Nat. Hazards Earth Syst. Sci. Discuss.,
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Natural Hazards and Earth System Sciences Discussions
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Interactive comment on "Network-risk: an open GIS toolbox for estimating the implications of transportation network damage due to natural hazards, tested for Bucharest, Romania" *by* Dragos Toma-Danila et al.

Anonymous Referee #1

Received and published: 20 January 2020

Overall, this is an important paper on earthquake exposure risk of road networks in Bukarest. The novelty being an up to date study on this earthquake prone city - important also for international fellow researchers to compare their approaches and advance. Very explicit and useful maps, and tables making their approach transparent.

Language should be edited by a native speaker or professional editor.

Minor comments: Page 1 Line 26: More recent source than 2008 would be good to add

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Section 2 Line 99: I suggest avoiding suggestive expressions such as "is at first sight easy to follow" I guess, an -s is missing for "comprise"

Line 107: This needs more detailed explanation - what exactly is novel here? Level of serviceability, random network analyses etc already do exist?! The following sentences up to line 116 are fine, but still, what is novel about this? Maybe: few conducted studies on multiple hazards and specifically, in Bukarest...

Paragraph around line 125: reconsider wording, length of sentences and maybe, grammar. Also further down below, for instance, Lines 153-154 You state "A probability of 100% for a network segment would indicate certain blockage - very hard to consider for a transportation network, but worst-case scenario could use this value." What about single roads, dead end roads, last road segments before a harbour, hospital emergency entrance, airport etc.? Many more section, just an example: Line 190

What is missing a bit in section 2 is discussion of alternative models, such as QGIS, GRASS or A* algorithm - but mights also be taken up in the discussion chapter. So far, it looks rather that Dijkstra was selected as only available algorithm.

Regarding the structured research questions (which I think are fine by themselves) it could be reconsidered how much they fit to a) section 2 and b) the following assessment. For section 2, it would be good to know what the authors consider as "vulnerability" (of the road, of users. etc.), and "socio-economic" - why were no research mentioned on this specifically before to guide the reader that this aspect is in fact most relevant. And to the very last question segment - maybe add a methodology short description of state of the art location-allocation analyses?

It is a bit unusual to have methods both in 2 and 3.1 sections - maybe reconsider merging it and separating the results? 3.2 I suggest starting not with such a detail sentence but rather coming back to the research questions and following their structure, or, the nice structure/steps laid out in section 1.

Section 3.2 is written largely for experts familiar with such methodology, which is fine. However, some more structure could help, such as following the research questions. Also, an intro part easier to understand for non-experts. For the experts then, more explanation on why certain values were decided on such as 30min service area (would that be enough to save lives? (Make sure to match it also with Table 3 - 25mins...)Which sources support this "long" time - being more realistic to earthquake debris routing maybe, but following which estimations, sources, previous studies?). The same for weighting: it is common for modellers to pick weights themselves and the explanatory sentence is fine, however, the mobile rescue teams might not have the same resources treating >1000 wounded and might be blocked by the debris - any sources supporting this?

A discussion chapter is missing - the authors have decided to mix results and discussion / rather commenting of methodological steps. The paper would benefit from a sub-section on shortcomings and recommendations for fellow researchers regarding methodology, maybe also a sub-section how the study matches with current similar studies - or not and provides novelty. Conclusion (and maybe discussion) could also make good use of the structure of research questions.

While the text is well-written and the professionalism of the assessment and knowledge about the literature out of question, the text could use a bit more structure here and there, as in the long section texts in 2 and 3, for example. Setting key terms per paragraph in italics could be an option to guide the reader, or sub-sections, or summarizing flow-charts.

What is missing a bit, at least conceptually, (it must not all be analysed within one paper): the perspective of affected people or customers of roads and logistics/critical infrastructure. They also interact with roads and their usage (see Rinaldi et al. 2001), be it through geographical, physical or logical interaction. The article starts with a good understanding of the recent trend of balancing hazard and vulnerability, but then focuses too much on the exposure only. Maybe it would be sufficient expressing this demand more in chapter 1 and 2 and ... a bit, then it should be fine.

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Natural Hazards and Earth System Sciences Discussions
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Interactive comment on "Network-risk: an open GIS toolbox for estimating the implications of transportation network damage due to natural hazards, tested for Bucharest, Romania" *by* Dragos Toma-Danila et al.

Mihai Micu (Referee)

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1. General comments: the authors are presenting an approach which might have a consistent application (not only for Romania, but worldwide) in terms of exposure/vulnerability/risk analysis. Moreover, there are numerous stakeholders which may show practical interest in this application, both coming from the prevention/preparedness or response/recovery parts of the risk management spectrum. The manuscript follows a rather clear and logic structure. There are consistent chapters devoted to methodology, results but not so much discussions, overall witnessing a good

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knowledge of the authors in both theoretical and applied issues. The manuscript is written in good English (sometimes with long sentences) and the graphic part is (mostly) clear and strongly backs-up the written text. 2. Specific comments: to our opinion, the structure of the manuscript could be improved by rearranging the text according to the chapters. Consistent paragraphs in the Results chapter (e.g. those following line 250) are more fit to the Methodology chapter; meanwhile, at Results there are considerations which we find more suitable for the description of the study area (see Fig.6). There are some references which deserves an update (some 10-15 years old; see lines 26, 58, 82, 152), since in the recent years, similar applications have been developed (see rupok.cz). In our opinion, a consistent part of the discussions should be devoted to the following issue: how useful is such an application and which is its effectiveness? As mentioned by the authors, it is important not for the scientists, but a more consistent part should be devoted to: which is the main outcome - improved exposure analysis or improved vulnerability assessment; how it might improve the cost-benefit analysis if it addresses risk evaluation (as written in the abstract); which is its main applicability - prevention or response (since based on this, different stakeholders should be interested); was any feed-back requested in this respect? In the mean time, the authors are mentioning numerous uncertainties behind such an approach, which brought in the same context with its high applicability, deserve a larger explanation which could rank its effectiveness. 3. Technical corrections: - the graphic part may be improved by replacing some of the written names: Fig.6 - better if the names are in the legend, since on the map they look rather general. - lines 110-111: difficult to understand, is there something missing? "... to be considered" maybe? - line 177: already mentioned; - line 223: an explanation of the statement "very well updated and representative" is needed; - there are names which sometimes are in English, sometimes in Romanian (e.g. Piata Universitatii vs. University Square); they should all follow the same writing.

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Nat. Hazards Earth Syst. Sci. Discuss.,
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Interactive comment on "Network-risk: an open GIS toolbox for estimating the implications of transportation network damage due to natural hazards, tested for Bucharest, Romania" *by* Dragos Toma-Danila et al.

Anonymous Referee #3

Received and published: 26 February 2020

a. Considering that Bucharest represents one of the most exposed capitals in Europe to strong earthquakes that has a poor and crowded road infrastructure, this paper represents an important step for future worldwide studies. We consider that the paper is written in good English and that the figures are clear and easy to understand. b. Form our point of view the manuscript could be reorganised a little bit. Some paragraphs fit much better in different sections (e.g. from results moved to methodology). c. We consider that a discussions chapter should be defined in order to explain/ describe the efficiency of the methods and algorithms described in the paper and their associated

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errors. d. Some newer references could be added in the review of current studies.

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-409, 2020.

Relevant changes made in the manuscript

- New introductive phrases were added to chapter 3.3 (3.2 in the first version).
- We corrected the values in Table 3 with > 30 min. as maximum reclassification interval
- A discussion chapter was added at the end of the article; here there were also added commentaries about methodological shortcomings, recommendations and future plans.
- We have moved and rephrased many paragraphs in the new version of the manuscript, also creating new subchapters, such as 3.1 Case study area description, 3.2 Data and methods considered for Bucharest or 4.1 Discussion.
- We have added two newer and comprehensive references of top institutions:
    - Pesaresi M., Ehrlich D., Kemper T., Siragusa A., Florczyk A., Freire S., and Corban C.: Atlas of the Human Planet 2017: Global Exposure to Natural Hazards, Publications Office of the European Union, doi: 10.2760/19837, 2017.
    - Gu D.: Exposure and vulnerability to natural disasters for world's cities; United Nations Department of Economic and Social Affairs, Population Division, Technical Paper No. 2019/4, 2019.
    - Pinto et al. (2012), Sevtsuk and Mekonnen (2012), Gu, 2019; Pesaresi et al., 2017; Vodak et al., 2015; Koks et al., 2019, Jenelius and Mattsson, 2015; Santarelli et al., 2018 etc.
- We have re-read the manuscript and made significant adjustements in order to split long sentences in smaller ones.
- We have added clearer paragraphs such as "Stakeholders such as emergency situations managers provided us important feedback, acknowledging that final products can fit well in their procedures, both for scenarios development and for near-real time implementation. Practical applications can consist on determining new locations for emergency facilities, on increasing facility capacities, for traffic management planning or efficient and safer routing of emergency intervention vehicles." in the results and discussion section.
- We have added a preliminary qualitative assessment of uncertainties, in the (newer) section 3.3.
- We have modified figure 6 in order to move labels outside the map, to make it more visible, still pointing to the names desired to highlight (which also appear in the text). We modified also Fig. 4.
- We kept the Romanian name version, because otherwise they will not be well understood by local stakeholders.

Comparison: manuscript version 2 modifications to manuscript version 1

Network-risk: an open GIS toolbox for estimating the implications of transportation network damage due to natural hazards, tested for Bucharest, Romania

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Abstract. Due to their widespread and continuous expansion, transportation networks are considerably exposed to natural hazards such as earthquakes, floods, landslides or hurricanes. The vulnerability of specific segments and structures ~~such as~~among bridges, tunnels, pumps or storage tanks can translate not only in direct losses but also in significant indirect losses at systemic level. Cascading effects such as post-event traffic congestion, building debris or tsunamis can contribute to an even greater level of risk. To support the effort of modelling the natural hazards implications at full transportation network scale, we developed a new applicable framework relying on i) GIS to define, ~~geo-spatially~~ analyze and represent transportation networks; ii) methods for determining the probability of network segments to fail due to natural hazard effects; iii) Monte Carlo simulation for multiple scenario generation; iv) methods ~~(using Dijkstra algorithm)~~ to analyze the implications of connectivity loss on emergency intervention times and transit disruption, v) correlations with other vulnerability and risk indicators. Currently, the framework is integrated in ArcGIS Desktop as a toolbox ~~(~~entitled “Network-risk~~”) - making~~”, which makes use of the Model Builder functions and ~~being~~is free ~~for~~to download and ~~customize~~modify. Network-risk is an attempt to bring together interdisciplinary research with the goal of creating an automated solution to deliver insights on how a transportation network can be affected by natural hazards, directly and indirectly, ~~aiding~~assisting in risk evaluation and mitigation planning. In this article we present and test Network-risk at full urban scale, for the ~~entire~~ road network of Bucharest ~~-~~. This city is one of ~~the world’s~~Europe’s most exposed capitals~~ due~~ to earthquakes, with high seismic hazard values and a vulnerable building stock, but also significant traffic congestion problems not yet ~~quantified~~accounted in risk analyses and risk reduction strategies.

1 Introduction

The complexity~~, size~~ and exposure of our society to natural hazards has significantly increased in the last decades (Gu, 2019; Pesaresi et al., 2017; Fleischhauer, 2008), and will keep on doing so. Transportation networks are one of the fundamental pillars of development and support for countries~~ and regions~~, whether they ~~are represented by road, railway, pipeline, communications and~~consist of roads, railways, pipelines, communication lines, maritime, aerial or other types of networks. ~~Also, we should start to see them in our analysis not just as isolated systems, but as interconnected infrastructures.~~ Transportation networks are a requirement for almost every inhabited place - residential, commercial or industrial~~,~~ and they continue to upgrade per location and also expand. As such, they become more and more exposed, if not also more vulnerable. Recent large-scale natural hazard events, such as ~~the~~ earthquakes (in Italy 2016 and 2009, Nepal 2015, Haiti 2010, China 2008 etc~~.)~~.), some accompanied~~ in some cases~~ by very destructive tsunamis (Japan 2011 or Indonesia 2018 and 2004), hurricanes and typhoons (in Mozambique 2019, Puerto Rico 2017, Philippines 2013 and 2012, Myanmar 2008 or USA 2005) or heat-waves (constant in the last years in countries such as USA, Australia, Greece or Spain~~),~~) proved that transportation networks are extremely vulnerable, but also vital immediately after the event occurrence. Directly contributing on the economic loss balance of such events, transportation networks have a more and more significant percentage, especially in developed countries (Wilkerson, 2016~~), and when adding~~). Taking into account also the indirect losses (hard to quantify), ~~it's~~it is even more obvious that their vulnerability needs to be reduced.

~~Transportation~~The functionality of transportation networks ~~are~~is very important both immediately after a hazardous event - constituting support for emergency intervention~~,~~ and long time after - in the recovery and prevention phases. ~~Not to mention also that their damage~~ Damage on networks can inflict direct risks - collapse of vehicles or trains, fire outbreaks etc. ~~Functionality~~Still, functionality and redundancy are essentials, in order to ensure ~~the reduction of~~ that socio-economic losses~~.~~ do not increase significantly. In any transportation network analysis it should be considered also the interconnectivity between systems and with other networks. In the post-disaster reaction phase, especially road networks ~~are~~prove to be very important~~,~~ (Jenelius and Mattsson, 2015), since they link almost all destinations~~, but~~; in some cases other transportation networks can be ~~more~~also relevant: railways, maritime or aerial networks. Communication networks are~~ also~~ critical in all disaster cycle phases. Utilities are important for a faster recovery and overall, for ensuring resilience. Previous experiences show that transportation networks ~~can be~~are mostly affected by natural disasters:

- Directly: by the collapse of critical components such as bridges, tunnels, storage tanks, pumps etc., cracks in roadways due to ground motion effects (settlement, liquefaction), railway displacement, pipe cracks;
- Indirectly: road blockage due to collapsed buildings (especially in urban areas), blockage due to triggered landslides, flooding or tsunamis, ~~blockage~~ due to traffic congestion generated by post-disaster behavior, emergency imposed restrictions etc.

For studying the impact of natural disasters on transportation networks, multi and inter-disciplinary approaches are needed, combining methods belonging to geosciences, engineering, sociology, economy or informatics. Also, multiple perspectives need to be considered (Franchin et al., 2011):

- Temporal (the disaster management cycle));
- Spatial: local (structural element studies), regional, national or multinational;
- Actor involved (Levellevel of management)).

In the last two decades, significant progress has been achieved in transportation network vulnerability and risk analysis - not just at structural level but also at functional level. For a comprehensive review we recommend the studies of Jenelius and Mattsson (2015), Miller (2014), Tesfamariam and Goda (2013), Franchin et al. (2011) in the framework of the Syner-G Project, by Miller (2014), Tesfamariam & Goda (2013) or Kiremidjian et al. (2007). These reveal that the fundamental steps in evaluating the seismic risk of transportation networks are:

- the proper definition of the network, with detailed knowledge at the level ofdata regarding component characteristics and connectivity. One of the problems is still in most cases the lack of official data: in developed countries there can be usedavailable good and updated GIS databases, however in most other countries transportation network data (at least for roads or railways) is not well officially defined and/or shared with the general public, therefore alternative data sources need to be used, such as OpenStreetMap (open-source) or commercial products (), Google Maps, Here Maps etc.).. There are currently many software solutions providingcapable of network definitiondevelopment (including AutoCAD Civil 3D, OpenRoads or ESurvey Road Network), but not so many providingwith risk analysis capabilities; among them arewe mention popular solutions such as ArcGIS for Desktop with the Network Analyst extension, PTV Visum/Vissim, Maeviz/Eqvis or STREET;
- the determination of direct damage probability of individual components. For this, earthquake engineering analysis methods are mostly used, such as dynamicaldynamic elastic and inelastic analysis using grids and numerical methods: finite element method, pushover or time-history analysis, response spectra etc. A good synthesis of these methods can be found in Costa (2003) and Crowley et al. (2011) and Costa (2003));
- the need to define relevant performance indicators, reflecting time or cost differences between pre and post-disaster network behavior; many performance indicators for networks can be found in literature, some of the most common at system level being Driver Delay, Simple/Weighted Connectivity Loss (Pinto et al., 2012; Poljanšek et al., 2011; Pinto et al., 2012), System Serviceability Index (Wang et al,., 2010) or Serviceability Ratio (Adachi and Ellingwood, 2008).

In the even more recent years, new technologies such as Internet of Things devices, Big Data, Remote Sensing, drone surveillancedrones, low-cost sensors and Machine Learning started to be quickly adopted sinceas they can provide practical solutions for transportation network data collection and analysis. It is expected that the impact of future natural hazards on transportation networks will be much better recorded (as shown by Voumard et al., 2018), allowing for a much neededbetter validation of risk models and opportunities to better understand what went wrongcreate more representative methodologies for the analysis of network risk, also in near-real time.

In order to analyze systemic risk (and not ~~just~~only component risk), networks need to be evaluated from the perspective of direct damage implication on connectivity, traffic changes or new traffic flows created, leading to indirect damage. Recent studies have addressed these aspects (Koks et al., 2019; Vodak et al., 2015; Caiado et al., 2012; Bono and Gutierrez, 2011; Douglas et al., 2007; Franchin et al., 2006~~, Douglas et al., 2007, Bono & Gutierrez, 2011; Caiado et al., 2012~~), going beyond the simple summarization of direct effects and eventually of reconstruction costs generated. These studies also highlight an important aspect to consider (Pitilakis ~~și~~and Kakderi, 2011): interactions between the components of the system (inter-interactions) and with components of other systems (intra-interactions).

After analyzing available methodologies and solutions in the field of study, we reached the conclusion that nowadays capabilities can be better exploited, enabling a more flexible but also standardized analysis of transportation network implications due to natural hazards, compared to previous works. We consider that many has been done theoretically and too little practically (at least at full city scale analysis), leaving also room for new technologies and that is what motivated us to create a new GIS solution sharable with the community and applicable world-wide. In this paper that provides a settled methodology after preliminary studies such as Toma-Danila (2018) or Toma-Danila et al. (2016), we will focus on:

- presenting ~~our flexible~~a methodology for evaluating direct and indirect transportation network risk due to natural hazards, embedded in ArcGIS Desktop as an open-source toolbox ~~–~~called “Network-risk~~” (can be downloaded, with user manual and sample data from www.infp.ro/network-risk);~~”;
- demonstrating its capabilities for a representative case study: ~~implications of earthquakes on the entire urban road network of~~ Bucharest - one of the most under risk capitals in Europe due to the implications of earthquakes; results represent an important contribution to emergency management risk reduction planning.

2 Methodology and implementation

The ~~idea behind~~generalized steps of the ~~proposed~~ methodology ~~is at first sight easy to follow, and it comprise~~comprises of:

- defining a transportation network in a GIS;
- evaluating which segments could be affected by a natural hazard (directly or indirectly) - accounting also for the ~~damage~~ probability of damage;
- generating random damaged network scenarios based on this probability;
- evaluating which are the implications, in terms of connectivity and serviceability losses and then socio-economic consequences.

This concept was previously defined in studies such as Hackl et al. (2018), Zanini et al. (2017), Vodak et al. (2015), Chang et al. (2012) or Argyroudis et al. (2005). However, the way each of the tasks are treated, linked and implemented in GIS is what we consider to be ~~of novelty, allowing~~a progress toward standardization and usability in real situations (also in near-real time). The methodology presented in Fig. 1 allows among others the consideration of multiple transportation network types (road, railway, utilities etc., represented at local, regional or national level) and of different natural hazards. The methodology~~,~~

presented in Fig. 1, can accommodate, for example, to the analysis of earthquake implications, where damage will beis widespread and building debris and, traffic patterns are necessary to consider, as well asand a good level of details for network definition; for are necessary to be considered. For landslides, the factors to be considered will change, since damage will be much more punctual and random simulations might not be so representative; for. For flooding, vulnerability analysis of networks such as road or railways will require knowledge on topography - not so representative for earthquake analysis. Still, the methodology will accommodate all these hazard types and influences, as long as, for example, loss analysis will lead to the identification of possibly affected network segments. There is also flexibility in the way the risk analysis is oriented - toward emergency intervention, economic losses evaluation or urban planning.

-Most of the input data (yellow boxes in Fig. 1) is required, also with GIS reference, with the exception that, depending on the analysis type, emergency intervention facilities or origin-destination (OD) pairs will not necessary be needed. In addition, an analysis without typical traffic data can be performed, although it might be representative probably just for night traffic conditions.

The process of building a consistent transportation network, from more or less complex datasets, is an essential part in every network analysis to be performed using Network-risk.. To assist in this effort we created a guide, models and layer symbologies for properly converting and editing data partially manually, following also the ArcGIS Desktop Network Analyst extension help recommendations. An alternative solution can be to use the ArcGIS OSM editor (https://github.com/Esri/arcgis-osm-editor) for OpenStreetMap data, (possible however to have limitations in expressing Z-elevation, or of), GRASS GIS v.net. The or procedures such as Karduni et al. (2016). Eventually, the converted data is expected by Network-risk to be similar to the sample files provided on the Network-risk webpage, essential. At the moment, the compulsory columns beingrequired in the analysis are "name", "oneway", "F_ZLEV", "T_ZLEV", "hierarchy", "maximum_speed", "FT_minutes" and "TF_minutes" (to which we". To these, further columns accounting for traffic, scenario travel times or lack of functionality due to earthquakenatural hazard effects will need to be added)., depending on data availability and analysis type. In the process of defining the rules for the Network Dataset (ND), the Network-risk toolbox requires to add more evaluators beside the ArcGIS Network analysis extension defaults, with the most important being for obstructions (used in service area analysis in the impedance field to reveal inaccessible road areas) and other for different typical traffic scenarios or for economic costs.

Both pre and post-earthquake traffic data are highly important, since they show the typical functionality status of the network and the premises for new traffic jam occurrencecongestions, immediately after an earthquake (with correlations also to road segments blocked by e.g. building debris or bridge collapse), all impacting the risk.). Typical traffic data can be retrieved from local data sources (such as traffic management authorities) or from companies taking advantage of new device capabilities, such as Google Traffic, Here Traffic or Waze, providing. This sources provide live (or statistical) data regarding traffic values and reported incidents –, although to integrate this data into our framework it will needis needed to be converted asconvert this data into travel speed per road segment, or to manipulate afterwards the network in a custom manner.turn into barriers or restrictions GIS layers. Other solutions with near-real time analysis capabilities can be to use GPS data - from emergency vehicles and, or the knowledgeexpertise of their drivers, especially for emergency management analysis.

The network layer represents the exposure; to evaluate the vulnerability of network segments to a specific natural hazard (or multi-hazard - the analysis can also take this dimension), it is required to associate failure probabilities~~ – using for example vulnerability functions.~~. For individual structures (such as bridges, tunnels, pump facilities, electricity poles) or for buildings (including network buildings), vulnerability functions are commonly used to determine damage probability or even more: functionality loss or resilience ~~indicators~~functions such as closure time or recovery cost. Although it is recommended to use structure-specific (local) functions, considering particular properties of the structure and of the construction practices in the specific country/region, there are currently available fragility function libraries, collected and harmonized in projects such as Hazus~~ or~~, Syner-G or SERA, which can be associated, preliminary, to some of the assets in other region. In some cases, analyzing the probability of a building to collapse can be further linked to the probability of road blockage, due to debris for example (in case of earthquakes, there are equations ~~for~~in this ~~task,~~purpose such as ~~Moroux~~Santarelli et al., ~~2004,~~2018; Zanini et al., 2017; Argyroudis et al., 2005~~ and Zanini~~; Moroux et al., ~~2017). Also, knowing~~2004). Knowing where affected areas are ~~will contribute~~also contributes to ~~an~~the evaluation of indirect risk~~ –~~, aiding for example~~,~~ to calculate the chance of people caught under debris to survive~~ (~~, using results of on-field studies such as ~~Goncharov, 1997 or~~ Hekimoglu et al. (2013), Coburn and Spence~~,~~ (2002~~), given a long intervention reach time.~~) or Goncharov (1997).

After including references to the natural hazard, in the form of ~~a map~~maps with ~~relevant~~transferable values to ~~the hazard and~~ vulnerability functions, the result would be an evaluation of the direct possible damage ~~(and implications on the network),~~ and as such a probability of network segment blockage. This ~~will~~can be used for generating random scenario simulations using the Monte Carlo approach (potential acknowledged by Burt and Graham, 1971), in order to test the behavior of the network in multiple probable situations. ~~A~~Assigning a probability of 100% for the failure of a network segment ~~would indicate~~(indicating certain blockage~~ – very hard to consider~~) is useful for ~~a transportation network, but~~ worst-case ~~scenario could use~~scenarios or clear cases of vulnerability (for example: a highly vulnerable bridge which will certainly not withstand high acceleration values due to an earthquake or a road segment where rock falls happen even without a significant trigger). However, in most of the cases this ~~value.~~probability will need to be smaller, allowing for random simulations to show multiple implication patterns. Also, post-~~event~~disaster traffic can be ~~included in these simulations.~~considered independently for each simulation. Monte Carlo scenarios are usually supposed to come in large number (~~at least~~ hundreds or thousands of runs~~),~~) and, depending on the size of the network, the amount of computational time is expected to be considerable. However, ~~in many network analysis cases,~~ the need for a vast number of Monte Carlo scenarios ~~is~~might not be really ~~needed to be considerable.~~necessary. The existence of many viable detour ~~alternatives~~routes in urban areas~~ (where also network segments are most exposed to damage)~~ or the small number of identified network segments expected to be highly damaged can determine the need of a smaller sample of Monte Carlo scenarios - that is why the stabilization of ~~aggregated result~~results must be traced.

For estimating post-event traffic patterns, it is ~~need also~~needed to include assumptions providing travel speed modifications for road segments located close to affected areas, especially in urban agglomerations. Some hints for determining these patterns can be found in the work of ~~Chang et al. (2012) and~~ Zanini et al. (2017~~).~~) or Chang et al. (2012). More complex approaches~~,~~

relying on individual driver behavior simulations or decision patterns (, as described in Asaithambi &and Basheer, (2017) or Munigety &and Mathew, (2016) can be implemented.

At the core of the network riskimplication analysis isthere can be used different shortest path routing algorithms (by short not referring always to distance, but also to less risk), such as Dijkstra, A*, Johnson's Algorithm or Floyd-Warshall. In our implementation and case study we preferred the Dijkstra algorithm (Sniedovich, 2016),, which was used for computing the shortest distance (in real meters or costs) for various network configurations - pre and post event (for Service Area/Route/Closest Facility/OD Matrix analysis). This algorithm is widely used in systemic network analysis, (Sniedovich, 2016), providing a good balance between precision and performance (Bast et al., 2016).2016), being also chosen as preloaded algorithm in ArcGIS. Depending on user preferences, other algorithms can be applied – using for example an alternate approach relying on QGIS with pgRouting (https://pgrouting.org/) or A* in ArcGis. For Service Area analysis – basic for, used in the emergency intervention travel time evaluation, we recommended as analysis parametermethod using Detailed Polygon Generation, with results of prior analysis for identifying inaccessible network areas as barriers, since the results will better reflect small inaccessible areas.

The entire methodology is embedded in a toolbox called Network-risk, which currently inruns under ArcGIS Desktop Advanced (10.1+ version),) with the Network Analyst extension, as the Network-risk toolbox enabled, using ModelBuilder capabilities (Fig. 2) and taking2). This toolbox takes advantage of the already available geo-processing and location-allocation algorithms, not yet previously linked however for and enables a standardized, non-hazard dependent and automated large-scale network risk analysis in an automated framework, shared with the research community. In this direction, we acknowledge the previous works of Vodak et al. (2015), Pinto et al. (2012) or Sevtsuk and Mekonnen (2012), which we consider however not fully usable especially in the more recent context. Having the methodology implemented in ArcGIS offers extended analysis support, through cartographic, spatial analyst modules, available basemaps, plug-ins such as ArcCASPER (Shahabi and Wilson, 2014) for computing evacuation routes and others. We chose to split Network-risk in multiple separate modules (such as for network creation, Monte Carlo scenario creation, disrupted network building, service area analysis or aggregation of results into a final index), making it easy to identify errors at different steps. The toolbox is available for download at www.infp.ro/network-risk and is free to use and customize. On the other hand, having the methodology implemented in ArcGIS offers extended analysis support, through cartographic, spatial analyst modules, available basemaps, plug-ins such as ArcCASPER (Shahabi and Wilson, 2014) for computing evacuation routes etc.

Overall,Considering the methodologysteps described in Fig. 2, ArcGIS Network Analyst capabilities and the results which are later shown by our case study, Network-risk toolbox can is capable to answer to important questions (for emergency management, city planning, commercial, insurance, industrial or real-estate agents and many others),, such as:

- How vulnerable is an area due to the direct and indirect implications of natural hazards on the transportation network serving it?
- Which areas could become inaccessible after a natural disaster? Which are the vital access routes in case of a disaster? Are there viable detour routes?

- Which is the socio-economic ~~risk~~impact (in terms of human or financial losses) in case of a natural disaster, correlated also with emergency management capabilities?
- ~~Which are the vital access routes in case of a disaster? Are there viable detour routes?~~
- How would new network segments, hospitals~~ or~~, fire stations or other facilities contribute to reducing the risk? Where should they be placed?

3 Bucharest road network case study, considering seismic hazard

3.1 ~~Data and methods~~Case study area description

For testing the methodology, we selected Bucharest - one of Europe's ~~most under~~endangered capitals due to high seismic risk ~~capitals~~ (Toma-Danila and Armas, 2017; Pavel, 2016~~): Bucharest- a~~). The city was previously affected by strong earthquakes in the Vrancea ~~Area~~seismic area (such as the ones on November 10th, 1940, Mw 7.7 at 150 km depth and on March 4th, 1977, Mw 7.4 at 94 km depth~~), waiting~~) and is currently still poorly prepared (Pavel, 2016) for a next major event ~~to~~which will most certainly happen anytime in the next 100 years. Compared to 1977 (when 1578 people died in Romania, from which 90% in Bucharest), the city now faces an additional challenge, beside the high vulnerability of the building stock: the vulnerability ~~of~~due to road network~~.~~ and urban traffic. In a city with over 2 million inhabitants~~ in 2018~~ there are 1.2 million registered vehicles (NIS, 2018). To this number can also be added the contribution of transit vehicles not adequately serviced by an external ring road (Fig. 3c) or vehicles of numerous commuting persons from nearby counties or students. In the absence of efficient urban development and mobility measures, in combination with mentality issues (the self-requirement to own and use a car), the city faces regular traffic jams, being ranked as Europe's number 1 ~~capitals~~capital (and 5th in the world in 2017/11th in 2018) when it comes to typical congestion level (TomTom, 2018; typical traffic examples in Fig. 3d, 3e and 3f). Beside traffic, Bucharest's road network ~~health~~maintenance and serviceability status is precarious, with many dysfunctions related to the quality of embankment, bridges, over or underpasses (Fig. 3a), poor repairing works, limitations in the full utilization of road's length due to illegal (and unsanctioned) parking in many cases (Fig. 3b) or constantly exceeded deadlines for repair or new road works. Another important aspect is that many buildings, not solely in the city center, are highly vulnerable to earthquakes (Toma-Danila et al., 2017~~): more~~). More than 31430 residential buildings were constructed prior to 1946 (294 having more than 4 storeys - a vulnerable category due to long fundamental periods of intermediate-depth Vrancea earthquakes~~) and 26349~~), according to the 2011 National Population and Housing Census. In addition, 26349 residential buildings (237 having more than 4 storeys) were constructed between 1946 and 1960~~ (according to the 2011 National Population and Housing Census), without any~~, in a period with no compulsory seismic design code, ~~passing through~~enduring at least one major earthquake with limited evaluation and ~~consolidation~~seismic retrofitting afterward (Georgescu and Pomonis, 2018~~); just~~). One should realize that if only 1% of ~~their complete~~them will completely or ~~partial~~partially collapse, it could clearly lead to many deaths and injuries, difficult to manage considering hospital capacity and equipment, as the recent Colectiv Club fire disaster proved (Marica, 2017), but also due to severe road blockages. In 1977, central boulevards ~~(~~such as Magheru~~)~~

were closed for at least ~~one week~~3 days after the ~~4~~ March 4th earthquake, still the typical traffic was not severely affected due to low traffic values and the wide use of public transport in those days. ~~Considering~~We aim to how that nowadays, such a measure would have much more adverse implications. Considering also the nowadays much wider expected damage scale (Armas et al., 2016; Pavel and Vacareanu, 2016), emergency interventions will have to be provided from multiple locations ~~-~~ (inside and outside the city~~,~~) and usual traffic patterns (not to mention the ones right after a major earthquake, depending also on the time of occurrence) will clearly act against proper reaction. All these problems make Bucharest a highly representative ~~test bed~~testbed for the methodology proposed in this article~~, providing a better understanding~~ .

Preliminary analysis of ~~indirect~~the associated seismic risk ~~due to limitations in~~of the Bucharest road network ~~serviceability capabilities. Pilot analysis for the city where~~was performed in the recent years, using slightly different approaches (Toma-Danila, 2018; Ianos et al., 2017), however not so flexible ~~and not~~or at full city scale, ~~but just for~~concentrating only on the city center. ~~Our results represent~~ Our goal for the analysis is to play an important role in the mitigation of seismic risk in Bucharest, being the first ~~road network seismic implication~~ analysis for entire Bucharest~~, offering an important support for emergency management preparedness (being already considered in the SEISM 2019 exercise) and for risk analysis.©~~.

3.2 Data and methods considered for Bucharest

The starting point for the analysis was the development of a road network GIS database, respecting connectivity and elevation rules. Currently, an official database of such kind is not available for Bucharest. That is why we used data from OpenStreetMap (OSM~~) data,~~), which is one of the most successful crowdsourcing project aiming to create a ~~very well updated and representative datasource worldwide and~~geospatial database of the whole world, with relatively up-to-date data for Romania~~,~~ thanks also to the involvement of many local volunteers~~.~~ (https://forum.openstreetmap.org/index.php), with good applicability in vehicle routing (Graser et al., 2014). OSM road vector data was downloaded using the Geofabrik GIS Data Portal (http://download.geofabrik.de), requiring additional processing in ArcGIS Desktop's ArcMap (~~using also~~ Network-risk toolbox template and guidelines are provided), in order to convert it in the ArcGIS network format, accounting for connectivity, hierarchy, travel direction (From-To - FT and To-From - TF), Z-elevation (creating distinctions between roads at ground level, bridges or underpasses) and travel time. For Bucharest - up to the external ring road and its connections to city center, the final number of individual road segments resulted (everything represented in Fig. 3) was 50412. We used data from September 2016; since then, up to December 2019, no major road network modifications ~~occurred~~happened in Bucharest (the main exception being the extension of A3 up to north-eastern Bucharest, but with no major influence on our analysis). When analyzing statistics (especially road length) it is important to account for road segments difference of drawing roads per lane or as a whole in OSM - otherwise the real number of kilometers will in some cases be doubled. That is why we prefer not to present statistical road length graphs. ~~In the process of defining the rules for the Network Dataset (ND), the Network-risk toolbox requires to add more evaluators beside the ArcGIS Network analysis extension defaults, the most important being for the obstructions (if a road segment is affected, according to the scenario, the service area analysis using as impedance this evaluator will reveal inaccessible road areas), and other being for different typical traffic scenarios or for economic costs.~~

For determining ~~(also in a Monte Carlo manner)~~ which road segments can be affected by earthquakes ~~- directly or indirectly, losing connectivity properties,~~ we used the procedures described in Table 1. ~~These account also for~~ In total were determined, totaling 1.41% of the total number of road segments in Bucharest:

- 1324 segments with variable length which can become affected by debris (partially shown in Fig. 4, just 32,6% however with a damage probability ~~of damage - important when~~ > 50%);
- 985 which can become affected by bridge collapse.

After performing ~~Monte Carlo simulations. For this article we performed only~~ 20 Monte Carlo simulations (each ~~taking on~~with an average runtime of 12 minutes on a normal desktop computer ~~12 minutes~~ - from simulation to service area results), we considered ~~however~~results stable enough to reflect the damage patterns for the rather extended road network of Bucharest~~.~~ ~~After 20 runs we observed a stabilization of the results (showed also when comparing aggregated results from 10, 15 or 20 scenarios).~~

~~For this study,~~ and stopped our ~~approach~~simulations, which are not time intensive but still difficult to summarize automatically. In order to account for traffic - ~~representing as we showed~~ a major ~~vulnerability~~issue for Bucharest, ~~was based on replicating~~we followed the patterns shown by typical ~~patterns reflected by~~ Google Traffic, for various representative scenarios:

- Monday ~~2AM~~2:00 AM - no traffic;
- Monday ~~8AM~~8:00 AM - morning traffic;
- Monday ~~6PM~~6:00 PM - end of work traffic.

Traffic values were obtained by~~-~~:

- digitizing areas described qualitatively in Google Traffic (very slow, slow, moderate or fast traffic~~),~~);
- identification of roads in these areas (also considering FT and TF ways~~),~~);
- modification of travel times (for fast traffic - using the maximum allowed speed, for very slow traffic - 2 km/h~~),~~);
- validation with the Google Traffic Direction service (for representative routes crossing the city~~) and~~);
- corrections applied in areas with a considerable deviation from the expected values.

Although time consuming, this procedure yielded good results. Giving that our analysis focuses on the intervention of emergency vehicles, the influence of traffic lights was neglected (although it can be considered ~~in~~for other analysis purposes) and the travel speed was considered 50 km/h for fast traffic road segments. For regional and national studies, detailed traffic values might not be needed, since many ~~highway~~highways or inter-city roads (generally not crossing urban areas) ~~don't~~do not have typical traffic jams impacting furthermore the emergency management intervention times.

For estimating post-event traffic patterns, we used a simplified approach, ~~using~~based on the following traffic modification parameters:

- For areas closer to 100 meters (calculated on roads as service area, not as buffer): 2 km/h;
- For areas closer to 500 meters: 5 km/h.

This approach has obvious limitations and uncertainties; however, it provides a flexible and easy-to-compute method of accounting for traffic shifts right after an earthquake, following the findings of Zanini et al. (2017). Modeling traffic driver individual behavior, also over time, is a next step which we will integrate in future studies, also trying to create the means for validation (recording the traffic patterns after major earthquakes affecting Bucharest or after local incidents in the area of vulnerable buildings).

In order to enable service area analysis for emergency intervention, hospitals and fire stations were used as facilities. We identified all representative locations in Bucharest and nearby (not including children emergency hospitals, therefore the analysis can be considered as relevant for the adult population). Although of high importance, we could not include for the moment data regarding the capacities of each facility (for example: number of ambulances, hospitals treatment capacity or fire engine's equipment); these can be considered, reflecting limitations or restrictions in the emergency intervention process (for example: how many addresses can be reached within an amount of time due to vehicle availability, how many people can be transported to and hosted by a hospital or where are vehicles with ladders, necessary for intervention in areas with high rise buildings). We will address these issues in further studies when more complex data ~~becomes~~become available; ArcGIS Network Analyst extension can easily accommodate such information and also special evaluators can be added.

The main toward-risk analysis for Bucharest ~~are~~was represented by service ~~areas~~area analysis for emergency management facilities (ambulances for emergency hospitals and fire engines), reflecting which are the times of intervention right after a major earthquake affecting Bucharest (the ultimate limit state design earthquake), at three different times for which traffic values are considered. Results ~~can~~ provide a check upon the capabilities to offer ~~a~~intervention within the golden hour in medicine (Lerner and Moscatti, 2001) ~~fit intervention~~ - when emergency treatment is most likely to be successful. ~~Also, we~~We also analyzed the pre and post-earthquake time differences for representative economic transit routes, through closest-facility analysis. ~~For these, we used the analysis parameters provided in Table 2. For a single scenario, including Service Area creation, the running time on an average performance desktop PC is less than 10 minutes, given the dense road network of Bucharest~~The parameters used in analyzes are described in Table 2.

~~**3.2 Results and discussion**~~

~~In the following figures we present just some of the results obtained for the multiple Monte Carlo and worst-case scenarios run with Network-risk toolbox (described in Table 2), but also an example aggregation methodology which we used for creating a final index of vulnerable road accessibility for Bucharest.~~

~~Fig. 5a and 5b reflect differences between considering all potentially blocked roads and bridges affected and results from Monte Carlo simulations; therefore, Fig. 5a presents for some areas slightly more increased intervention time values. Figure 5c shows service area intervals when considering only emergency hospitals in category I of importance; it can be seen that their distribution is generally satisfactory, however there is a gap, reflected also by Fig. 5a and 5b, in the south-west area of Bucharest (Rahova and Ferentari neighborhoods) - an area known also for its socio-economic vulnerability (Armas et al., 2016). Due to the significant damage expected in the central area, intervention times are expected to be considerable (given also the traffic values for the considered scenario). The impact of a central hospital such as Coltea, who has currently limited resources to treat the large expected number of patients affected by a major earthquake in the city center is reflected in the~~

~~partial decrease of ambulance intervention times for city center, but in the post-earthquake chaos, especially if the earthquake will strike at rush hour, traffic jams are going to pose a considerable threat; our framework partially shows these effects. Bridge dysfunctionalities do not pose great influences (when comparing also with no damaged bridge scenarios), since in general there are many nearby alternatives; Basarab Overpass (north-west to the center - labeled in Fig. 3) is the only one who could lead to considerable increase of intervention times. Figure 5d is, although difficult to comprehend at first sight, important since it provides a visual check upon the correlations between minimum intervention times and the number of hospitals who provide this time; if an area is colored towards green and is also hatched, this means that the area is close to multiple emergency hospitals, ensuring a low vulnerability in case of medical emergencies. Data behind this type of maps add an additional understanding to the overall accessibility analysis.~~

~~Figure 6 shows service area results for fire stations; the distribution of fire stations is more symmetrical in Bucharest then the distribution of hospitals, also with a unit in the city center ("Mihai Voda" fire department), behind the Bucharest City Hall building. For this particular scenario (Monday 8AM typical traffic), a good influence of this distribution can be seen south of Union Square (Fig. 6b zoom map), were also boulevards are not expected to be blocked by debris, but north - toward University and Romana Squares, post-earthquake congestion and road segment blockages are expected to significantly increase the time needed to reach the hotspots. To help in the effort of reducing the intervention times in the central area, the "Victoria Palace" (Government's building) fire department could contribute (if the procedure and situation allows), however we did not find appropriate at the moment to consider it in the analysis.~~

The total amount of service area maps resulted ~~(~~for all Monte Carlo scenarios~~)~~, for service area analysis, is considerably large and not relevant independently (the map by map evaluation is more important for quality check and in order to see the stabilization of result patterns). That is why it is needed a further procedure for aggregating data - as it happens with big-data. Providing a data synthesis easier to grasp~~, but also showing uncertainties,~~ is ~~also~~ very important for stakeholders. In this purpose we developed a procedure ~~(and a model in the Network-risk toolbox),~~ based on the following reclassification and aggregation procedure:

a) ~~Reclassification~~reclassification of service area polygons for post-earthquake scenarios, according to Table 3~~.~~;

b) ~~For~~for each service area polygon with identified number of facilities providing the best and second-best intervention time: determination based on Eq. (2) of a counter (C1) reflecting the dependency to a specific facility~~.~~;

$$C1 = Ni + 0.5 * Ns, \quad (2)$$

where Ni = number of facilities providing the best intervention time; ~~if the service area polygon ≥ 30 minutes, Ni = 0;~~ Ns = number of facilities providing the second best intervention time~~.~~; if the service area polygon ≥ 30 minutes, Ni = 0;

c) ~~Determination~~determination of an index (Vi) for each scenario, reflecting the reclassified vulnerability, applied to all polygons, following the considerations in Table 4~~.~~;

d) ~~Weight~~weight overlay of Vi values calculated for emergency hospitals and fire stations, for a specific scenario, applying 25% (0.25) for emergency hospitals and emergency hospitals in category I of importance (in order to reflect the contribution of truly important hospitals in emergency situations), and 50% (0.5) for fire stations (in Bucharest it is relevant to have an important weight for fire stations since they do not provide just equipment for fire extinguishing, but also Mobile Services for Emergency, Reanimation and Extrication, abbreviated SMURD units), leading to a new final vulnerability index per scenario: Vf~~.~~;

e) ~~Averaging~~averaging of Monte Carlo scenario simulations with Vf values~~.~~;

f) ~~Further~~further averaging of resulted maps with Vf values (6 in total for Bucharest: 3 for the worst-case model and the three traffic scenarios, 3 for Monte Carlo averaged scenario results) for a final ~~results~~result map, revealing the combined index of vulnerable accessibility (Fig. 7).

~~Figure 7 is the first map of this kind for all of Bucharest, but uncertainties and limitations incorporated in its development are necessary to consider (whether regarding typical traffic scenarios considered, the limited dataset regarding buildings which could collapse during an earthquake or the post-earthquake traffic patterns). The map reflects some of the expected features: a high accessibility vulnerability in central area of the city, due to vulnerable buildings and not so far but difficult to reach in case of an earthquake hospitals (especially in Category I of importance) and fire stations. Also, it shows another area hard to reach by emergency vehicles: western Bucharest. The map also shows areas with good accessibility (the inner green belt north to the inner ring road) - which are close to hospitals and fire stations and are not considerably influenced by traffic and disrupted road segments.~~

~~Another important result is the one presented in Fig. 8.~~ By merging polygons representing areas which can become inaccessible after an earthquake~~ due to road blockages~~ (for each simulation) and also accounting for the number of times these polygons are generated, a very useful representation of areas difficult to reach can be generated. ~~By using~~After reclassification (in our case based on 5 equal intervals), a qualitative probability for areas to become inaccessible can be expressed. Areas with the lowest probability are generated just for the worst-case model, not appearing during the Monte Carlo limited number of simulations (Fig. 8).~~. As expected, inaccessible areas are mostly in the city center (streets such as Blănari, Lipscani, Șelari, Smârdan, Sf. Dumitru, Franceză, Tonița, Eforiei or Biserica Doamnei), where many buildings are expected to block roads and detour routes to the locations. Other blocked road segments with lower probability could be on streets such as Bărăției, Pătrașcu Vodă, Vasile Lascăr, Poiana Narciselor, Dr. Vasile Sion, Ion Brezoianu, Tudor Arghezi, Batiștei, Jules Michelet etc. Due to the algorithm for Service Area computation, some areas between roads are colored as being blocked (as in Cismigiu Central Park for example), however this is a method limitation and can be eliminated through clipping.~~

A different product which can be obtained using the network database and ~~the~~ Closest Facility Analysis ~~with~~are maps showing relations between emergency hospitals or fire stations (as destinations) and high-risk buildings (as origins~~ are maps such~~), as ~~the ones presented~~routes or best facility in ~~Fig. 9. They were~~terms of safe to reach proximity. Useful maps or routing services which could become available in near-real time can be obtained by combining the fastest routes for OD pairs, for a given scenario, ~~and show~~showing also which roads are vital in an emergency situation (need to remain functional since they are critical, providing the quickest access time in the origin).~~ This analysis also shows which hospitals would be preferred (based on adjacency - no medical capabilities are considered) to orient patients to - setting premises for a better preparedness of hospitals expected to have a high patient demand (medical supplies, hospital beds, doctors etc.).~~

The seismic risk due to road network dysfunctionalities can be expressed not just by considering the impact of road blockage and traffic on emergency intervention, leading to time limitations in reaching patients. When roads are closed, connectivity throughout the city can be lost for days, weeks or years, with a high impact on economy - due to delays in stock supplies and production, greater costs for carburant or loss of clients. ~~The created~~Our network dataset can also be used ~~also~~ to monitor which are the differences between pre and post-earthquake travel times, for representative OD pairs. For this case study we selected 8 pairs in relevant ~~to~~ cardinal points, some with links to the city center and some aimed to show if in case of an earthquake the initially preferred route throughout the city is going to change in favor of the external ring road.

Uncertainties and limitations are an important aspect to account for. As a preliminary evaluation we provide the following qualitative uncertainty evaluation, regarding:

- the road network dataset accuracy - small source of uncertainties;
- the limited dataset regarding buildings which could collapse during an earthquake – moderate source of uncertainties;
- limitation in evaluating and validating the travel times for emergency intervention vehicles (as recently the allowance of using tramway separated tracks lead to improved intervention times) – moderate source of uncertainties.
- typical traffic scenarios considered – small source of uncertainties;
- post-earthquake traffic patterns – high source of uncertainties.

3.3 Results ~~are~~

The figures presented in this subchapter summarize our main findings and are obtained for the multiple Monte Carlo and worst-case scenarios run with Network-risk toolbox. Results are foreseen to contribute to:

- operational procedures of the Inspectorates for Emergency Situations (such as the National Concept for Post-Earthquake Intervention - implementation discussion on-going);
- risk-reduction strategies elaborated at national and local level;
- the new planning of new emergency hospitals in Bucharest;
- the identification of easy to access locations for emergency containers.

Figure 5a and 5b reflect differences between worst-case scenario (all roads and bridges with a probability of damage affected) and results from Monte Carlo simulations. As such, Fig. 5a presents, for some areas, slightly more increased intervention time values. Figure 5c shows service area intervals when considering only emergency hospitals in category I of importance. It can be seen that their distribution is generally satisfactory, however there is an area with significantly greater intervention times, reflected also by Fig. 5a and 5b, in the south-west area of Bucharest (Rahova and Ferentari neighborhoods) - an area known also for its socio-economic vulnerability (Armas et al., 2016), also with no major hospital in adjacency. Due to the significant damage expected in the central area, intervention times are expected to be considerable (given also the traffic values for the considered scenario). The impact of a central hospital such as Coltea is reflected in the partial decrease of ambulance intervention times for city center. However, in the post-earthquake chaos, especially if the earthquake will strike at rush hour, traffic jams are going to pose a considerable threat to road accessibility; our study reveals some of these effects (Fig. 5-9) and that some areas could be much easier accessed by ambulances from non-central locations. Bridge dysfunctionalities do not seem to pose great influences (when comparing also with no damaged bridge scenarios), since in general there are many nearby alternatives. Basarab Overpass (north-west to the center - labeled in Fig. 3) is the only one who, if inaccessible, could lead to considerable increase of intervention times. Figure 5d is, although difficult to comprehend at first sight, important since it provides a visual check upon the correlations between minimum intervention times and the number of hospitals who provide this time; if an area is colored towards green and is also hatched, this means that the area is close to multiple emergency hospitals, having a lower vulnerability in case of medical emergencies. Data behind this type of maps adds an additional understanding to the overall accessibility analysis, being however more demanding in their creation (requiring service area analysis per facility and counting of number of overlapping polygons with a certain value).

Figure 6 shows service area results for fire stations; the distribution of fire stations is more symmetrical in Bucharest then the distribution of hospitals, also with a unit in the city center ("Mihai Voda" fire department), behind the Bucharest City Hall building. For the chosen scenario (Monday 8AM typical traffic), the influence of this distribution can be seen south of Piata Unirii (Fig. 6b zoom map), were also boulevards are not expected to be blocked by debris, but north - toward Piata Universitatii and Piata Romana, post-earthquake congestion and road segment blockages are expected to significantly increase the travel times. To help in the effort of reducing the intervention times in the central area, the "Victoria Palace" fire department (devoted to the Government's building) could contribute, however we did not find appropriate at the moment to consider it in the analysis, until learning more about their attributions.

In order to facilitate the understanding of results, also from the point of view of non-experts, we further show the results of the aggregation methodology used for creating a final index of vulnerable road accessibility for Bucharest. Figure 7 - the first map of this kind for the entire territory of Bucharest, reflects some of the expected features: a high vulnerability of accessibility in central area of the city, due to vulnerable buildings and difficult to reach (in case of an earthquake) hospitals (especially in Category I of importance) and fire stations. Also, the figure shows other areas more difficult to reach by all types of emergency vehicles right after an earthquake: western Bucharest (Militari neighborhood) or south-western and south-eastern Bucharest. Areas with good accessibility appear to be in the inner green belt north to the inner ring road – where there are hospitals and fire stations nearby and no disruptive traffic (although quite intense during rush-hours) and disrupted road segments.

Another important result of the analysis, proving the Network-risk capabilities, is presented in Fig. 8. As expected, inaccessible areas are mostly in the city center (streets such as Blănari, Lipscani, Şelari, Smârdan, Sf. Dumitru, Franceză, Tonița, Eforiei or Biserica Doamnei), where many buildings are expected to block roads and detour routes to the locations. Other blocked road segments, with lower probability, could be on streets such as Bărăției, Pătraşcu Vodă, Vasile Lascăr, Poiana Narciselor, Dr. Vasile Sion, Ion Brezoianu, Tudor Arghezi, Batiștei, Jules Michelet etc. Due to the algorithm for Service Area computation, some areas between roads are colored as being blocked (as in Cismigiu Central Park for example), however this is a method limitation and can be eliminated through clipping.

Fig. 9 is the result of Closest Facility Analysis, showing the safest and fastest routes (and the density of these routes) between buildings in seismic risk class I and emergency hospitals and which hospitals would be the preferred facility for a certain building, based on adjacency (no medical capabilities are considered) - setting premises for a better preparedness of hospitals expected to have a high patient demand (medical supplies, hospital beds, doctors etc.). Figure 9a highlights, for the specific scenario, 3 routes in high demand: from city center toward east, west and north-west. Figure 9b shows that Coltea Hospital is not although in the city center, not the best option for many vulnerable buildings.

Table 5 and ~~in~~ Fig. 10~~.~~ show results for representative OD pairs to the economic transit routes – any other OD pairs can be introduced. For the 2 AM traffic scenario, differences are not significant, as post-earthquake traffic is not expected to be a significant problem, however for the ~~others~~8 AM and 6 PM scenarios - especially for routes which need to reach the city center (Piata Universitatii for example), there are clear values showing a mean travel time increase from 110-120% to 300-432%, for the Centura (external ring road) - Otopeni -> ~~University Square~~Piata Universitatii route.

4 Conclusions

In this paper we presented a new methodology for evaluating ~~of~~ direct and indirect implications of natural hazards on transportation network~~,~~. This methodology was designed to be generally applicable and adaptive to various types of hazards, networks or ~~data availability~~available vulnerability and exposure data. Starting from structural evaluation, the analysis focuses on systemic or functional assessment, expressing furthermore the risk ~~due to lack of~~inflicted mainly by connectivity~~, for example.~~ loss. After determining hazard, exposure~~,~~ and vulnerability ~~and hazard~~ factors~~,~~ - leading to the definition of the network and the identification of segments which can become unusable (and the probability of this to happen), ~~the methodology can perform~~ Monte Carlo simulations ~~resulting in~~can be performed. This enables the creation of multiple scenarios evaluated individually in terms of generated risk (for emergency intervention or socio-economic aspects) and aggregated into final risk indexes. There are also capabilities ~~on~~of accounting for pre and post disaster traffic and for emergency facilities capacity or equipment. In order to facilitate the use of the methodology we ~~also integrated it into an open toolbox (collection of models) - free to download and customize, entitled Network-risk (available on www.infp.ro/network-risk). This toolbox is for now dependent on the geoprocessing algorithms implemented in the widely used commercial software ArcGIS Desktop Advanced, with Network Analyst extension. In the near future we will try to integrate Network-risk also in non-commercial GIS software such as QGIS, who still require at the moment more development toward advanced network analysis. Network-risk toolbox is under continuous development and in future versions more features will be available, so please check regularly the website~~integrated it into an open toolbox (collection of models) entitled Network-risk, which is free to download and customize.

To prove its capabilities, Network-risk was tested on the entire road network of Bucharest, Romania, one of Europe's most endangered capitals due to earthquakes, considering the high seismic hazard ~~of~~values generated by intermediate-depth Vrancea earthquakes, the vulnerable building stock (349 high or moderate rise buildings are categorized in the seismic risk class I in January 2016, representing just the tip of the vulnerability "iceberg~~)~~") but also major traffic congestion patterns. One of the most difficult parts in the analysis ~~is~~was the proper input data collection. As we showed, this can be achieved (at least for a preliminary form) ~~more easily~~ in a satisfactory form, by using OpenStreetMap data along with a Network-risk module designed to arrange (partially automatically) the network data into ArcGIS network format~~, digitized~~. Digitized traffic areas based on Google Traffic layers or empirical formulas, literature fragility functions and expert judgement for determining road segment failure probabilities~~.~~ also contribute to the input. Our analysis focused both on the evaluation of emergency intervention times~~, –~~ (for emergency hospitals and fire stations) and on the evaluation of economic implications for representative commercial routes (time delays in post-earthquake conditions).

Results show that the city center would be significantly vulnerable not just because of collapsing buildings but also due to the difficulty to reach these sites by ambulances and firefighters~~ –~~; although there are facilities nearby, such as the Coltea Hospital (however not of category of importance I) and the "Mihai Voda" fire department~~;~~, these do not provide safe routes to all potentially affected buildings, due to road blockages and traffic jams, considering especially the Monday 8AM and 6PM typical traffic scenarios~~, these could have quick access just to a few surrounding streets. The aggregated~~. Aggregated results in Fig. 7 and 8 show that also for the western, south-western and south-eastern parts of Bucharest overall intervention times ~~could~~can be significant~~. When calculating service areas, we believe~~ – valid supposition confirmed verbally by members in the emergency intervention forces.

4.1 Discussion

Stakeholders such as emergency situations managers provided us important feedback, acknowledging that ~~our approach yielded better results due to considering the dependency to a single facility to provide the minimum intervention time. Results are very useful for~~the final products can fit well in their procedures, both for scenarios development (prevention) and for near-real time implementation (reaction). Practical applications can consist on determining new locations for emergency facilities, ~~for~~on increasing facility capacities~~ in facilities near vulnerable areas or~~ , for traffic management planning~~. The~~ or efficient and safer routing of emergency intervention vehicles. As a comment for future methodology users, we want to mention that, when calculating service areas, it is very useful to account for the dependency to a single facility to provide the minimum intervention time and we will aid a module in Network-risk to provide a performance indicator in this purpose.

In our opinion, the service area analysis ~~of emergency hospitals also~~for Bucharest shows the necessity of ~~such a~~an emergency hospital in the south-western part of Bucharest - an area also known for its high socio-economic vulnerability~~ (Armas et al., 2016).~~. For the city center, a strategy in case of an earthquake has to be elaborated and put into place, referring to ~~facilitating~~ measures to facilitate/restrict the access in the area in case of natural disasters, traffic redirection and design of safe road access corridors~~; considering also that~~. As highlighted, the vulnerability of routes connecting the city center, especially with north or south destination~~ is~~, can be significant, with travel time increase greater than 150% in typical scenario conditions.~~ Since there was no capability and relevance, considering previous earthquakes (the ones in 1940 or 1977), we will also be working on creating the means for result validation, as for Bucharest a major earthquake is certain to happen and new devices and technologies are certain to record what happens to traffic and road blockages. We will also be testing Network-risk for regional analysis, using also rapid seismic loss estimations generated by the Seisdaro System of INFP (Toma-Danila et al., 2018).~~

As Network-risk is for now dependent on the commercial software ArcGIS Desktop Advanced, with Network Analyst extension, we will try in the near future to integrate its methodology also in non-commercial GIS software such as QGIS. However, this still require at the moment more development toward advanced network analysis. The current Network-risk toolbox is under continuous development and in future versions more features will be available, so please check regularly the website. We also aim to test it more consistently, with analyzes at regional/national scale (using also rapid seismic loss estimations generated by the Seisdaro System of INFP, presented by Toma-Danila et al., 2018), for multiple hazard scenarios and also for more detailed vulnerability datasets comprising also on the social behavior and interaction of people with transportation networks.

We hope that this article will provide researchers important practical guidelines on how to analyze the risks of transportation networks affected by natural hazards and a ~~practical~~useful tool to be applied in other parts of the world and stakeholders an example of useful results which they could benefit from, in their efforts to better understand and mitigate risks.

Code and data availability

The Network-risk toolbox for ArcGIS Desktop and sample data for Bucharest (used for this study) can be downloaded, with user manual, at www.infp.ro/network-risk. Please revisit the address and check for new versions, since the toolbox is constantly being upgraded.

Author contribution

DT-D and IA developed the methodology and DT-D and AT implemented and tested it in GIS, obtaining results analyzed also by IA. DT-D prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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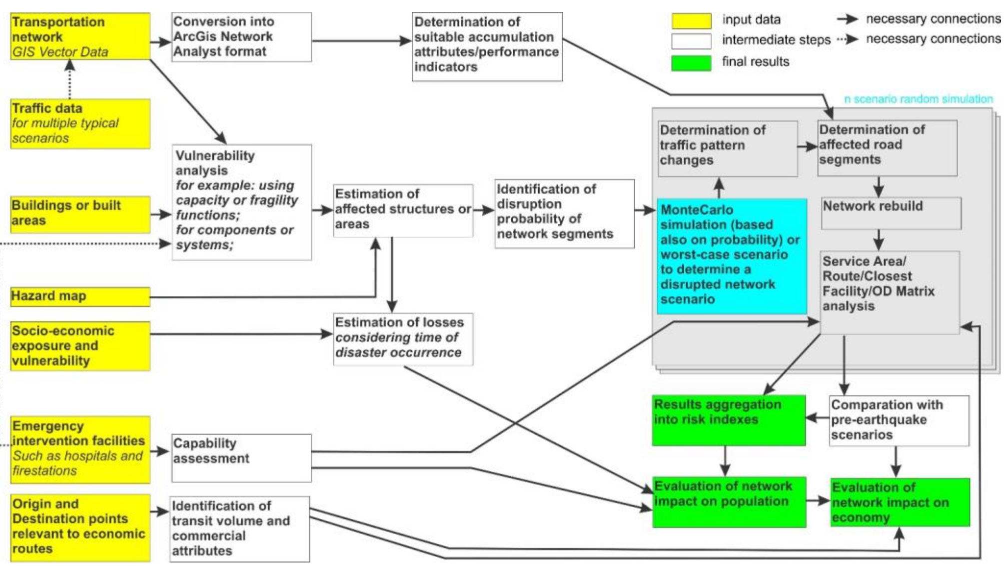

Figure 1: Graphical representation of the proposed methodology for evaluating the implications of transportation network damage due to natural hazards, integrated in the Network-risk toolbox.

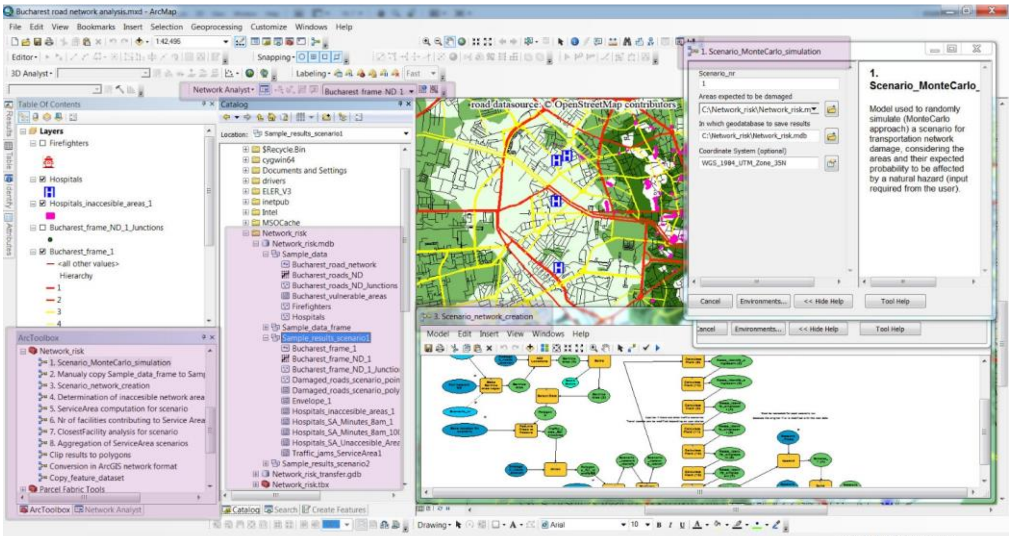

Figure 2: Screen capture of ArcGIS Desktop ArcMap with Network-risk toolbox added, contributing to the analysis of Bucharest's road network risk analysis; the framework of one of the models (3. Scenario network creation) can be seen, as well as the model run interface (1. Scenario Monte Carlo simulation), the Network-risk toolbox modules and the sample data results created using these modules (highlighted with purple).

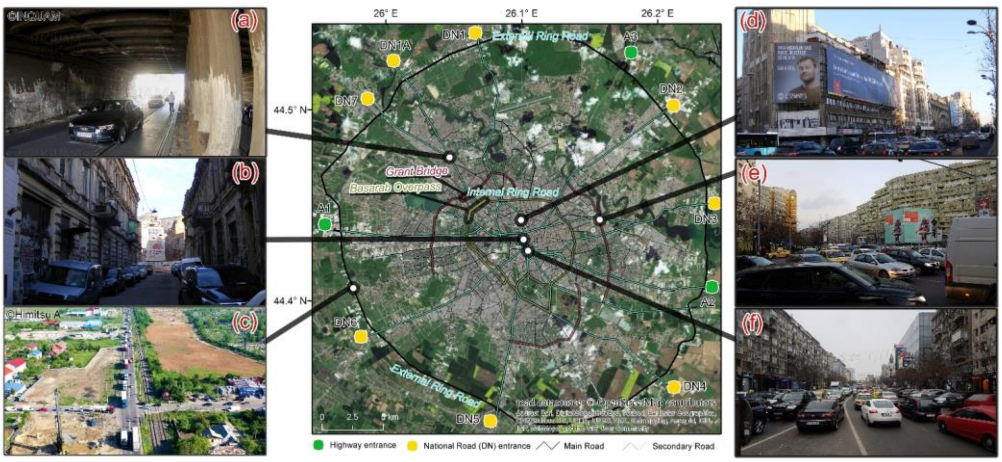

Figure 3: Bucharest road network map, highlighting main roads and connections with highways and national roads (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License, data from September 2016; basemap: © ESRI and contributors), and examples of vulnerable underpasses [(a) Constanta Bridge, © INQUAM], illegal parking (b), southern External Ring Road ~~disfunctionalities~~dysfunctionalities [(c) © Himitsu A.], typical rush-hour traffic (d, e, f) and vulnerability due to old buildings with seismic risk (b).

Table 1: Factors considered for determining the probability of road segments to be affected by earthquakes.

Factor	Method of analysis
Bridges	Mean fragility functions from Crowley et al. (2011), for the corresponding structural typology (mostly reinforced concrete) were used. Considering the microzonation map of Marmureanu et al. (2010) for maximum PGA values in Bucharest due to the largest probable earthquake in Vrancea, the complete damage probabilities obtained were small: 1.5 - 2%. For the Basarab Overpass fragility functions were adapted due to different characteristics (suspension and steel arch bridge sections, seismic passive dampers), considering descriptions in Sartori M. (2012).
Roads blocked by building debris	We used Eq. (1) (from Moroux et al., 2004) to determine the probability of roads to be blocked by the debris generated by the collapse of buildings in the seismic risk class I, which are most likely to collapse during the limit state design earthquake (349 in total, mostly with more than 4 storeys, according to Bucharest City Hall data from January 2016 - https://amccrs-pmb.ro/liste-imobile); the footprint of buildings was determined, and buffers were added according to debris area; the output (Fig. 4) was supplemented by expert judgement based on satellite images, building structural considerations and building vicinity, road width etc., to attribute road blockage probabilities - ranging from 1 to 70%, since no building is certain to collapse. $\text{Debris area (meters)} = \frac{2}{3} * \text{Number of floors}$ (1)
Liquefaction	We attempted to use some data (Neagu et al., 2018), but eventually the liquefaction map was considered totoo generic; after more detailed analysis we can integrate it into the analysis.

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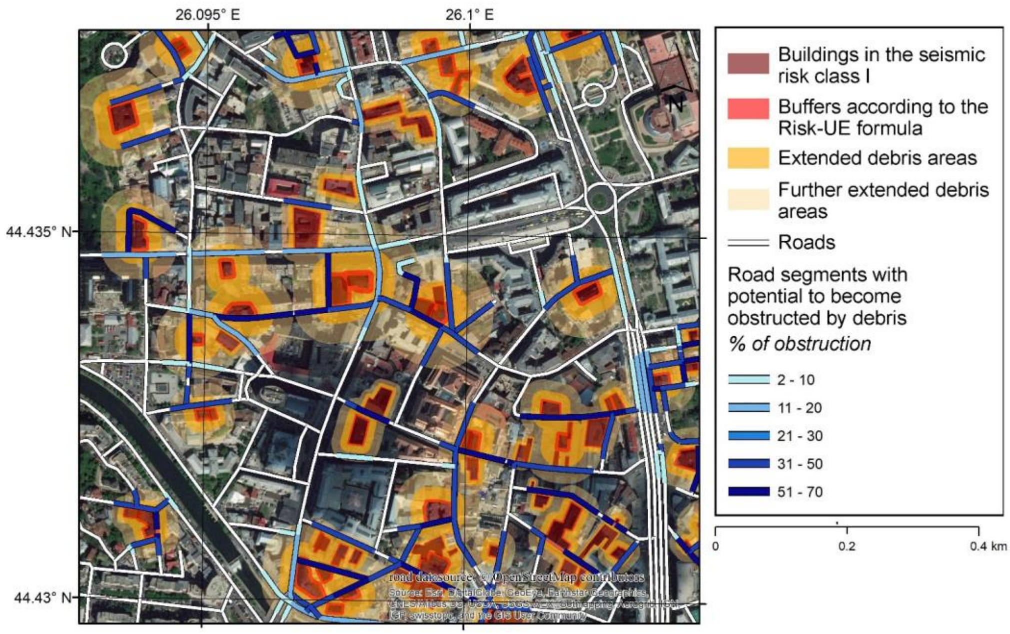
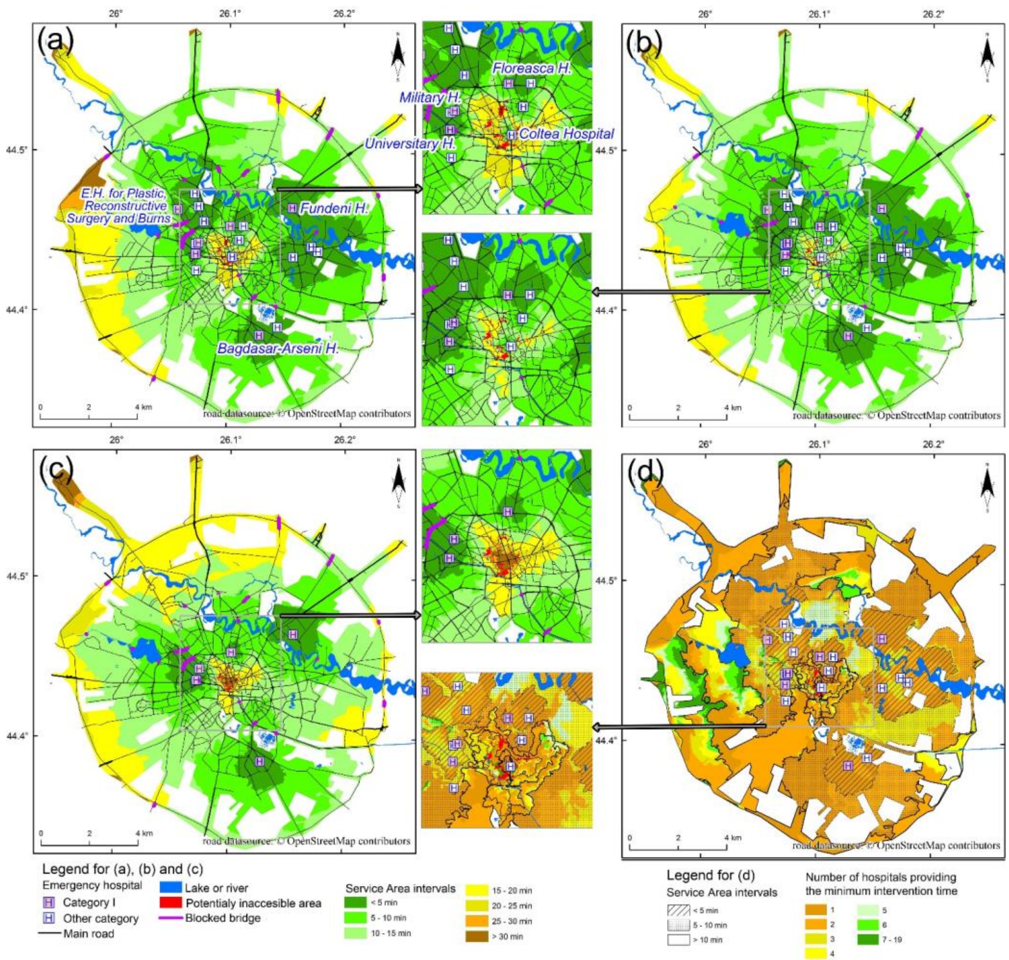


Figure 4: Example of road blockage analysis due to building debris, applied for the historical center of Bucharest (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License, data from September 2016; basemap: © ESRI and contributors).

Table 2: Parameters used for of Bucharest post-earthquake road network risk analysis.

<table>
<tr><th>Facilities</th><th>Analysis parameters</th><th>Considered scenarios</th><th>Number of maps resulted</th></tr>
<tr><td>Emergency hospitals</td><td rowspan="3">Analysis type: Service Area
- impedance attributes: minutes (depending on traffic scenario);
- Default breaks: 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60 minutes;
- no one way restrictions (emergency management vehicles are allowed not to respect these restrictions);
- travel from facility;
- restrictions: polygon barriers (inaccessible areas provided by identifying holes from initial Service Area analysis using the “obstruction” column as impedance attribute - module provided in the Network-risk toolbox).</td><td rowspan="3">For three traffic scenarios (2AM, 8AM and 6PM) - pre and post-earthquake, considering 20 Monte Carlo scenarios and the worst-case model (failure of all listed segments) for blocked roads and bridges (which for Bucharest have a very low damage probability~~,~~ and that is why for our worst-case simulations we made a custom selection based on their health condition, year of construction and length).</td><td>3 (pre-earthquake) + 9 (post-earthquake - worst-case model, including analysis of facilities which provide the number best and second-best times for intervention) + 20 (post-earthquake, Monte Carlo scenarios) + 3 (post-earthquake, Monte Carlo averaged scenarios)</td></tr>
<tr><td>Emergency hospitals in category I of importance (since they have the main capacity and responsibilities in case of an earthquake)</td><td>3 + 9 + 20 + 3</td></tr>
<tr><td>Fire stations</td><td>3 + 9 + 20 + 3</td></tr>
</table>

Facilities	Analysis parameters	Considered scenarios	Number of maps resulted
Origin-destination pairs for representative economic transit routes	Analysis type: Closest Facility - impedance: minutes (depending on traffic scenario); - Facilities to Find: the total number of origins/destinations (to be able to extract not just the statistics as with Cost Matrix analysis, but also the path of the route). - accumulators: minutes (depending on traffic scenario) and meters; - analysis was performed also by changing initial origins within destinations (to show differences due to traffic ways and one-way restrictions).	For three traffic scenarios (2AM, 8AM and 6PM) - pre and post-earthquake	3 (pre-earthquake) + 3 (post-earthquake - worst-case scenario) + 3 time difference tables


(a)
(b)
(c)
(d)
26°
26.1°
26.2°
44.5°
44.4°
Floreasca H.
Military H.
Coltea Hospital
University H.
E.H. for Plastic, Reconstructive Surgery and Burns
Fundeni H.
Bagdasar-Arseni H.
0 2 4 km
road datasource: © OpenStreetMap contributors
Legend for (a), (b) and (c)
Emergency hospital
Category I
Other category
Main road
Lake or river
Potentialy inaccesible area
Blocked bridge
Service Area intervals
< 5 min
5 - 10 min
10 - 15 min
15 - 20 min
20 - 25 min
25 - 30 min
> 30 min
Legend for (d)
Service Area intervals
< 5 min
5 - 10 min
> 10 min
Number of hospitals providing the minimum intervention time
1
2
3
4
5
6
7 - 19

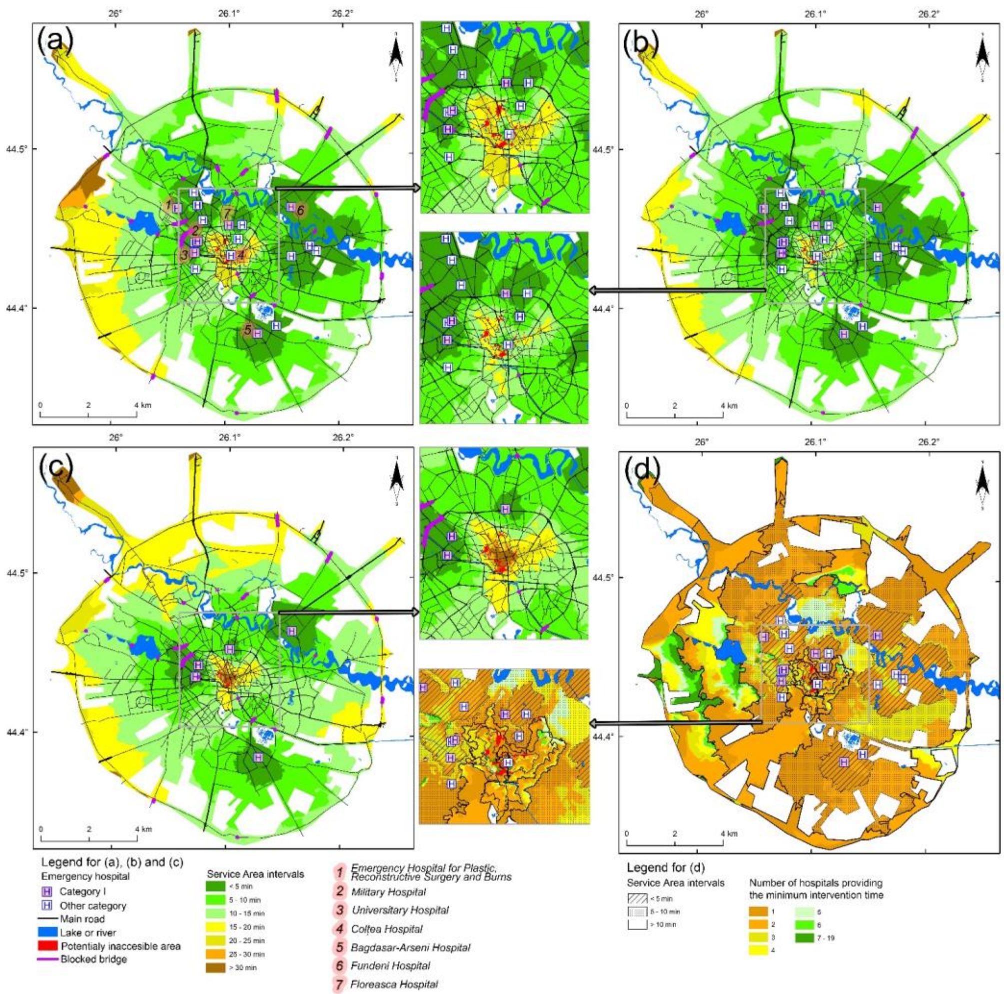


Figure 5: Service Areas for emergency hospitals, for the Monday 8AM typical traffic scenario and for: (a) the worst-case model; (b) a Monte Carlo scenario; (c) emergency hospitals in category I of importance and the worst-case model; (d) the number of emergency hospitals providing the minimum intervention time in the worst-case model (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License, data from September 2016~~).~~); (a) also shows the labels of emergency hospitals in category I of importance and the Coltea Hospital in the city center.

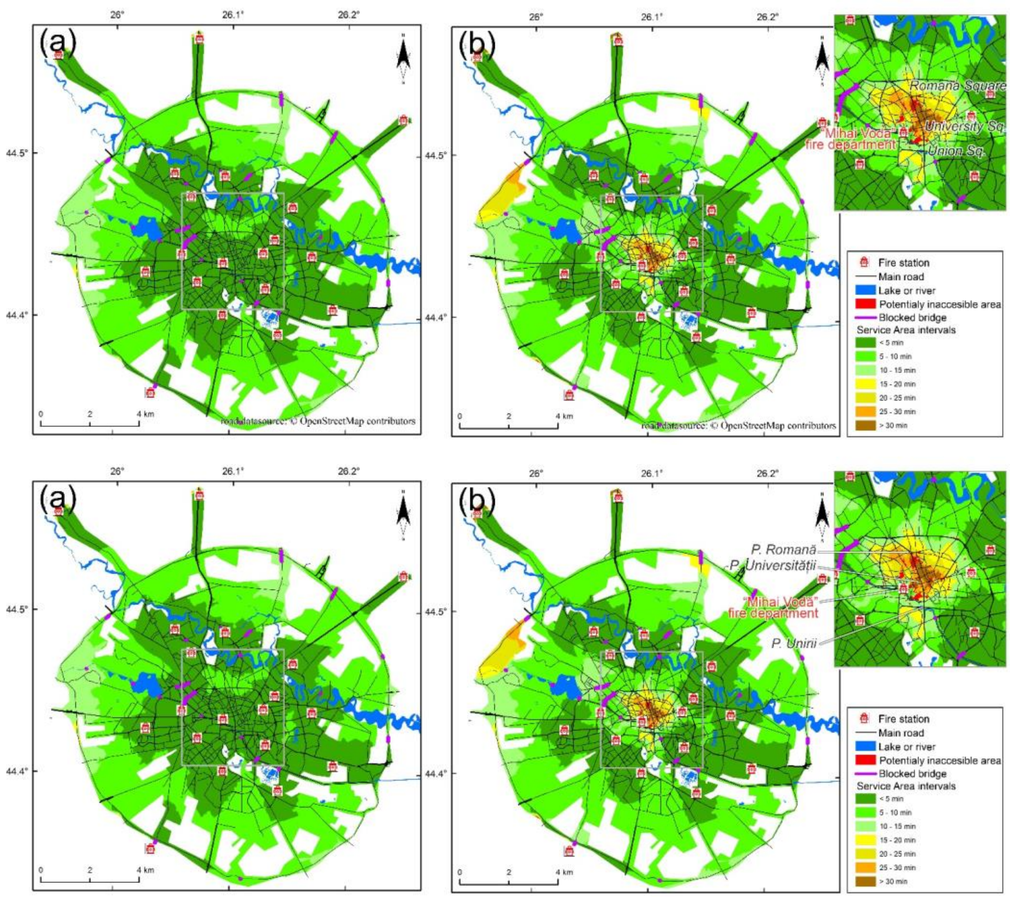


Figure 6: Service Areas for fire stations, (a) pre-earthquake and (b) post-earthquake, considering the worst-case model, for the Monday 8AM typical traffic scenario (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License, data from September 2016).

Table 3: Reclassification intervals for service area polygons.

Default breaks for service areas	Reclassification values (Vr)
≤ 10 minutes	1
10 - 15 minutes	2
15 - 20 minutes	3
20 - 2530 minutes	4
≥ 25 minutes> 30 minutes, chosen to correspond to the golden hour in medicine principle - Lerner and Moscatti (2001), given also the necessary round-trip.	5

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Table 4: Formulas for calculating the index for reclassified vulnerability (Vi); C1 intervals are relative to the facility database and study area characteristics.

Formula for Vi	Conditions - depending on C1 values
Vi = Vr - 0.5	if C1 >= 5 for emergency hospitals and fire stations
	if C1 >= 3 for emergency hospitals in category I of importance
Vi = Vr (applied also to scenarios without calculated C1 values)	if 2 >=<= C1 < 5 for emergency hospitals and fire stations
	if 2 >=<= C1 < 3 for emergency hospitals in category I of importance
Vi = Vr + 0.5	if C1 < 2 for emergency hospitals and fire stations
	if C1 < 2 for emergency hospitals in category I of importance

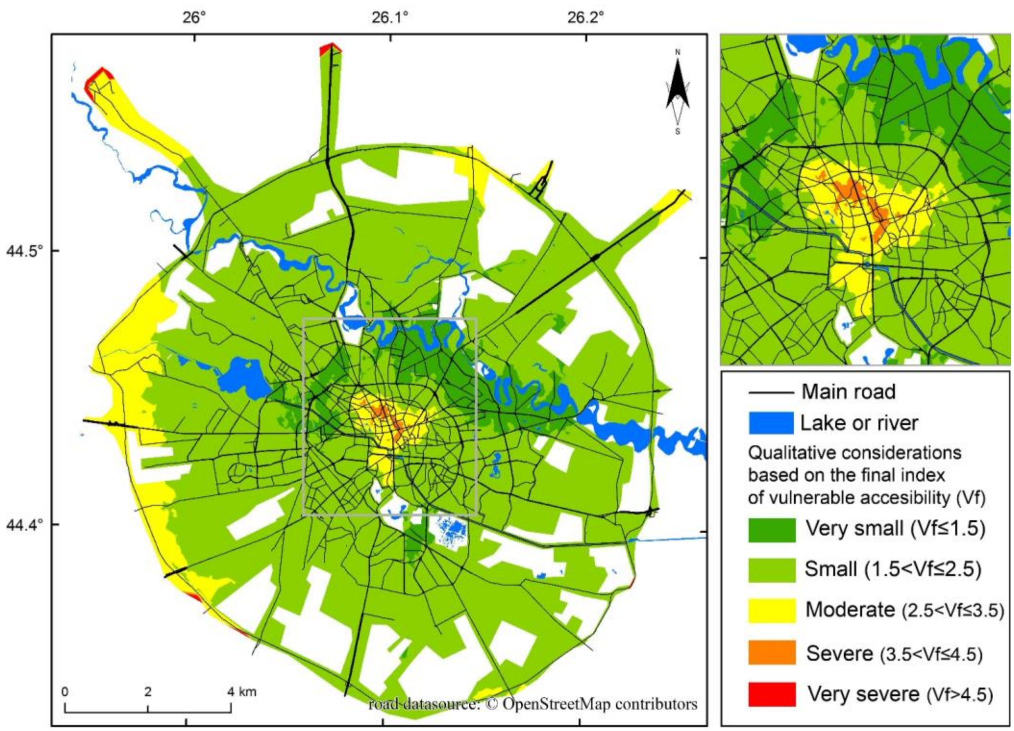

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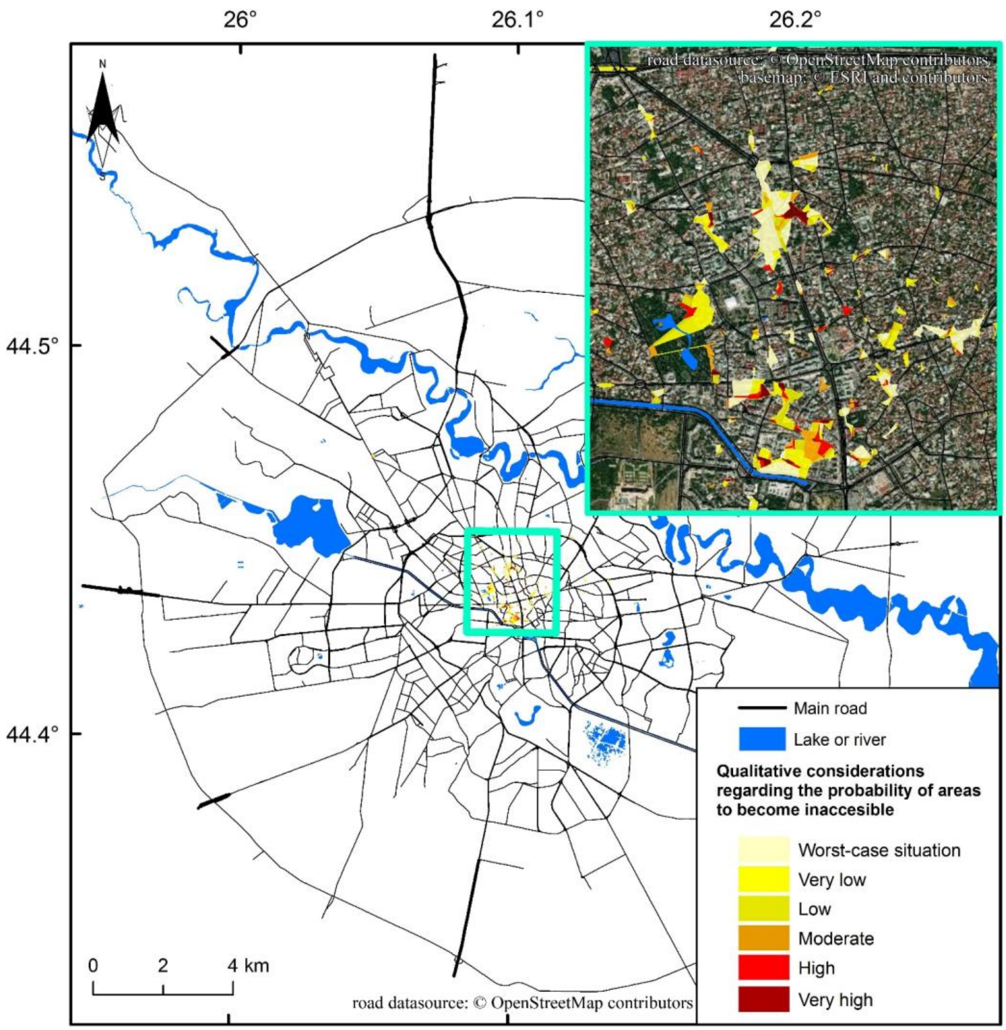
Figure 7: Final map showing qualitative values for the combined final index of vulnerable road network accessibility (Vf) for Bucharest (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons 625 BY-SA License, data from September 2016).



840 **Figure 8: Areas who can become inaccessible immediately after an earthquake (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License, data from September 2016; basemap: © ESRI and contributors).**

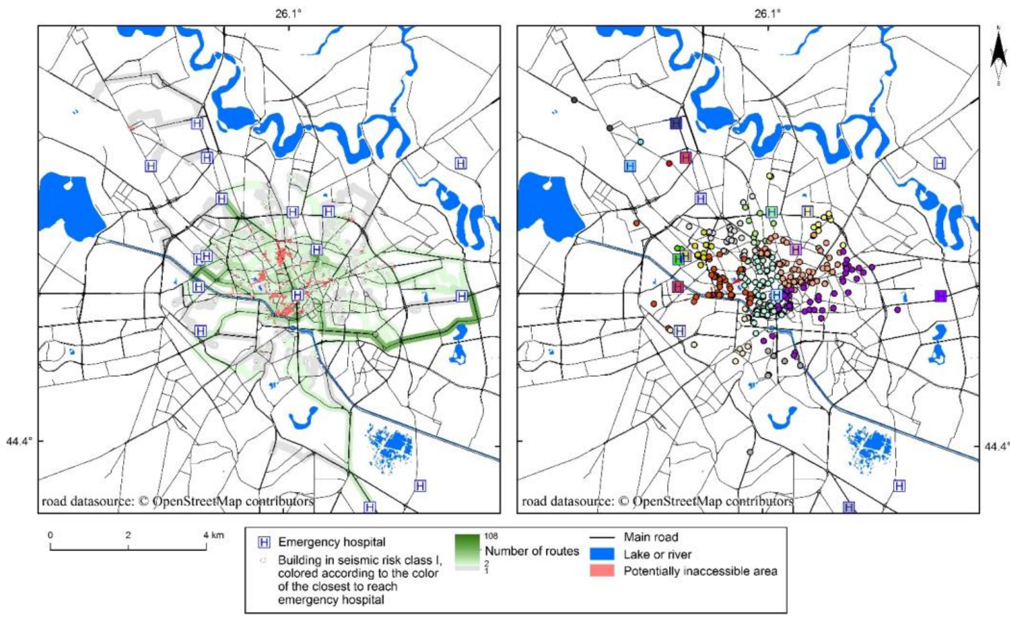


Figure 9: Maps reflecting fastest routes (and the density of these routes) between buildings in seismic risk class I and (a) emergency hospitals, and (b) the closest hospital, for the Monday 8AM typical traffic scenario (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License, data from September 2016).

Table 5: Time differences (expressed in minutes) between various OD pairs shown in Figure 10 and for pre and post-earthquake conditions.

Route	From-To (FT), minutes			To-From (TF), minutes		
	2 AM	8 AM	6 PM	2 AM	8 AM	6 PM
Centura-A1 -> Piata Unirii	0	25	19	1	24	21
Piata Unirii -> Metrou Pantelimon	0	11	14	0	8	10
Centura-Otopeni -> Piata Universitatii	5	72	77	8	62	63
Piata Universitatii -> Centura-Giurgiului	1	30	33	3	45	44
Centura-Chitila -> Centura-Oltenitei	1	0	0	1	10	0
Drumul Taberei -> Centura-Splai	0	4	5	0	5	4
Centura-Magurele -> Gradina Zoologica	0	18	7	0	1	9
Metrou Eroii Revolutiei -> Spitalul Fundeni	1	6	11	1	6	10

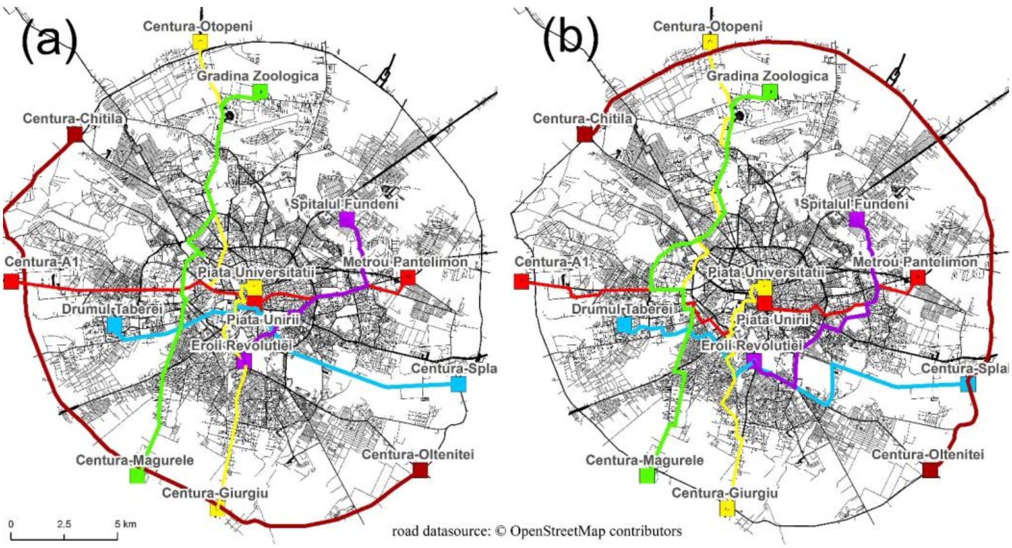


Figure 10: Fastest routes for 8 representative OD pairs for Bucharest, for the (a) FT directions and for the Monday 2AM and (b) 6PM typical traffic scenario (road datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SABYSA License, data from September 2016).