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Probabilistic Vulnerability Assessment Framework for Road Networks Considering Social Variables

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Abstract: Community wellbeing is dependent on access to a variety of critical infrastructure. When access is disrupted, it can result in societal impacts that are often difficult to quantify. The Capability Approach has been used in several research domains to quantify community wellbeing as it provides a degree of objectivity in identifying metrics that reflect individual freedoms and opportunities. This study proposes a methodology for vulnerability assessment of communities based on the level of access they have to critical infrastructure and uses a Capability Approach based framework to estimate access-vulnerability subjected to flood hazard. A Monte Carlo simulation-based model is proposed that generates a synthetic population using weighted random sampling that mirrors the individual characteristics based on census data. The access of this population to infrastructure deemed necessary for their continued wellbeing based on the Capability Approach is then evaluated using travel-cost as a metric. The model simulates disruptions in the network through stepwise random link or node removals incorporating randomized flood distribution with varying return periods. The proposed methodology is applied to the County Fingal region of Ireland and presented as a case study, specifically focusing on three central human capabilities': life, bodily health, and bodily integrity. Vulnerability indices are computed for various locations based on these randomized scenarios, reflecting the varying degrees of risk faced by different demographic groups. The findings emphasize the importance of social variables in understanding and mitigating the impact of access disruptions on communities.
Keywords: Capability Approach, Flood risk assessment, Community Wellbeing, Transport network analysis.

1. Introduction

Transportation networks play a fundamental role in sustaining community wellbeing by providing access to essential services, economic opportunities, and social engagement. The resilience and functionality of road networks directly impact the quality of lives for individuals, particularly in the face of disruptions caused by natural disasters, or infrastructure failures. Traditional vulnerability assessments of road networks have primarily focused on functional metrics such as travel time, connectivity, and network efficiency (Chen et al. 2007; Jenelius, Petersen, and Mattsson 2006). However, these approaches often overlook the social and human dimensions of transportation, particularly the differential impact of disruptions on various demographic groups.

To address this gap, this study introduces a probabilistic vulnerability assessment framework that integrates social variables using the Capability Approach (CA) as a theoretical basis.

The Capability Approach (Sen 2017; M. Nussbaum and Sen 1993; Frediani 2010) provides a structured method for assessing wellbeing of communities by evaluating individuals' real freedoms and opportunities rather the resources that care available to them. This perspective can be particularly relevant in transportation planning (Smith, Hirsch, and Davis 2012; Ryseck and Behrens 2024) as access to infrastructure does may not always lead to enhancements of individuals' 'freedoms', and 'functionings'. Some basic definitions associated with the capability approach relevant to this study are:

- Resources: These are commodities, and goods available to a person which allows them to achieve their capabilities.
- Conversion factors: Personal, social and environmental factors that determine the conversion of resources into capabilities.
- Capabilities: Capabilities are freedoms available to person to do or be what they value in life.
- Functionings: Functionings are what people actually achieve based on their capabilities.

For instance, an individual's ability to reach essential services such as healthcare, education, and employment may depends on including income level, physical ability, public transportation availability, and urban design. Thus, a vulnerability assessment framework of the transport network incorporating the CA evaluates how a disruption impacts their capabilities, which in turn provides a more comprehensive understanding the impact on different segments of society.

This study employs a Monte Carlo simulation-based methodology to assess vulnerability by generating a synthetic population using weighted random sampling based mirroring the demographic characteristics of a given region based on census data. The accessibility of this population to essential infrastructure, in this can the nearest hospital with an emergency room, is then evaluated. Disruptions in the transport network are simulated by applying, representing flood hazards with varying return periods. The methodology is applied to the Fingal County region of Ireland. The findings underscore the importance of social variables in understanding and mitigating the effects of access disruptions, offering a novel approach to integrating the same into transport vulnerability assessments

2. Methodology

2.1 *Conceptual Framework*

The Capability-Based Transport Network Assessment Framework (Fig. 1) aim to create a user-centric, wellbeing-focused approach over purely functional metrics. Thus instead of measuring performance alone, it assesses how transport systems enhance user capabilities considering their needs and characteristics. The Capabilities considered in this study is based on Nussbaum's (M. C. Nussbaum 2011; M. Nussbaum and Sen 1993) central human capabilities. However the scope here is limited to Life, Bodily Health, and Bodily Integrity. All the three capabilities require access to healthcare and thus the access to hospitals is considered as a contributing factor. The primary goal here is to integrate accessibility, hazard risk, and human capabilities into a single, comprehensive metric for assessing transport networks.

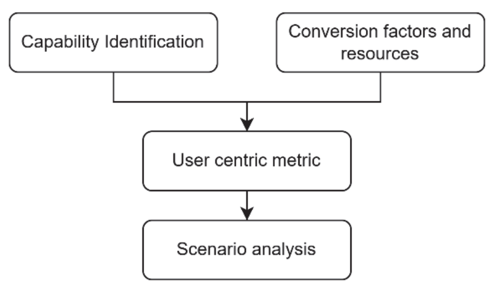

Fig. 1.Conceptual Framework

The framework (Fig. 1) consists of four key components. Capability Identification defines essential transport-related capabilities such as access to healthcare in this case. Conversion Factors and Resources examine how individual (e.g., age, income), social (e.g., cultural norms, access to information), and environmental (e.g., urban-rural differences, climate risks) factors influence transport capabilities. These are combined to create User-Centric Criticality Metrics to identify how transport supports key capabilities. Scenario-Based Analysis tests system resilience against disruptions like natural disasters, or congestion. Finally, based on this scenario analysis the metric that has been developed can be validated through feedback from stakeholders.

2.2 *Application of the CA Framework in transport network analysis*

The capability approach has been utilized in various transport studies; however, its application in research involving network analysis remains limited. Some of these include analyzing the effect of natural hazards such as earthquakes on transport infrastructure and access (Boakye et al. 2022), assessing transport-related social exclusion (Bantis and Haworth 2020), or evaluating access to daily activities and perceived levels of accessibility in rural areas (Pot, Koster, and Tillema 2023). A common approach when assessing 'Capability' in the context of transportation is to consider capability as equivalent to the access (Vecchio and Martens 2021; Vecchio 2020). afforded by the transport infrastructure to the facilities and infrastructure which enable an individual to achieve their 'Functionings'. Thus, analyzing a transport network through the lens of the Capability Approach involves measuring the access of a target population to a specific destination, where a Capability is considered fulfilled if access falls within a defined travel time threshold.

A list of capabilities by M. C. Nussbaum (2011) outlined fundamental human abilities necessary for a dignified life. This includes ten central capabilities: life (being able to live a full lifespan), bodily health (good health, nourishment, and shelter), bodily integrity (freedom of movement and safety from violence), senses, imagination, and thought (education, and creative expression), emotions (forming attachments), practical reason (critical reflection and life planning), affiliation (employment, and social interaction), other species (connection with nature and animals), play (recreation and enjoyment), and control over one's environment (political participation and property rights). Since each of these capabilities is linked to access to specific infrastructure, a holistic framework for operationalizing the Capability Approach in transport network analysis should ideally assess access to all relevant infrastructure. For example, the capabilities of life, and bodily health would involve access to several critical healthcare infrastructure such as general practitioners (GPs), hospitals, emergency rooms, pharmacies, and emergency services. Similarly, access to educational institutions and workplaces are critical to fulfilling a number of capabilities, particularly 'affiliation', 'senses, imagination, and thought' or 'control over one's environment'.

In this study, we consider access to healthcare—specifically emergency healthcare for vulnerable individuals—as a key metric within a holistic Capability Approach-based transport network vulnerability assessment framework. Emergency health care visits data has shown that emergency room visit rate is higher among younger individuals (age less than 5 years), older individuals (age greater than 65 years), and people with disabilities (Park and Park 2023; Cairns and Kang 2021). Therefore, this analysis focuses on assessing the impact of disruptions to emergency healthcare access for populations with higher healthcare needs.

A 15-minute threshold for travel time from a household to a hospital with emergency facilities is assumed. While there are specific guidelines (e.g. the Medical Priority Dispatch System) which categorize health emergencies and the ideal response times, there are no specific guidelines regarding travel time from a household to an emergency room. An assumed target travel time threshold of 15 minutes is considered in the analysis based on the '90th percentile under 15 minutes' response time target for life threatening emergencies used in a number of Priority Dispatch Standards.

The final objective is to evaluate the impact of network disruptions on individual well-being, using the Capability Approach to systematically assess how such disruptions affect various dimensions of well-being. The analysis presented here represents only one component of this broader framework, with future work addressing additional dimensions of well-being within its scope.

2.3 *Case study: Flood risk assessment in Fingal*

The python-based framework performs a geospatial analysis of residences, flood zones, and travel times to hospitals with emergency units in Fingal County, Ireland, considering three demographic factors: age, health status, and disability status. It utilizes Python libraries, including *geopandas* for handling spatial data, *osmnx* and *networkx* for road network analysis, and *matplotlib* for visualizations. Fig. 2 illustrates the data input and key steps in the analysis.

The analysis incorporates the following datasets:

- Demographic Data: Census data from the Central Statistics Office of Ireland provides population distribution and socioeconomic variables at the census small area level.
- Flood Risk Data: Office of Public Works Ireland supplies river and coastal flood risk maps including the current scenario and future “mid-range” and “high-end” scenarios. Each of these scenarios have maps corresponding flood predicted for different return periods. For this analysis two flood risk maps are used: the current river floods scenario map and the high-end future flood scenario map, both with a 100-year return period.
- Road Network Data: The road network data is extracted from OpenStreetMap (OSM) using the python library *osmnx*, representing the drivable road network within County Dublin which includes Fingal. *OSMnx* is a Python library for downloading, visualizing, and analyzing street networks and urban infrastructure from OSM. *OSMnx* integrates other geospatial analysis packages like *GeoPandas* and network analysis package: *NetworkX*, to perform operations like shortest path calculations, accessibility analysis, and network-based spatial queries.
- Residential Buildings Data: The residential building data is used to assign a geolocation to the simulated population. This is sourced from the GeoBuilding Intel Dataset which is a collaboration between An Post and Ordnance Survey Ireland with comprehensive intelligence on residential and commercial buildings across Ireland.
- Hospital Locations: This analysis considers access to hospitals serving the Fingal County with an emergency unit. Their location data is obtained from Health Service Executive (HSE) Ireland.

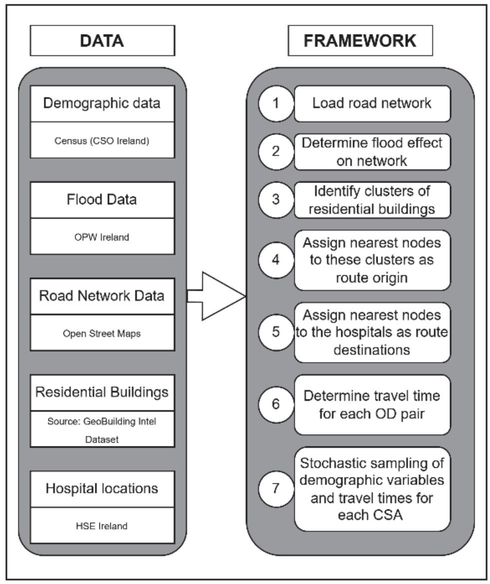

Fig. 2.Flood risk assessment for access to hospitals

The methodology begins by loading the drivable road network using *osmnx* for County Dublin, with the default speeds and travel times are assigned to each road segments. The flood zones shapefile is then spatially intersected with the road network to identifying flooded road segments. A baseline scenario is also analyzed without any flood conditions.

The following steps are carried out for each CSO small area (CSA) to create a ‘dataframe’ with each row representing a CSA.

- Travel time analysis (1-6 in Fig. 3): The residential buildings are identified from the GeoBuilding Dataset, and are then clustered into groups using K-Means clustering (Fig. 4) from the *sklearn* python library. The clustering is done considering 100 houses representing a single cluster. Each cluster is assigned a single origin point in the Origin-Destination (OD)

Pair. This origin is the node in the network that is nearest to the cluster point. Similarly, the nearest nodes to the hospitals are identified as route destinations. For each OD pair (i.e., residential cluster to hospital), travel time to the nearest hospital is calculated. The nearest hospital is determined by the shortest path through the road network, weighted by travel time. OSMnx utilizes Dijkstra's algorithm to compute the most efficient route. Through this analysis each cluster in each CSA is assigned a travel time to the nearest hospital. Flooding is included in the analysis by overlapping the flood maps with the links (Fig. 4). A travel time penalty of 90% is applied to all links identified as flooded.

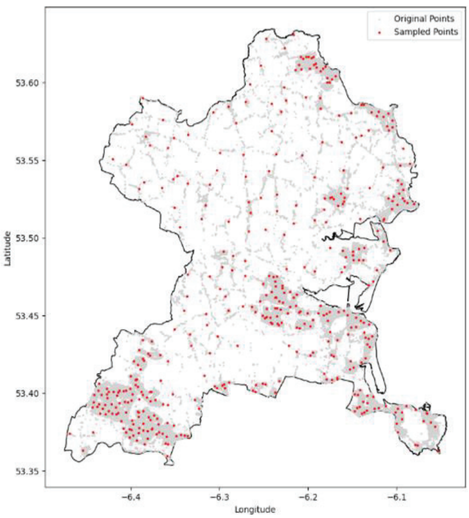

Fig. 3.K-means clusters of residences in Fingal

- Stochastic Sampling for Demographic Variability: In order to account for the population characteristics that determine the 'resources', 'conversion factors' and 'capabilities' in the Capability Approach Framework the census data is utilized. A stochastic sampling approach is used such that demographic variables corresponding to each census area: population density, age distribution, reported health status, and reported disability status are sampled randomly per the distribution available in the census area. For this analysis 10,000 samples of each random variable is obtained.
- Stochastic Sampling of travel times: The travel times for each census area is sampled. If an area has *n* clusters, *n* travel times are calculated initially. Based on these travel times, 10,000 samples are generated for each area such that the probability of occurrence of any one of the *n* travel times is the same (uniform distribution). Each travel time is the mean free flow travel time, with a COV of 0.1 (Chung and Recker 2014).

Finally, based on the demographic variables and travel times associated with each samples the probability that the travel time to the nearest hospital exceeds a certain *threshold* for a certain *category* of population is calculated for each census area. The category is defined here as 'high health needs individuals' and the threshold is set as 15 minutes. A 'high health needs individual' is assumed to be any person who is either aged less than 5 years or more than 65 years, or has a disability, or has a self-reported health status as 'Bad' or 'Very Bad' per the census data.

3. Results and discussion

The initial analysis under normal conditions (without flooding) shows that the average travel time to the nearest hospital for residents in Fingal County is ranges from 1 minute to 23 minutes. The spatial distribution of travel times across the county is shown in Fig. 5. When considering flood disruptions, the average travel time increases to a maximum of 30 minutes under the high-end river flood scenario. The most affected regions are to the north of the county where key road segments are inundated. However, as Fingal County has a considerably dense network of roads the affect can be considered to be marginal as the maximum change or delay in travel time is around 6 to 7 minutes.

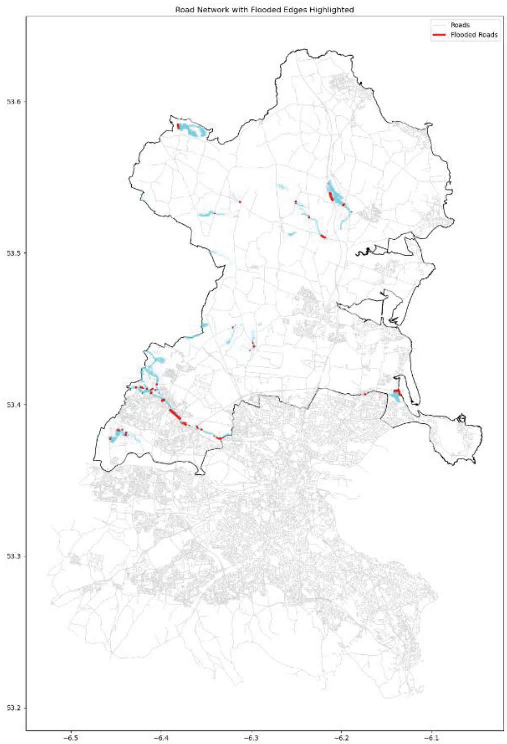

Fig. 4.Flood effect on the road network

Stochastic sampling results (Fig. 6) indicate that a maximum of 6% of the population in any of the census areas in Fingal County falls into the "high health needs" category and have a travel time to the nearest hospital exceeding 15 minutes. Since all hospitals considered in the analysis are located in the southern part of Fingal, and the flooded roads are primarily in the central and southern areas, the highest concentration of vulnerable individuals is predominantly in the northern regions of the county.

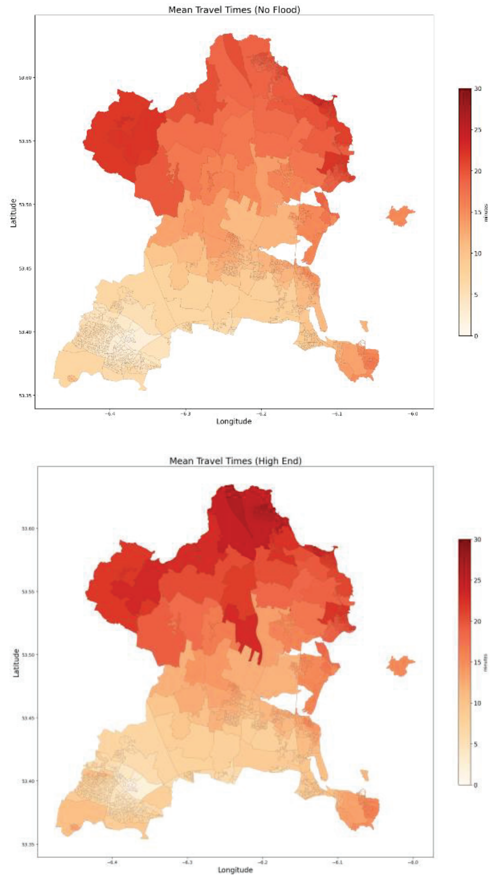

Fig. 5. Average travel times before and after floods

Thus, combining demographic data, travel times, and flood scenarios, the most critical CSAs where both high health needs populations and excessive travel times coincide can be identified. If necessary, areas that require urgent policy interventions, or attention for flood-resilient transport infrastructure, or alternative emergency response strategies can be formulated.

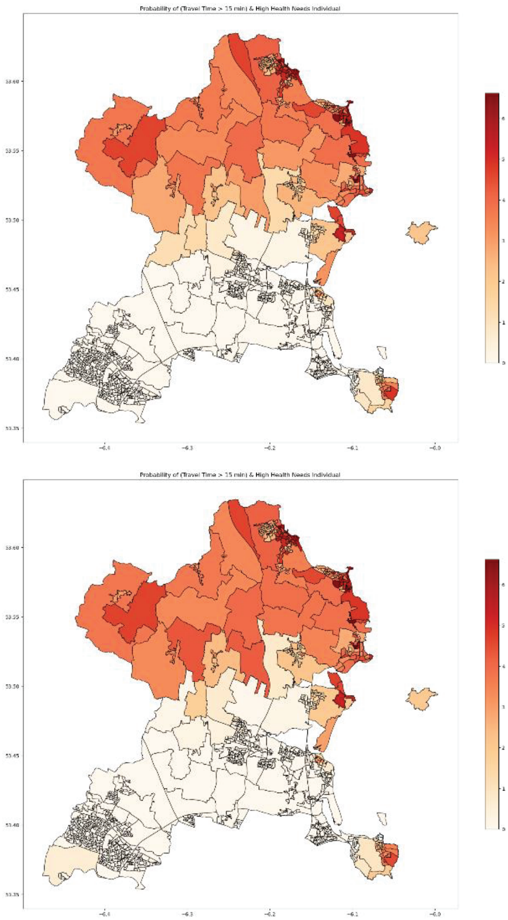

Fig. 6. Accessibility to hospitals map for high needs individuals

4. Conclusions

This study presents a Capability-Based Transport Network Assessment Framework that integrates social variables into traditional transport vulnerability analyses. Using a Monte Carlo simulation-based model, the framework evaluates accessibility disruptions caused by flood hazards, emphasizing their impact on specific sections of the population. The case study in Fingal County, Ireland, illustrates that flood-induced delays in hospital access and its effect on high-health-need individuals.

The findings highlight the necessity of incorporating social and demographic factors in transport resilience planning. Future research will be focused on refining this model by incorporating real-time further sources of uncertainty, depth-disruption curves for better modelling of flood induced delays, a wider range of climate change projections, a more comprehensive list of capabilities, and alternative transport modes, providing a more comprehensive risk assessment framework. This approach aims to bridges the gap between infrastructure resilience and societal effect, incorporating just efficiency of the system but also fundamental human capabilities.

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