INTERNATIONAL JOURNAL OF

ADVANCED SCIENTIFIC RESEARCH AND INNOVATION

PRINT ISSN 2785-9533 VOLUME 3, ISSUE 1, 2020, 16 – 38. ONLINE ISSN 2785-9541

Measuring Criticality in Urban Systems: A Quantitative Approach for Assessing Urban Vulnerability to Natural Hazards

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Abstract

This paper introduces criticality analysis as a tool to identify and rank the most critical elements of a city system when impacted by natural hazards. This research discusses the limitations of current vulnerability assessment tools in providing details on how and where to distribute hazard mitigation resources. It proposes criticality analysis as a quantitative approach that goes beyond vulnerability assessment. The analysis of this paper provides a detailed description of the criticality analysis procedure and highlights the multifarious considerations that determine how criticality is defined.

This research explains the steps involved in conducting criticality analysis. The analysis involves developing research questions and defining the unit of analysis, identifying vulnerable entities and hazard sources, establishing analytical scenarios, and selecting models to measure criticality. The objective is to detect critical components under disaster scenarios and quantify their significance to the entire system. Researchers need to identify the unit of analysis by using quantitative indicators, and the measurement scale must also be identified. At least one disaster scenario needs to be constructed, and the disaster scenarios typically couple with those of the units of analysis. Once these scenarios are defined, criticality assessors can

proceed to abstract mathematical formations and model specifications from the descriptive facts of scenarios. Simulation-based approaches are preferable when the study area is medium-to-large scale and required data sets for modeling are affluent. The analysis involves the development of models to predict the landing of a hypothetical hurricane and possible inundation areas with different water depth and to calculate congested travel time along each link within the city territory. Finally, a coupled system synthesizing the two seemingly disconnected models should be designed to measure the criticality of each link.
This study concludes by stating the objectives of criticality analysis as identifying and ranking the most critical elements of vulnerable infrastructure, economic sectors, transportation links, or other sub-components of an urban system to provide priority information for long-term or short-term planning schemes.
Key Words: Criticality Analysis; Climate Change Adaptation; Vulnerability; Urban Resilience; Natural Hazards

1. Introduction

Climate change has induced prevailing discourse for its profound implications for humanity. It is neither a scientific fiction nor a political hoax, and its impacts are being widely observed and will exacerbate into the future (IPCC 2014). From breathtaking wildfires to devastating hurricanes, owing to climate change, natural disasters are occurring more frequently and severely. Along with rapid urbanization, human beings are facing escalating pressure from global change to ensure a sustainable and resilient future. On one hand, we are fighting against climate change through mitigation, aiming to reduce greenhouse gas (GHG) emissions by, for example, shifting our reliance on fossil

PRINT ISSN 2785-9533 VOLUME 3, ISSUE 1, 2020, 16 – 38. ONLINE ISSN 2785-9541

fuels to renewable energy such as solar and wind power. We have to date observed a significant increase in global average temperature since the pre-industrial period and are collaborating internationally to keep the temperature rise below 2 degrees Celsius above pre-industrial levels as well as to pursue efforts to limit the increase below 1.5 degrees Celsius according to the Parris Agreement. On the other hand, as the mitigation efforts have not been successful, we cannot rely on the mitigation efforts alone. We must accept that climate change will continue to take place so that adaptation increasingly becomes the dominant alternative.

Climate Change Adaptation: As the impacts of climate change are becoming more apparent, adaptation planning is also emerging rapidly across international borders and governmental scales. There is no single best framework to plan for climate change adaptation and selecting the "best" procedure usually depends on the context and the project's normative objectives. As a result, many adaptation planning emerges to help communities to countries plan for adaptations. The following will provide several examples of adaptation planning frameworks to demonstrate the common procedures and steps involved in these planning endeavors.

The United Nations Framework Convention on Climate Change (UNFCCC) developed a national adaptation plan (NAP) framework to help least-developed countries (LDC) to initiate adaptation planning for climate change impacts (UNFCCC 2012). Figure 1 exemplifies an adaptation plan framework from the UNFCCC. As highlighted in the red boxes, this national adaptation planning framework consists of four principal elements: 1) lay the groundwork and address gaps, 2) preparatory elements, 3) implementation strategies, and 4) reporting, monitoring and review. Within each element, there are specific steps incrementally to achieve a

PRINT ISSN 2785-9533 VOLUME 3, ISSUE 1, 2020, 16 – 38. ONLINE ISSN 2785-9541

comprehensive adaptation planning process. Although the process is generalized, how it shall be undertaken will vary across the countries adopting the framework owing to their financial, technical, and political environments. It is also not prescriptive; this framework is also noted to be used with consideration of different levels of local progress with adaptation and countries should select which steps or activities to take to move forward.

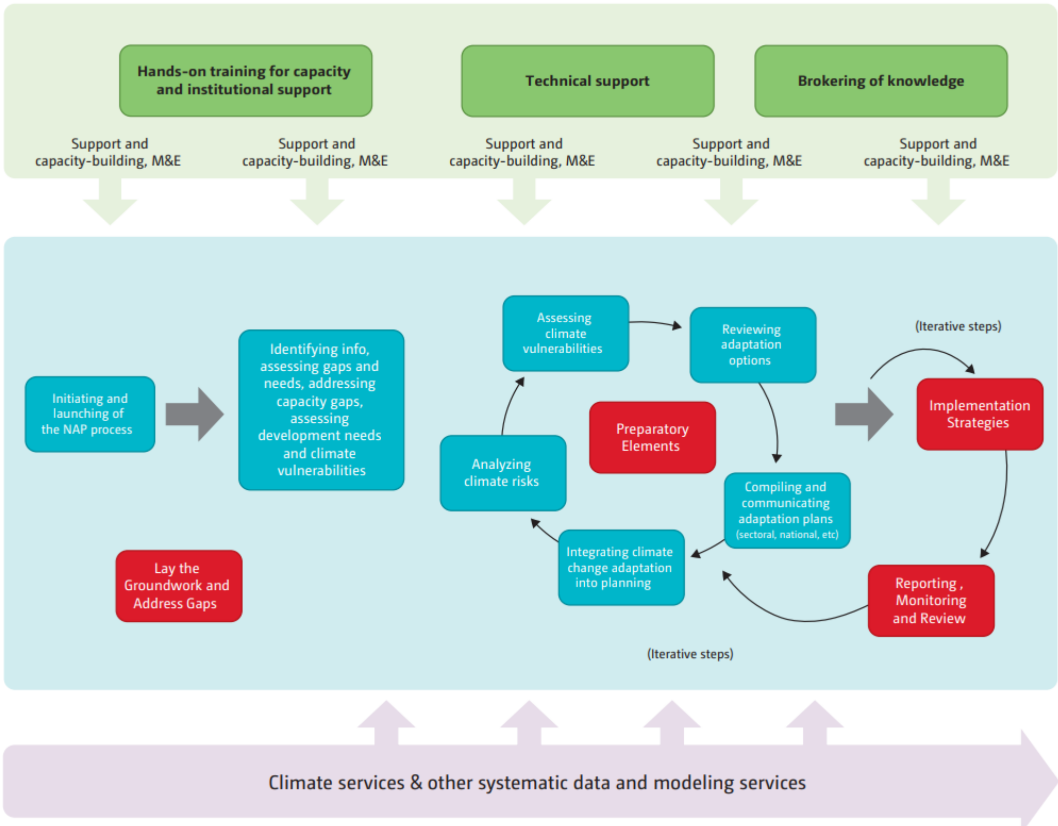

Figure 1. An Example of the UNFCCC Adaptation Plan Framework (UNFCCC 2012)

Another national framework that is widely known is established by the NCA (Bierbaum et al. 2014). Unlike the previous framework which is incremental from step to step, the NCA framework, as illustrated in Figure 2, stresses that "adaptation planning is not a stepwise or linear process and various stages can be occurring simultaneously, in a different order, or be omitted completely". The generalized process includes: 1) characterizing vulnerability, 2) developing options, 3) implementing actions, 4) monitoring outcomes, and 5) reevaluating strategies.

Figure 2. Generalized Adaptation Process from NCA (Bierbaum et al. 2014)

Despite the diversity of adaptation planning frameworks, adaptation planning generally involves four principal steps that are (1) goal setting, (2) stock-taking, (3) decision making and (4) implementation and evaluation (Preston, Westaway and Yuen 2011). Additionally, adaptation planning is an iterative and adaptive planning process that should be constantly evolving to reflect new socioeconomic, political, technical, and environmental changes (Füssel 2007a; Füssel and Klein 2006).

Vulnerability Assessment: Among various adaptation planning frameworks, identification of climate change impacts (i.e. vulnerability assessment) at the scale of concerns remains the fundamental starting point for designing adaptation (Adger 2006; Brooks et al. 2005; Cooper et al. 2013). Consequently, a variety of vulnerability analytical methods and tools have emerged at various scales

PRINT ISSN 2785-9533 VOLUME 3, ISSUE 1, 2020, 16 – 38. ONLINE ISSN 2785-9541

(Figure 3) (Hinkel and Klein 2009; Mcleod et al. 2010; Nicholls 2011; Poulter and Halpin 2008). While adaptation is place-based and usually occurs at a fine spatial scale, vulnerability analysis at the community or jurisdictional level become pronounced (Picketts et al. 2014). Despite the proliferation of vulnerability analyses, recent studies still consensually find that lack of information and certainty is a major obstacle to adaptation decision-making (Butler et al. 2016; Measham et al. 2011; Tol et al. 2008). Given the fact that the perfect information for future climate change impacts will not be available anytime soon, a certain level of risk must/ be accepted and, therefore, how to manage such risk by using existing information to conduct vulnerability analysis that could be used to support planned adaptation become an urgent research agenda (Pelling 2010; Pelling et al. 2015). Prior to analyzing vulnerability, conceptualizing ‘vulnerability’ is vital since vulnerability is a highly contextual and fuzzy concept due to its origins from multiple disciplines (Krellenberg et al. 2016).

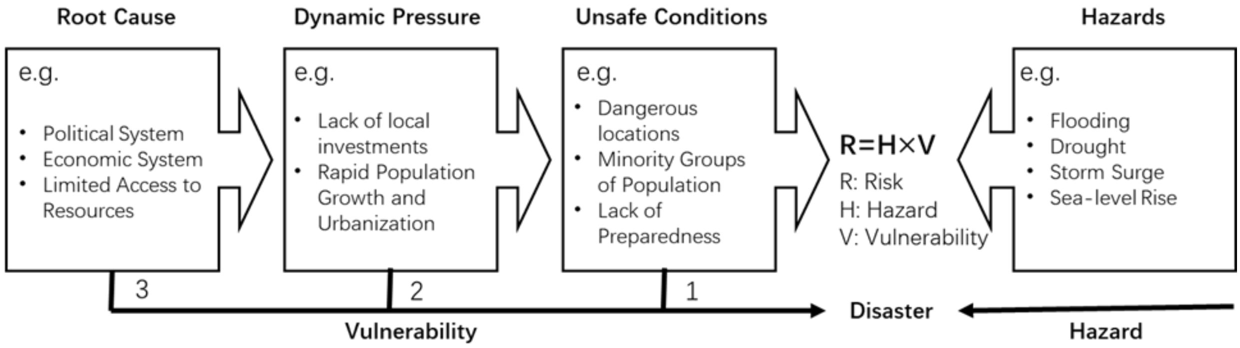

Figure 3. Pressure and Release Model diagram for vulnerability assessment, Adapted from Blaikie et al. 1994

2. Th Need for Criticality Analysis

Facing serious consequences of natural hazards like extreme precipitation and storm surge, many communities have conducted vulnerability assessments and many tools have

PRINT ISSN 2785-9533 VOLUME 3, ISSUE 1, 2020, 16 – 38. ONLINE ISSN 2785-9541

been developed to identify the most vulnerable locations and facilities (Ahumada-Cervantes et al., 2017; Hinkel & Klein, 2009; Mallick, Tao, Daniel, Jacobs, & Veeraragavan, 2017; Nicholls & Cazenave, 2010). These vulnerability assessments have provided important information for adaptation in comprehensive planning and the plan making for specific sectors, such as conservational land (Beier, Patterson, & Chapin, 2008), land use (Metzger, Rounsevell, Acosta-Michlik, Leemans, & Schröter, 2006; Rounsevell et al., 2006), and transportation (Papaa thoma-Köhle, Zischg, Fuchs, Glade, & Keiler, 2015; Scawthorn et al., 2006). However, these pieces of information are not sufficient to assist short-term planning which requires accurate information regarding what segments of a community should be prioritized when concrete hazard prevention engineering projects are to be implemented. For instance, short-term planning like the transportation improvement program (TIP), which is a five-year plan that identifies, aims at optimizing the allocation of funding for transportation projects that are consistent with the Long-Range Transportation Plan. Due to the fixed amount of transportation budget and extremely vulnerable transportation infrastructure, metropolitan transportation organizations (MTO) and local governments need specific information that could help them to prioritize the transportation facilities and road segments that are the most susceptible in the TIP.

Given the growing concerns on the inadequate ability of traditional vulnerability tools in identifying short-term impacts, both academia and industry advocate more advanced tools that address such inability. Criticality analysis was developed by this research, responding to a need to pinpoint the paramount and the most critical infrastructure, urbanized region, and natural resources in the face of natural hazards. It goes beyond vulnerability assessment which lacks

PRINT ISSN 2785-9533 VOLUME 3, ISSUE 1, 2020, 16 – 38. ONLINE ISSN 2785-9541

a ranking and priority component. Criticality analysis is defined as the identification of the most critical elements of a city system when these elements are impacted by natural hazards and the generation of a criticality list that includes ranked critical elements – given a specific disaster or a combination of disasters.

Current vulnerability assessment tools lack sufficient details on how and where to distribute hazard mitigation resources – in a quantifiable approach. For the all talk of building a resilient city on grounds of vulnerability analysis, an intermediate link is absent, and the linkage is criticality analysis. Vulnerability analysis is methodologically insufficient in terms of several aspects. First, the vulnerability term itself is a vague expression (Hinkel, 2011) and therefore a wide range of definitions exist. Second, vulnerability assessment often generates a series of hotspot maps but fails to differentiate from the vulnerable hotspots in terms of the degree of exposure to hazards. A trend surface map, for instance, is normally created at the end of the analysis (Babiker, Mohamed, Hiyama, & Kato, 2005; Mavroulidou, Hughes, & Hellawell, 2004; Witkowski, Rubin, Kowalczyk, Różkowski, & Wróbel, 2003). The map often visualizes the patterns of vulnerability by the variations of standard deviations of vulnerability scores but the result is highly qualitative and could not guide land use planning in the short run. Criticality analysis employs a quantitative approach, though, and the analysis can be conducted at a very high level of resolution.

Determining critical elements is a multifarious consideration (Orencio & Fujii, 2013) and difficult task, and yet strongly required by short-term plan making practices. How criticality is defined in the first place is key-influencing in affecting the final list of critical elements. We use a road network as an illustration. Hypothesize that a flash flooding happened in an urbanized area, and couples of road segments were inundated. A plausible criticality criterion is the degree to which the reduced capacity of a flooded roadway leads to total travel time delays of the whole road network. Alternatively, a criterion may be the significance of a link regarding its accessibility to residential areas. For example, there may exist only one highway connecting two highly populated regions, and thus the shutdown of the highway likely triggers a catastrophically significant consequence on people's commuting time from the two areas. Hence, with this regard, and from the accessibility point of view, criticality analysis may create a totally distinct ranking landscape. In addition, some links may be critical for evacuation purposes or for some important industries that are essential for the region's economy. Although there does not exist a universal measurement baseline for criticality, the ranking results based on a specific objective (or a combination of them) can offer actionable information to transportation planners and engineers who may simply allocate transportation improvement funds among critical links in proportion to the links' position in the ranking outcomes.

The overarching objective of criticality analysis is to identify and rank the most critical elements of the vulnerable infrastructure, economic sector, transportation links, or other sub-components of an urban system, and provide priority information for the long-range or short-term planning schemes (such as zoning, transportation planning, and economic planning, five-year TIP, and so on), basing on different premises of criticality measurements including travel time, economic impacts and residents' accessibility, and additional indicators for systematical performance.

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3. Results and Discussions

3.1Criticality Analysis Framework

Developing a typical criticality analysis involves a sequential flow of actions: the development of research questions and the definition of study objective, the confirmation of analytical scenarios, mathematical formation and relevant numerical models, verification and calibration of employed models, and the visualization and interpretation of results.

I. Identify a research question and define the unit of analysis

First and foremost, an investigator shall develop a research question and the purpose of criticality analysis. To exemplify the illustration of a research question, the following statements are a sequence of research objectives characteristic of the central problem of a study regarding the criticality evaluation of transportation infrastructure in coastal regions.

- The overarching research question is how to detect critical transportation components under disaster scenarios and quantify the significance of these transport facilities and road links as to the whole urban system.

Thus, under this scope, a few goals of the analysis could be:

- To quantify the measurement of criticality aspects, be it total travel delay or economic disturbance.
- To demonstrate system-wide delays of travel time for each inundated transportation facilities (e.g., bridges and multi-modal transportation centers), and road segments due to sea level rise, storm surge, and extreme weather conditions.
- To determine potential economic losses of the shutdown of transportation facilities and road segments to the regional economy as a whole.

- To measure accessibility, change because of the closure of transportation facilities and road segments.
- To develop integrated criteria to rank the importance of transportation facilities and road segments by incorporating the impacts of system travel-time delays, economic loss and accessibility reduction.

After a central research question and several concrete objectives are crafted, the second step is then to specify what types of study objective criticality analysis focuses on and to whom the units of analysis are vulnerable. In other words, vulnerable entity (quantitative description and scale) and hazard source (type and intensity) are two crucial and necessary inputs of criticality analysis. Again, for example if an analyst intends to conduct a criticality analysis on transportation facilities, a possible unit of analysis may be roadways, bridges, public transit hubs, or a combination of these. In addition, the analyst may consider heavy rain or flash flooding as a representation of the threats that roadways (the units of analysis, for instance) are susceptible to. While the general logic of the first two steps is straightforward, researchers do need to be aware of two caveats. First, analysts should be able to describe the intended unit of analysis by some kinds of quantitative indicators. If a census block is a research unit, latent indicators may be population density, housing unit density, land use diversity index, and son. Second, the units' measurement scale must be identified, be it mile and meter for linear units, square mile of square foot for areal units. And the intensity of hazards must be clarified.

II. Establish analytical scenarios

At least one scenario of disasters needs to be constructed, and the disaster scenario(s) typically couples with those of the units of analysis. In order to generate high-fidelity and realistic results, scenario settings should be as specific as

PRINT ISSN 2785-9533 VOLUME 3, ISSUE 1, 2020, 16 – 38. ONLINE ISSN 2785-9541

possible. We again take a transportation facility research as an instance. Disaster scenarios may be an extreme coastal flooding that occurred at afternoon peak hours on a typical workday. The flooding event is supposed to have a probability-based damage functions such as 100 years, 200 years, or additional reoccurrence interval and associated inundation depths. The analytical units' scenarios can be the traffic conditions of roadways at pear hours on Monday. Often, different scenarios of disasters and the study units are coupled, and thus a scenario matrix may be used to display a number of analytical scenarios. Once these scenarios are well defined, criticality assessors can proceed to abstract mathematical formations and model specifications from the descriptive facts of scenarios.

III. Select models measuring criticality

Once we embark on this step, quantitative calculations and/or numerical simulations will take up the rest of assessment process of criticality. Models or mathematical formations are majorly applied to quantify natural hazards' effects on the variation of some indicators describing a vulnerable unit. And criticality is measured by the deteriorating effects of such variation on systematical performance of the indicators. This quantification can be done either by on-site observation or computer aided simulation.

On-site observation is essentially an empirical method focusing on some case study sites and adopting field data collection strategies. To examine the criticality of a few major highways under a flooding scenario, for instance, field investigators go to the sites to count the change of traffic flows before and after the waterlogging occurs. Yet, the collection of field data and on-site investigation may be time inefficient and costly, particularly when a large-scale study area is selected. Therefore, simulation-based approaches are

PRINT ISSN 2785-9533 VOLUME 3, ISSUE 1, 2020, 16 – 38. ONLINE ISSN 2785-9541

preferable when the study area is medium-to-large scale and required data sets for modeling is affluent. And the following sub sections focus majorly on computer aided simulation.

To conduct a criticality analysis, at least two models have to be identified. To interpret, we continue to discuss the transportation vulnerability research basing on a hurricane-prone coastal city. Here, flooding depth was an indicator of a hypothetical hurricane, a subject denoting a natural hazard, and congested travel time represents a quantifiable aspect of a major road, a unit of analysis. Next, a model is developed to predict the landing of a hypothetical hurricane and possible inundation areas with different water depth. And a model is to calculate congested travel time along each link within the city territory. These two models are somehow separated, and how to measure the criticality of each link remains unknown. Hence, a coupled system synthesizing the two seemingly disconnected models should be designed and this process will be discussed in the next section.

IV. Assess the criticality of the analysis of unit

Next, an algorithm needs to be formulated to pack abovementioned models into a computer program and to operationalize the concept of criticality. Consider the following scenario: a simulated flash flood occurred within a municipality and ten highways shut down due to the flooding. And suppose that a flooding model was employed and an inundation map was developed, and that congested travel time of each link and the whole system in the municipality was calculated before the occurrence of the flooding. Next, the representation of the criticality of the ten highways is to develop an algorithm that probes into how the shutdown of a particular highway out of the ten candidates, while keeping the capacity of the other links in normal conditions, would affect system-level travel time. This process is iterative and

PRINT ISSN 2785-9533 VOLUME 3, ISSUE 1, 2020, 16 – 38. ONLINE ISSN 2785-9541

applied to each out of the ten highways – in order to generate a sorted criticality list that displays total travel time associated respective to each highway. Consequently, the first three highways with the highest travel time owing to the closure by a flooding would be considered as critical links, and transportation engineers can use such information to deploy transportation improvement projects.

V. An analytical example

To see how a typical criticality analysis works, witness the following analytical example. Specifically, in this section, the case study will walk audience through the criticality analysis step-by-step from the crafting of research questions and the final delivery of a hypothetical criticality list.

1) Overall research question and sub objectives

An overall question is to develop criteria and methodologies that assess the importance of susceptible transportation facilities and road links in the face of coastal hazards and extreme weather events by considering total travel time delays, economic impacts, and the reduction of accessibility. Following this overarching aim are several sub research objectives that have logic connections with each other:

Objective 1: To calculate system-wide delays of congested travel time for every single transportation component that is a highway, bridge, and transit hub and would be flooded because of sea level rise induced hurricane.

Objective 2: To estimate potential economic losses of the shutdown of transportation facilities and road segments from the perspective of the regional economy of Bay County where Panama City is situated.

Objective 3: To determine accessibility reduction of the detrimentally flooded transportation facilities that have a

PRINT ISSN 2785-9533 VOLUME 3, ISSUE 1, 2020, 16 – 38. ONLINE ISSN 2785-9541

significant role to play for regional transportation connectivity. These may be pre-selected and are interstate highways, bridges, multi-modal transportation hubs.

Objective 4: To design an algorithm to rank the criticality of transportation facilities and road segments by incorporating the consequences of systematic travel-time delays, economic loss and accessibility decrease.

Objective 5: To offer concrete procedures on how to integrate the priority rank of critical transportation facilities and road lines in the long-range transportation plan and the identification of five-year transportation improvement projects.

2) *Analytical scenarios*

The first category of scenarios reflects the intensities of sea level rise and hurricane resultant flooding. Sea level may rise up from 20-30 cm to approximate 1 m by the end of 21st century, contingent upon the low, medium, or high global emission models applied. Further, flooding intensities are associated with probability-based time intervals, be these 100, 300, or 500 years in the worse scenario. The second category of scenarios denote the current-day traffic conditions in Panama City and those in predicted years. However, in this example only present-day conditions were considered for illustration and simplicity purposes.

3) *Model selection and criticality assessment*

There exist numerous parametric or non-parametric climatic models replicating the landing of a hypothetical hurricane and the formation of flooding zones after the landing. We can adopt an analytical model developed by Hsu (2014) and (Udoh, 2012), which is shown below:

$$\lambda_i = e(\lambda_0 + SLR) + \beta \qquad (1)$$

PRINT ISSN 2785-9533 VOLUME 3, ISSUE 1, 2020, 16 – 38. ONLINE ISSN 2785-9541

where λ_i denotes the forecasted values of storm surge height, λ_0 the present-day height values without the effects of climate change, and e, β adjustment variables to calibrate height values by local data .

Next, a storm surge height map can be overlapped with the digital elevation image, resulting in flooded areas. As for traffic condition simulation, a traditional 4-step travel demand model may be applied. Analytically, the 4-step model relies on socioeconomic and traffic calibration data sets to distribute traffic flows on the city's highway network. And it includes trip generation, distribution, model split, and trip assignment. To measure economic impact, a computational generation equilibrium model can be feasible to model the goods and materials flows within an economic system.

To see how the criticality of transportation facilities is assessed after models are determined, we will demonstrate the justification of critical links based on a criteria of total travel delays. And the same analysis process can be conducted regarding economic impact and accessibility reduction, but will not be addressed in this study due to page constraint.

The criticality analysis is comprised of two components that examine the criticality of links under different intensities of sea level rise induced flooding through the landing of a hurricane. First, critical links will be assessed from the perspective of total travel time delays. Following this, analysts can collaborate with local stakeholders such as would-be affected residents, governments, and transportation practitioners to design integrative criteria regarding criticality ranking.

Analysts can identify extremely vulnerable road segments whose shutdown due to hurricane flooding likely leads to high-level travel time delays at the city-wide scale. To rank affected road links from the travel time perspective, analysts can utilize the latest Northwest Florida Regional Planning Model (NFRPM). It will run the analysis using the Cube platform and ArcGIS. Below we will use sea level rise as an example to illuminate the hazard impacts on travel time delays. The scenario analysis of the impacts of storm surge and excessive precipitation will follow a similar procedure.

First, the NFRPM is run to forecast the distribution of congested travel times among different traffic analysis zones in the year 2040. The congested travel time is posited to represent the commuters' driving times under congested conditions when travel times rise with increased traffic demands (Elefteriadou, 2014). The prediction will follow a traditional four-step travel demand modeling framework, considering population growth and land use changes. The model will generate Origin-and-Destination (OD) matrixes which contain such information as the number of trips of different purposes and congested travel times. It will calculate the system-wide congested travel time TT_{NSLR} – without the inundation of rising sea levels–according to the following equation:

$$TT_{NSLR} = \sum\sum t_{ij} * \mathrm{Tr}_{ij} \qquad (2)$$

where t_{ij} denotes the congested travel time from traffic analysis zone i to j based on the shortest path algorithm, and Tr_{ij} is the total number of home-based trips from traffic analysis zone i to j.

Second, the proposed project will posit that those road links exposed to the inundation of sea level rise have a capacity of

PRINT ISSN 2785-9533 VOLUME 3, ISSUE 1, 2020, 16 – 38. ONLINE ISSN 2785-9541

zero. For instance, if there would be 100 links that will be under water due to a 2-foot sea level rise, we will then assign each link a label ranging from No. 1, 2…100. Next, the link of No.1 will be shut down with zero capacity. The NFRPM is run again, and the travel time of the whole system, TT_{SLR_L1} will be determined using equation (2). Therefore, the increased travel time is the total delay due to the shutdown of this link. Furthermore, a time-delay index can be described by

$$TD_{L1} = \frac{TT_{SLR2\_L1} - TT_{NSLR}}{TT_{NSLR}} \tag{3}$$

Finally, the time-delay indexes will be ranked, and the links with, for example, top-ten largest values will be regarded as critical facilities.

Together with the ranking results from similar analytical processes based on economic impact, and accessibility reduction, analysts can finally identify a list of transportation facilities that are the most critical according to a comprehensive criterion, one that can be developed with the involvement with local planning and transport agencies, vulnerable residents, and other stakeholders. The final outcome of criticality analysis will provide crucial information when public and private sectors at risk ponder over their budgetary plans on urban infrastructure and properties, and hazard mitigation teams can also be benefited for better allocating resources and manpower.

4. Conclusions

This research commences with a brief discussion of the concept of criticality analysis and its relationships with vulnerability assessment. It then justifies why in nowadays both academia and practice need a better comprehension of criticality analysis and its latent application potential. Following the background, the text further proposes an analytical approach to operationalize criticality analysis, which includes research question and goals, scenario establishment, model selection, and the development of criticality list. A preliminary example is then employed to illustrate the process. The proposed tool can be helpful for planners and transportation engineers to improve long-range land use planning and short-time (e.g., 5 to 10 years, etc.) transportation improvement projects.

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