coordinated actions between countries (Table 1). Currently, an important gap in risk management is represented by the action policies that are different between countries according to geographical locations. For example, in Europe, procedures focus on managing the consequences of disasters. This demonstrates the need to bridge the gap between planning and action by promoting practical exercises and advanced transport models to improve the effectiveness of evacuations [6].

Table 1. The importance of the evacuation plan according to Agenda 2030 criteria [2–4].

Goals	Targets	Indicators
1 End poverty in all its forms everywhere.	**1.5** By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters.	**1.5.3** Number of countries that adopt and implement national disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015–2030. **1.5.4** Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies.
11 Make cities inclusive, safe, resilient and sustainable.	**11.b** By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015–2030, holistic disaster risk management at all levels.	**11.b.1** Number of countries that adopt and implement national disaster in line with the Sendai Framework for Disaster Risk Reduction 2015–2030a. **11.b.2** Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies.

(*continued*)

Table 1. (*continued*)

Goals	Targets	Indicators
13 Take urgent action to combat climate change and its impacts.	**13.1** Strengthen resilience and adaptive capacity to climate related hazards and natural disasters in all countries.	**13.1.2** Number of countries that adopt and implement national disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015–2030. **13.1.3** Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies.

Transport systems have a strong influence on risk planning and management in urban areas, as they are the main means of allowing people to evacuate in case of emergency.

Some of the disastrous events that have marked the world in recent years, such as the attacks on the Twin Towers, Hurricane Katrina and the tsunami that hit the Fukushima nuclear power plant, have highlighted the need for standardized strategies for responding to emergencies. Above all, they showed the importance of evacuation planning as a preventive measure. Although risk studies traditionally focus on indoor areas, it is evident that efficient evacuation planning on an urban scale is essential to improve the safety of the population.

Developing appropriate exposure reduction models is therefore a major priority. Accurate investigations are required for the development of exposure reduction models by evacuation to provide descriptive statistical models or advanced behavioral models.

This study aims to develop a survey model to analyze the behavior of transport users under risk conditions referring to evacuation plan. This approach is part of the class of discussion-based exercises aimed at making the planned evacuation procedures familiar to the participants [7]. To this end, a questionnaire combining Revealed Preference (RP) and Stated Preference (SP) information was designed in order to obtain representative user data that can be used for modelling TSM. The purpose is to understand the decision-making behavior of users in the absence and the presence of eICTs and to assess the impact of ICT provided information on their choices.

This work aims to provide planners, emergency managers and policy makers with a methodology to study risk exposure and enable the simulation of planned emergency procedures. The work is important for evacuation analysts and planners because it allows them to prepare appropriate evacuation plans. It is important, more generally for route choice analysts because it allows to study the dynamic update of choices.

After this introduction, the remaining part of the paper is organized as follows. Section 2 describes the methodology, starting with the main state of the art for each component up to the model for studying user choice behavior and TSM characteristics under risky conditions. Section 3 introduces the general structures of mixed RP/SP

questionnaires with and without e-ICT. Finally, Sect. 4 discusses future perspectives of the research.

2 Methodology

2.1 State of the Art

The main elements to be considered in the analysis of the state of the art on exposure reduction for risk management are Transport System Models (TSMs) and emerging Information and Communication Technologies (eICTs).

Risk analysis in transportation (TRA) is an extension of Quantitative Risk Assessment (QRA) [8], originally developed for the chemical industry [9–11]. The formalization of individual risk through three main components [12]: occurrence, which indicates the probability of an occurring event; vulnerability, which measures the level of damage that the event may produce on transport system; and exposure, which represents the number of people or property potentially affected. The exposure component can be addressed through an appropriate evacuation strategy that provides for way out and the mobility of people under emergency conditions. Thus, the planning of transport systems is a key issue in reducing the exposure component.

The analysis of transport systems is developed within the theoretical framework of TSMs, which include the study of demand, supply and their interaction [13]. In recent years, advanced models have been developed to analyze transport demand including Random Utility Model (RUM), Quantum Utility Model (QUM) and Fuzzy Utility Model (FUM) [14–19]. At the same time, the use of network analysis for the study of supply has improved the connection between infrastructure and routes [20–25]. Under emergency conditions, both demand [26, 27] and supply [28] changes. Users modify their choice behaviour without having a clear perception of the network, while the infrastructure itself may be subject to sudden closures and reductions in capacity [29–32]. Therefore, TSMs developed for ordinary conditions are not applicable in an emergency context, and specific plans must be produced [33, 34]. It is necessary to develop dynamic models that can predict and update user decisions according to congested conditions on the network [35].

An important innovation in the transport sector is the integration of eICTs into TSMs. Although these technologies are already widely used in the industry, their application in transport systems is still under development.

Among the main emerging technologies there are: the Internet of Things (IoT), that enables real-time data collection and analysis through smart sensors integrated in vehicles and infrastructures; the BlockChain (BC), that provides security in transactions and data exchange; the Big Data (BD), which allows large sets of information to be elaborated, the Artificial Intelligence (AI), that supports decision-making by improving efficiency in autonomous driving systems, traffic and route management; and finally, the Digital Twins (DT), that allow the creation of digital duplicate of transport systems, facilitating simulation and urban planning based on real data. Despite the potential benefits of these technologies, research on their specific application for the development of evacuation plans in transport systems is still limited [36, 37]. However, the use of eICTs is crucial to improve evacuation management, by providing real-time data to

users, reducing uncertainty in route choice and helping to make transport systems more efficient and relevant in emergency situations.

Following the reference literature concerning the study of TSMs and eICTs [6, 32, 37–49]. Risk analysis requires an integrated methodological approach, combining tools from different research fields. To this end, it is essential to follow a structured sequence: initially, through the formalization of the TRA, then through the development of the TSM and, finally, by integrating the extensions of the TSM to address the various levels of eICT with dynamic models. These models allow the analysis of a phenomenon, as the choice behaviour of users, that can be based on reality (RP) or on a hypothesis of reality (SP) (Fig. 1).

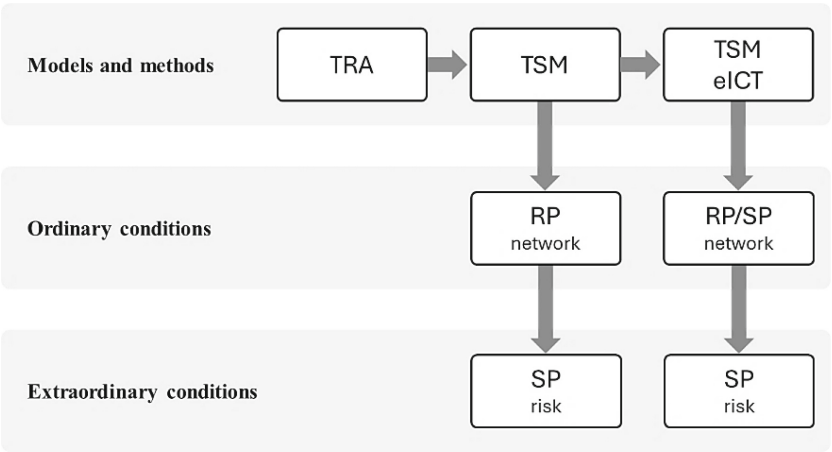

Fig. 1. Methodological framework for exposure analysis.

The behavior of users of the transport system in ordinary conditions is described by their revealed preferences (RP) during a survey or by observations using ICT. The behavior of users with respect to a hypothesis of risk (extraordinary conditions) is described by their stated preferences (SP) during a survey in which one or more hypothetical emergency scenarios are presented to them. In the case of extending TSM and integrating with eICTs, user behavior can be described using both revealed (RP) and stated (SP) data, as these technologies are not yet commonly deployed in the cities. Some examples of smart cities that have already integrated eICTs into their transport systems are Copenhagen, Helsinki and Amsterdam, where the use of these technologies contributes to improve the efficiency of urban mobility. The emergency scenario even in the presence of eICT must be studied by means of SP data.

2.2 Path Choice Model in the Exposure

The reference equation in TRA, that defines risk, is [12]:

$$R = O \times V \times E \tag{1}$$

where:

- O is the occurrence which relates to the type of event and its propagation,
- V is the vulnerability and depends on the structural state of the transport system,
- E is the exposure of the social elements to the effects of the disaster event and changes according to the location and timing of the event.

These factors depend on spatial and temporal variables as well as on the nature and intensity of the event, and their quantification requires advanced mathematical models. The exposure component is related to the average path flows of users (h) and the congestion of the transport system, and thus to the path costs (g). These elements are studied using assignment models, which are part of TSM.

$$E = E(h, g) \tag{2}$$

The network equilibrium model is one of the most advanced static models for analyzing the transport system under risk conditions. As the transport system is constantly evolving, or in other words it is not acceptable the assumption that both the variations of demand and the supply components are not far from average values inside a reference time periods, it is necessary to use models that consider the dynamicity of the effects on the transport system of the catastrophic event. In the literature there are various models that estimate the evolution of transport demand in the periods between the initial event and its effects. However, there is a lack of a comprehensive view of the problem that relates the dynamic components of demand with the network conditions during the emergency [38].

The interaction between transport supply and demand is modelled through equations that consider the path choice probability, the path costs and the socio-economic characteristics of the users:

$$h = P(SE, g)d(SE, g) \tag{3}$$

where h is the average path flows between an origin-destination node pair, d is the demand flow and P is the path choice probability matrix, which depends on the path costs (g) and the socio-economic characteristics of the user (SE). Starting from the flows on paths (h), it is possible to obtain the flows on individual link (f) through the link-path incidence matrix Δ, according to the relation $f = \Delta h$.

In congested systems, link costs (c) depend on link flows (f):

$$f = \Delta h = \Delta P(SE, c)d(SE, c) \tag{4}$$

In the emergency context, users' choices do not just depend on the path, so the probability P also depends on the vector of parameters β representing the references for the users' perceived utility. Choice behavior is linked to the utility perceived associated to each

path alternative by the user with respect to his/her choice set of path alternatives. This variable depends on a number of attributes characteristic of the specific path alternative and of the user. Since the utility associated by the user to each alternative belonging to the choice set is unknown, the probability that the user will choose the generic alternative conditional on his/her choice set is defined. The choice behavior of the generic user can be simulated through behavioral models, such as RUMs, QUMs and FUMs [14, 15, 17, 50].

The presence of eICTs, providing updated information on the transport system in real time, allows the β-parameters, and consequently the P-matrix, to be updated. The process of P-matrix updating, known as "path choice update process", is supported by dynamic path choice models.

According to the dynamic model proposed by [38], the probability that a user n, at time t, chooses a specific alternative j_t, is conditional on the choice s/he made in the previous period $t - 1$, i.e., the alternative j_{t-1}, both belonging to choice set S. This probability, defined as the transition probability, is expressed as:

$$\begin{aligned} P_{n,t}\left[j_t/j_{t-1}\right] = prob\left(U_{n,t}\left[j_t\right] > U_{n,t}[i_t] \quad \forall\ j_t, i_t \in S, j_t \neq i_t\right) \\ /prob\left(U_{n,t-1}\left[j_{t-1}\right] > U_{n,t-1}\left[i_{t-1}\right] \quad \forall\ j_{t-1}, i_{t-1} \in S, j_{t-1} \neq i_{t-1}\right) \end{aligned} \tag{5}$$

The model assumes that alternatives can change the values of the attributes over time, influencing user decisions, but without altering the overall number of available options, unless a new alternative is introduced. When the choice set available to the user remains unchanged, it is possible to obtain the probability of transition between different alternatives. However, if new options emerge, the continuity of the model is interrupted and it is not possible to represent the decision-making process as a sequence.

In order to model the transport system under risk conditions, information about users' behavior must be acquired. It is necessary to conduct a survey using a methodology that integrates both data based on current behavior and information obtained from hypothetical emergency scenarios.

Two classes of surveys are used to do this. Revealed Preference (RP) surveys identify the variables that influence users' travel decisions in the real transport system situation (in real-life contexts) based on information about their current travel behavior. Stated Preference (SP) surveys identify the variables that influence users' travel decisions with respect to hypothetical (realistic, but not real) transport system scenarios.

With reference to Fig. 1, RP information is derived in this work from the habitual behavior of users in the urban area under investigation, SP information is of two types. SP information that derives from user behavior with respect to the hypothetical, but realistic, emergency scenario under the current conditions of the transport system, and SP information that derives from user behavior influenced by the presence of eICTs with respect to the same emergency scenario.

The survey aims to investigate the risk exposure component and it is organized in two sections (Fig. 2). The first deals with understanding users' choices in case of evacuation with respect to an exogenous event occurrence and urban transport system vulnerability. The second integrates eICTs to assess how the availability of updated information influences user decisions in the same occurrence and vulnerability context described in the first section. In order to ensure a cognitive bias-free analysis, the two questionnaires are given to users separately during different periods of time.

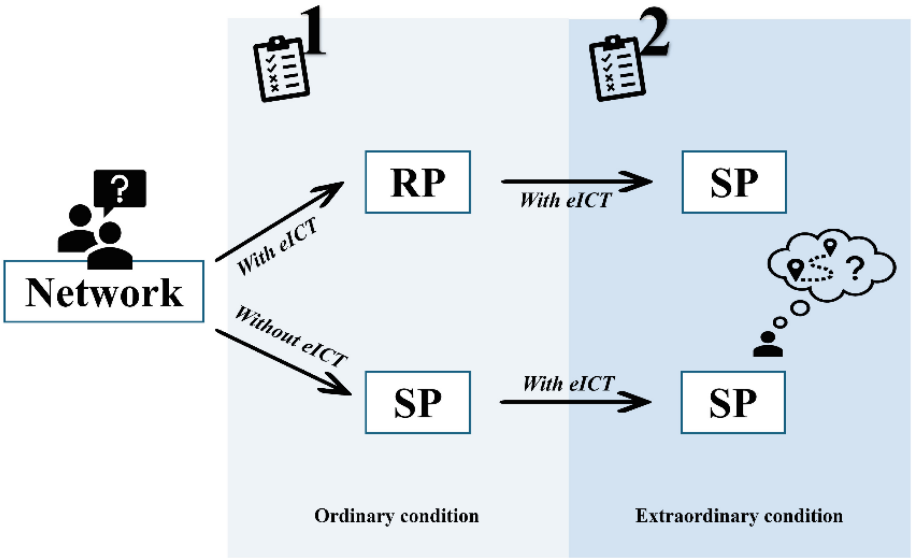

Fig. 2. Schematic example of sequence in a mixed RP and SP survey.

3 Results

According to the methodology described in Sect. 2, two questionnaires have been implemented composing the survey.

The first questionnaire consists of a first section in which socio-economic information is collected and users' mobility behaviour for travelling around the urban area is analysed. Then, the emergency occurrence and the vulnerability conditions of the transport system are introduced. Respondents are given the location of the occurrence (x), the origin location where the user would be in the emergency scenario (y) and the safe destination to reach (z) (Fig. 3). Following this, different routes are indicated to reach the safe zone reported on the evacuation plan, and respondents are asked to choose a route if they were in the emergency scenario assumed at the beginning.

The second questionnaire considers the same emergency scenario with the same conditions of occurrence and vulnerability and the same x, y and z, but introduces the use of eICT technologies that provide updated information about the evolution of the approaching calamitous event and the condition of the transport system.

The hypothetical, but realistic, emergency occurrence and the related conditions of the transport system are described at the beginning of the survey. The structure of the survey is developed in three stages. The first phase is the respondent registration, which belongs to Revealed Preference (RP), as it is based on socio-economic data and actual user behaviour. The next phases concern destination choice and route choice, both of which are classified as Stated Preference (SP). In these phases, users' decisions in the hypothetical scenario are analysed, assessing how factors such as perceived risk, real-time information received and infrastructural conditions influence their choices.

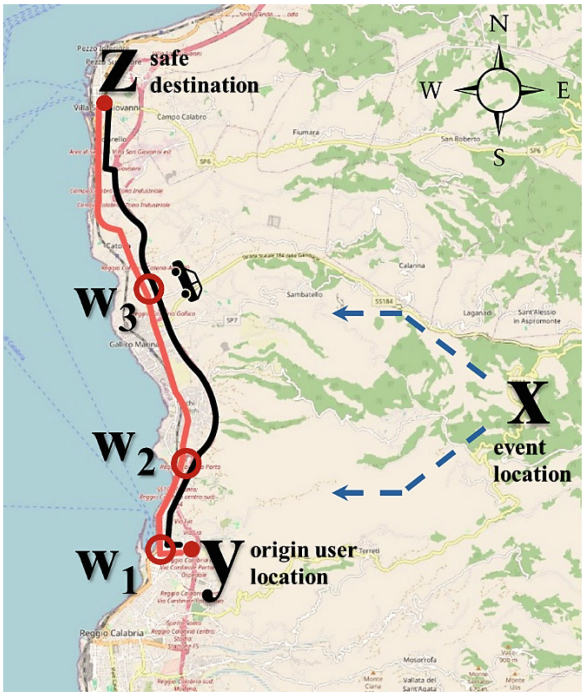

Fig. 3. Evacuation plan paths presented in the survey [51].

In order to facilitate the comprehension of the scenarios, representative images of the actual transportation network are showed to the respondents, clearly illustrating the alternative routes available to reach the location z. The questionnaire includes images with the aim of supporting respondents in decision making, ensuring more accurate and aware responses.

To test the methodology, a survey has been conducted on a prototypal sample with the aim of verifying the validity of the previously defined structure.

Specifically, two questionnaires have been submitted to the users with a time interval between them of 2 weeks (Fig. 4). In both questionnaires the same emergency occurrence and the same vulnerability of the network system at the start of the emergency is presented, with the difference that in the first one the users have no updated information on the condition of the system while in the second one updated information on the evolution of these events during the emergency are integrated, simulating the presence of eICTs.

The hypothetical emergency scenario considered a violent thunderstorm that could produce a flood risk and the overflowing of two torrents.

After identifying the study area, which can be a generic area, and providing images with the x, y and z points (event location, origin user location and safe destination), two routes with different characteristics available to reach the z point has been illustrated, in particular, three points (w_1, w_2 and w_3) have been defined where users can change paths (Fig. 3).

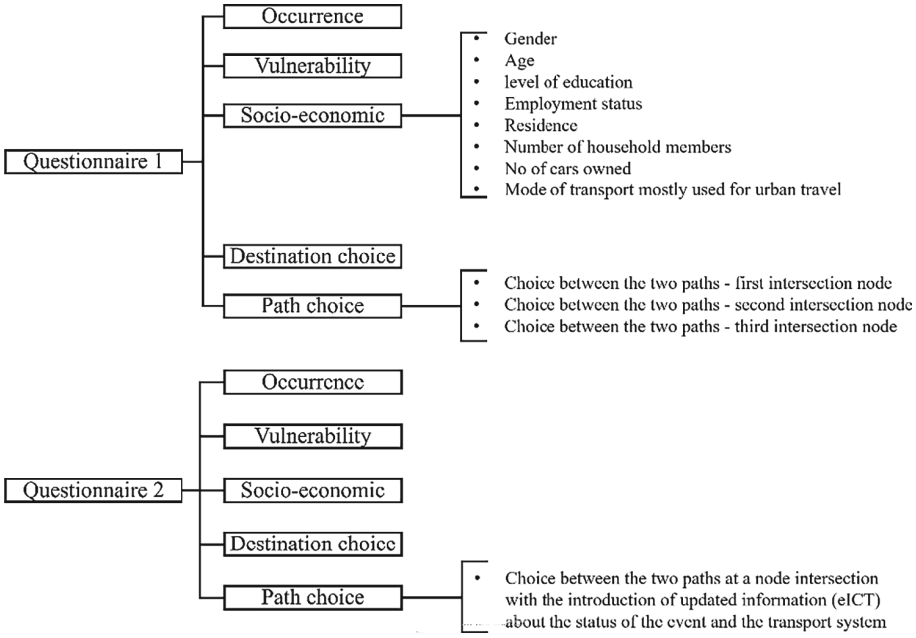

Fig. 4. Framework of the two survey questionnaires.

The first is an urban route, characterized by two-way direction, many intersections and a variable road width. This route involves a higher level of complexity that could affect user choice in terms of travel time. On the other hand, this road has the advantage of a less burdensome route. The second is a highway route, with independent carriageways of constant width but few exits. This route emerged as more linear but with less possibility of deviation. The choice of two alternatives with different characteristics is useful for understanding user behavior in case of an emergency.

After a period of time, the second questionnaire with the eICTs has been submitted to the same respondents. The structure of the questions has been modified. Each route choice question has been associated with information about the condition of the transport system.

Below is the statistical composition of the prototype sample to which the experimental survey has been carried out (Table 2).

The survey is fruitful because all respondents were able to follow the sequence of different types of situations, clearly identifying the route choice for each situation. This type of survey allowed to assess the choice behavior of respondents in a risk context, in the absence and presence of eICTs. This result is particularly useful for the application of dynamic models where the process of choice updating needs to be assessed.

Table 2. Composition of the prototype sample.

Socio-economic data		
Gender	Male	72%
	Female	28%
Age	<30	91%
	>30	9%
Level of education	Graduate	88%
	Master's degree	12%
Employment status	Employed	14%
	Student	86%
Main transport mode	Car	72%
	Motorbike	3%
	Public transport	19%
	Walking	6%

4 Conclusions

This study introduces the structure of a survey designed to analyse the behaviour of transport users under emergency conditions, with a focus on evacuation planning. The proposed survey design integrates Revealed Preferences (RP) and Stated Preferences (SP) techniques, allowing to investigate users' decision-making processes in hypothetical but realistic scenarios. The objective is to understand how to give information on evacuation choices, with and without the support of eICT.

The survey was structured in two questionnaires: the first collected socio-economic information relative to the users and introduced a hypothetical but realistic emergency scenario in terms of occurrence (fixed), describing the vulnerability of the transport system (fixed). The design is to propose to the participants a starting point, an event place and a safe destination and two available main routes to reach the safe zone with some possible deviation from one to the other route. The second questionnaire repeated the same scenario, but with the integration of eICT, which provided real-time updates on the evolution of the event and the condition of the transport network.

A key contribution of this research is the integration of eICT technologies within the survey structure design. This aspect is particularly relevant because, in emergency situations, access to updated information on the condition of the transport system can determine the effectiveness of an evacuation strategy and thus the reduction of the risk exposure component.

The data obtained from the survey are useful for the application of TSMs. Most studies in the literature focus on static models according to which users' decisions are based on pre-existing knowledge of the transport network. However, this study shows that the availability of real-time updated data can lead to dynamic changes in user choices. In

this context, the presence of updated information determines the updating of the user's route choice process and thus the use of dynamic models that consider this aspect [38].

The work belongs to the category of discussion-based exercises. Unlike operations-based exercises that include practical simulations of planned emergency procedures, discussion-based exercises allow for the analysis and understanding of different risk scenarios in a stress-free environment. This is a way to bridge the gap between planning and practical execution, with the ultimate goal of increasing preparedness and thus decreasing risk exposure [6].

Being a non-operational approach means that the analysed behaviours are not derived from the operational simulation of emergencies, where factors such as stress, time and environmental conditions can significantly influence users' decisions. Similarly, the effectiveness of eICT integration has been assessed only through stated perceptions and not through direct observation of behaviour, which introduces possible bias related to the nature of Stated Preferences (SP) methods. The Table Top exercise as well as the game activities represent an intermediate step between discussion-based exercises and operational exercises. Although it takes place in a non-operational environment, it is cheap and easy to organise, as it does not require any specific assets or infrastructure. Moreover, it allows planned procedures to be verified and alternative or unforeseen scenarios to be explored [6, 45].

Despite these limitations, the methodology presented in this paper proves to be practical and replicable in different contexts, offering a useful tool for analysing and planning evacuation strategies.

The survey design proposed in this work is useful also for other risk conditions in which reduction of exposure by evacuation has to be investigated. This work is particularly valuable for researchers and emergency planners, as it opens up new perspectives on how digital tools can improve risk management strategies.

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