Assessing Vulnerability Due to Infrastructure Capacity and Insecurity in Irregular Migration Routes: An Institutional Evaluation of the Mexico-U.S. Corridor

Pablo Uriarte[ab], **José Ramirez Marquez**[a]
[a]Stevens Institute of Technology, School of Systems and Enterprises, 1 Castle Point Terrace, Hoboken, New Jersey
[b]Tecnologico de Monterrey, School of Government and Public Transformation, Ciudad de México, México

Abstract. This work aims to understand and dimension the complexity of irregular migration flow in the Mexican corridor by integrating data through a computational multi-technique approach. The focus is to visually and quantitatively differentiate the vulnerability of migrants related to institutional capacity and the risks concerning human rights and identity. During the computational integration process, findings of social relevance will be reviewed. A goal is to have the framework or its segments be able to be reproduced and optimized for future projects, considering both temporal and regional applications to add consistency to research in the matter. Such an approach has the potential to improve the management of irregular migration, highlighting the collaboration between data models and the social and humanitarian sectors. This relates to the challenges in measuring and visualizing this phenomenon, contributing to its invisibility and negative consequences. Reviewing the framework reveals the complexity of the phenomenon, which involves variables such as risk sources, climate issues, transportation, demographics, cultures, language barriers, abuse, migration motivations, and varying migrant objectives. Migrants are vulnerable to criminal networks during their journey, contributing to their invisibility, as their status forces them to remain 'institutionally' in the shadows. The lack of impactful efforts or willingness from authorities exacerbates the situation. Efficient and humane public policies are needed to protect human dignity within this phenomenon, as the status quo leads to vague understandings of resource planning, furthering invisibility.

Keywords: irregular migration, institutions, infrastructure distribution, human rights vulnerabilities, policy, route dynamics, transnational migration flows.

Pablo Uriarte, pruiz4@stevens.edu

1 Introduction

Many communities face vulnerabilities so complex that they are incompatible with mainstream measurements. In some of these cases, this vulnerability becomes so unsustainable that they end up having more connections with the "underworld" or the informally and semi-undocumented 'in the shadows-like' schemes of crime and corruption networks. Things that, even in everyday life are difficult to observe, let alone measure even when we know they exist. It is often easier to react to their effects than to identify them. Many authors consider this true regarding irregular migratory transit, especially for migrants who were directly or indirectly forced into performing risky mobility, mostly due to misinformation or lack of economic means. In addition most Migrants in the condition of irregularity, actively try to remain invisible to authorities in host countries due to a lack of documentation certifying their stay or transit,[16] some using high-risk methods like stowing away on trains or relying on coyotes.[38] Gilodi et al. (2024) discuss how there is a link between irregular migration and corruption, as migrants often depend on criminal networks.[35] This increases their exposure to risks and distrust of institutional approaches.[16] This is very concerning, due to the increasing numbers of families, the elderly, and women with children traveling these routes annually.[35] Where, many migrant women, refrain from reporting crimes of sexual nature such as rape, abuse, kidnapping, and becoming objects of trafficking networks due to the necessity of continuing their journey.[35–37]

This work presents a framework for visualizing vulnerability in the geographic and spatial dimensions by analyzing the interaction of migrants with the infrastructural means that form the migratory corridor. The plan is to deliver metrics that assess vulnerability to quantitatively dimentionate the risks and challenges faced by migrants. As Gilodi et al. (2024) note, ”In socio-ecological systems, vulnerability is regularly referred to as the low capacity or inability of a system to respond to or withstand the perturbations of external stressors. Hence, a system is considered vulnerable when it possesses a low or null capacity to cope with hazards.” Understanding and improving this capacity is essential for effective governance and intervention by identifying higher-risk areas.

The evaluation of institutional capacity is particularly relevant in social domains using institutions to manage operations and dynamics. Originally introduced before World War I, primarily in education and public health,[33] by the 60s and 70s, more rigorous models were developed for urban planning, as seen in Freeman, 1977.[32] Government institutions manage infrastructure for populations, while educational institutions evaluate space and quality for student demand. Institutional capacity evaluation develops standardized methods for consistency and comparability across areas, this is well-represented in Kingsley, G. T., et al., 2003.[34]

This work aims to develop a bi-sectoral evaluation model with government and civil society, focusing on **irregular migratory transit (IMT)**. This is complex but necessary given the climate of harsh vulnerability related to migration irregularity. Community organizations play a critical role ”as mediating structures that facilitate the emergence and maintenance of values,” where ”strong institutions have implications for increasing public safety and reducing levels of violence,” as noted in Kingsley, G. T., et al., 2003.[34] Improving institutional capacity in one sector can benefit the other, as decision-making requires inputs from research and civil society.

Furthermore, the study focuses on **Irregular Migration across the Mexico-U.S. Corridor**, one of the world’s most traveled corridors for terrestrial irregular migration, involving a complex context with various risks. It serves as a pathway for migrants seeking better opportunities but is fraught with risks, including regional insecurity and inadequate institutional capacity. Despite efforts, gaps remain in protecting migrants’ rights and collecting consistent data on migratory patterns. Resuming the spatial analysis, we will identify, measure, and analyze elements of the Mexico-U.S. Corridor as geospatial data objects. Migratory routes, defined as pathways from origin to destination, can be recreated using GIS for detailed visualizations and insights.[9,10]

The work includes four additional sections. **Section 2** reviews human mobility under vulnerability, focusing on irregularity and data challenges, describes the North American corridor’s context and migrant community vulnerabilities, and explains the chosen methodologies for the aforementioned context. **Section 3** describes the technical methodology and data used, presenting descriptive results of the 'current' reality with 2023 data. **Section 4** discusses result interpretation, offering comparative analysis through the uncapacitated facility location problem, and includes public policy proposals. Finally, **Section 5** outlines future work identified from the framework.

2 Background

Human mobility, in migration, displacement, or other forms, is a complex, multifaceted phenomenon shaped by economics, political conflicts, religion, and environmental trends like climate change.[1] This review examines the complexity added to the mobilty while interacting to all those factors, focusing on IMT challenges in the Mexico-U.S. corridor.

For starters, most of the mainstream discussion of Irregular Migration centers on its causes and consequences, the public debates highlights in some cases the economic costs for the hosting community to support transit, and in some other places, integration or exclusion discussions raises 'cultural' concerns, many aligned with forms of xenophobia and racism,[2,3] policy agendas worldwide have yet to provide clearer solutions. However, research shows the binary approach of 'Yes or No, allow or stop Migration/Human Mobilities' fails to capture the phenomenon's full scope. This is evident in large-scale mobilizations from political conflicts, creating volatile integration and hostile climates involving racial and religious issues- Human rights protection, dignity, and vulnerable community resilience, then, often become secondary in the discussion.[1,18]

Mobilities of this nature are inherently linked to survival, making it a resilient and unstoppable force. Migrants often navigate and overcome policy barriers, adopting innovative approaches to achieve migration goals.[3–5] Thus, harsher, exclusier, and more coercive policies complicate managing Irregular Migration Transit (IMT) as a social issue, and could be really damaging to the migrant communities and transit countries. Unfounded or poorly implemented policies negatively affect efforts to make the phenomenon visible, keeping it invisibility in informality.[39,40]

This work's methodological integration addresses systematic injustices from migrant data underrepresentation.[18] IMT injustices manifest as violence received by migrants by means of informal labor schemes, corruption networks, inadequate policies, and racism and xenophobia in hosting regions.[19] Leading organizations struggle to develop comprehensive data sources, increasing human vulnerability,[20]and governmental institutions often inaccurately portray IMT dimensions with unspecific, ambiguous data collection, leaving research reliant on approximations.[15]

In addition to the lack of representation problem, IMT circumstances vary considerably based on the region hosting it, so understanding mobility phenomena of this nature requires addressing it as a singled case. Even, when currently active migration corridors generally involve developing countries moving toward larger economies, such as Mexico to the United States, Syria to Turkey, and India to the UAE. Most organization-issued numbers about migration often reflect nationals moving to different countries without assessing irregularity, because, these corridors only show overall migrant numbers, but irregular migration's broader scope complicates direct comparisons, as different nationalities within the moving population often share the same routes.[23] For that reason, this work's case study focuses only on the Mexico geographic area, as a 'terrestrial' multi-node pathaway to the U.S. from Latin America and the Caribbean.

2.1 Case Study: Irregular Migration Transit in the North American Corridor, Data from 2023

Few migration trends in the world are as characteristic in modern times as those seen in the Mexico-United States corridor. This corridor, primarily composed of populations from the Central American isthmus, including Guatemalan, Salvadoran, and Honduran nationals, has notably been joined by populations from Mexico and a small percentage of other South American, Caribbean, African, and Asian migrants, coming from diverse origins.[11] Geographically, the known paths of North American migration cover both the southern and northern Mexican borders, extending into key southwestern U.S. states and receiving the most 'on foot' migration flows through the border with Guatemala, though, there are also documented maritime routes or entries, especially in peninsular states. The terrestrial regions are key in shaping the dynamics of migration flows at the US-Mexico border. Given the vast expanse of the country, there are numerous and variable ways for migrants to cross.

For the North American migration corridor, the early 2000s marked a defining period for contextualizing the phenomenon of irregular transit migration. As the major countries in the north of the continent began to understand more concretely the factors that constitute the origins, development, and migratory destinations of the region, they also started to recognize at a governmental institutional level the significant challenges of addressing these issues. These challenges include national security concerns, economic and demographic impacts within the transit and destination societies, the nourishment of organized crime networks in the region,[12] and trends of political destabilization in origin societies.[13] Simultaneously, humanitarian organizations, including national and international human rights commissions, have raised critical concerns about the vulnerabilities of migrants' fundamental human rights, highlighting human rights violations within the entire infrastructural travel scheme, including governmental institutions established to oversee these matters.[41] A stark example is the atrocities occurring within the informal train railroad transportation system for migrants across Mexico,[14] exacerbated by criminal organizations engaging in sinister activities such as trafficking networks, kidnappings, and prostitution.[35,37]

However, the study has a special focus of relation to address the events from 2023 in Ciudad Juárez, Chihuahua, where a fire broke out in a facility for detaining irregular migrants. Reports highlighted the precarious conditions and overcrowding of the facility, which led to a state of shock and ultimately incited the fire, resulting in the deaths of 40 migrants.[42,43]

2.2 Literature Review

Before proceeding with the analysis, we need to conceptually clarify the phenomenon. Irregular Migration Transit (IMT) refers to the condition in which migrants, displaced individuals, or refugees in an irregular status find themselves in a temporal and geographical interval between departure and arrival points. This interval, often occurring in a 'third country' or 'transit country,' poses significant challenges due to the lack of documentation required for legal transit and entry into the destination country.[6]

In recent years, researchers studying irregular migration have increasingly emphasized the need for a more granular and migrant-focused visualization of the phenomenon.[14–16,20] Despite this, reports, bulletins, and publications from organizations like the International Organization for Migration (IOM) struggle to establish a consistent methodology for dimensioning and visualizing migration over time. While some proposals offer interesting ideas and certain visualization methods have persisted across studies, inspiring advancements in understanding narrative importance, challenges remain. To advance the methodological approach, research must focus not only on detaching problems from their origins but also on comprehensively understanding and addressing these roots.[21] This involves presenting all factors understandably while recognizing that each methodological element can and should be further developed individually but unified with the overall IMT analysis. Typically, migration analyses focus on origins and causes, but a comprehensive approach requires integrating these perspectives with an understanding of the migrant's journey, or what happens 'in-between'.

Returning to research in Mexico, some authors have identified promising opportunities to achieve the necessary granularity by focusing on established migratory routes within the corridor—a concept compatible with Lee's migration theory from 1966[1], and Casillas (2008) [2]. Focusing on these physical routes could yield significant insights in both qualitative and quantitative dimensions, as understanding the particularities of an IMT corridor would require examining the regional characteristics, including the infrastructure, and the risks within the migration terrestrial flow.

2.2.1 Theoretical Framework

In light of the above, this theoretical framework is divided into two parts: (1) the object-oriented construction of the corridor and (2) the intrinsic risks within the corridor and techniques to measure vulnerability.

(1) Following Casillas' work, this study focuses on the Mexico area. The visual model of the corridor is based on Casillas' "Una vida discreta, fugaz y anónima: los centroamericanos transmi-

[1] Lee (1966) writes that "migration tends to occur largely within well-defined paths" (p. 54) suggesting that planning and logistics are not as important for route choosing

[2] Casillas (2008) states that "migrants do not create paths; they make existing ones their own" (p. 7).

grantes en México, 2006",[16] adapted using object-oriented techniques as described in Glennon, A. (2010).[9] Casillas' pioneering work in Mexico has served as a foundation for other studies, including Llanos, 2022, which informed the characteristics of connectivity and permeability within the corridor used in my construction.

To plan the assignment and logical contextual integration of certain objects, particularly regarding migratory routes' direction, this study acknowledges the done by Martínez, G., et al.,[44] who reviewed railways' role in migratory transit in Mexico and other infrastructural elements forming part of the corridor. This is complemented by techniques for processing objects, such as projecting directions at the terrestrial level, as seen in Pérez Pereda, et al., 2023,[30] where instead I used the Direction Matrix API from Google Maps. Finally a grid segmentation similar to that used by Ali Mostafavi, and Chao Fan, 2022[46] helped to filter the routes without losing directional sense.

(2) The selection of major risks within the corridor, in alignment with irregular migration, begins with those reviewed in Isacson, A. 2014,[45] these will be re-sourced to the 2023 context in the continuing parts of the project. Continuing, the institutional evaluation planning is based on the conceptual foundations of Gilodi et al. 2024, to assess the interplay between institutional capacity and insecurity in transit spaces, enriching our understanding of institutional capacity's role in managing human mobility. The structure of the evaluation was reasoned based on the documentation review and methodologies described in Kingsley, G. T., et al., 2003, with adaptations for measuring vulnerability over demand. Additionally, the Uncapacitated Facility Location Problem (UFLP) is used for evaluation and comparative exercises, similar to those made by Pérez Pereda, et al., 2023.[30] And, previously mentioned demand will be given by irregular migration 'encounter events' records per city that will be discussed in the that collection section.

2.2.2 Research Gap

One of the main considerations regarding 'encounter events' data from the INM's irregular migration statistics bulletins is that, as Casillas mentions, these statistics have significant limitations and should be viewed as approximate sources when measuring migration dimensions.[16]

Additionally, I'm looking to address the trend of most previous similar papers (visualization products similarity) generalizing the corridor in mainstream reports, some studies simplify migratory routes with broad arrows, indicating involved countries but generalizing the dynamics that should be interpreted individually. To address that, I fragment the corridor into land routes by region, which is more appropriate due to the geographic composition of the corridor, particularly Mexico's position. This aligns with the necessity for research on Irregular Migration Transit (IMT) to delve into granular detail to adequately address vulnerability and resilience.

Finally, due to the lack of data availability. Most research articles, surveys, interviews, and film projects that aim to illuminate the "in-between" experiences focusing on injustices, human rights violations, and violence from the migrant's perspective, mostly come from a storytelling experience approach. Even though, these efforts are crucial for raising public awareness, often result in information only partially applicable to public policy as sensitive portrayals of reality. Few studies address specifics at a granular level using data presentation. The Missing Migrants Project, for example, has improved data on deaths and disappearances, especially concerning gender and age, critical for understanding women's and children's experiences. Despite these advances, working with available information remains challenging, adding ambiguity to data use in policy development and reporting, as highlighted in the World Migration Report 2022. [3]

3 Methodology Approach

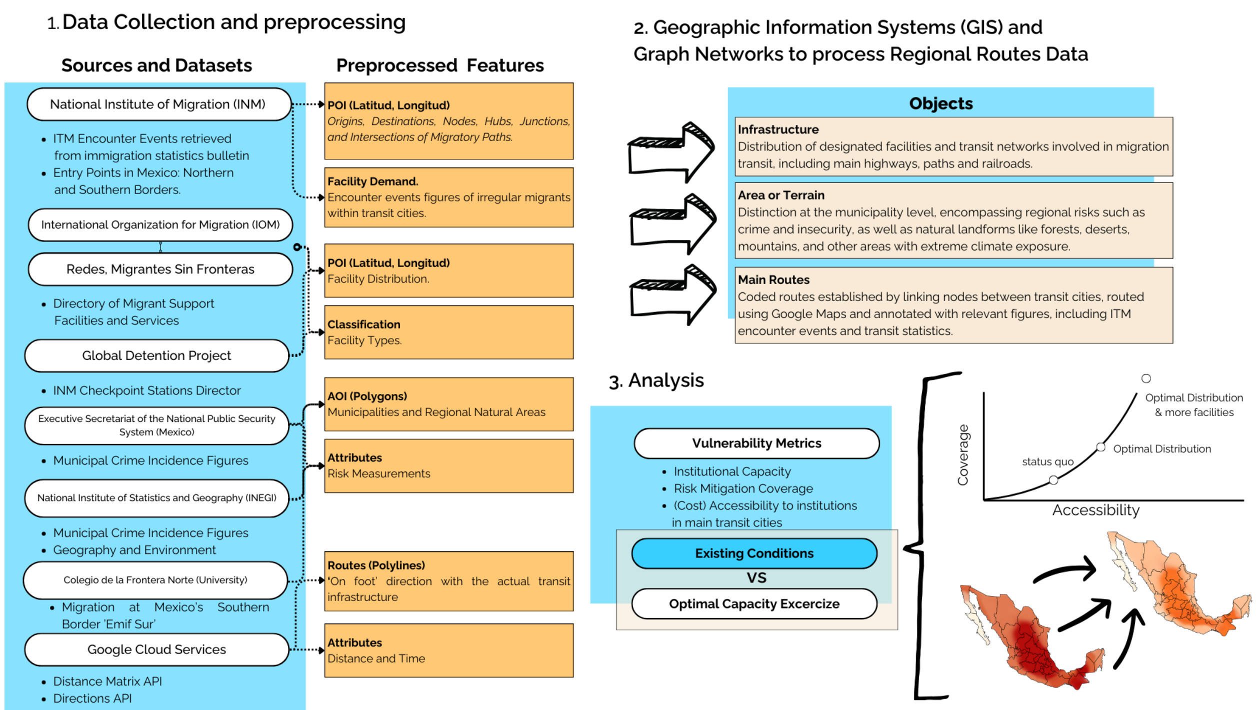

Fig 1 Methodology Framework

The framework we will use consists of three main parts, which are important to note because, in addition to providing a comprehensive vulnerability analysis, they also help break down the complexity of the phenomenon into different areas of observation.

1. **Data Collection:** This involves identifying the regions that form the basis of the migration corridor and gathering data sources related to irregular migration, institutions, and demographic dimensions relevant to the regions we will analyze.

[3]Primary data sources include Mexican immigration authorities and U.S. southern border officials, with information often fragmented, inaccessible, and inconsistently reported, retrieved from https://missingmigrants.iom.int/region/americas.

2. **GIS Systems and Network Construction:** This part involves using GIS systems to construct a representative graph network of the migration corridor, where each node represents a transit city and the edges correspond to segments of regional routes. Additionally, infrastructural elements specific to the corridor are represented as data objects, which are measurable and comparable, and integrated into our network for joint analysis.

3. **Analysis:** This involves analyzing the spatial distribution of vulnerabilities and comparing current conditions with optimal scenarios to identify gaps in institutional support and high-risk areas. This allows us to quantify vulnerabilities and propose data-driven recommendations for improving the protection of migrants' human rights. This section targets flaws in the structural management of infrastructure and institutions, focusing on two aspects, which, in alignment with our literature review, enables us to calculate vulnerability:

    - **Institutional Coverage Index (ICI):** Measures the ratio of migrant encounters to available institutions to host the migrants. This is identified as Vulnerability 1: Capacity over demand of government-designed facilities used to host and process migrants in irregular situations.
    - **Risk Mitigation Capacity (RMC):** Assesses exposure to high-risk zones and institutional coverage. This is identified as Vulnerability 2: Coverage and accessibility to public and civil society-originated institutional facilities, aimed at mitigating risks and providing assistance to migrants.

The framework should deliver a testing procedure aimed at identifying and ranking the severity of risk for migrants' human rights related to the availability of facilities during their journeys across regions and 'transit cities' within.

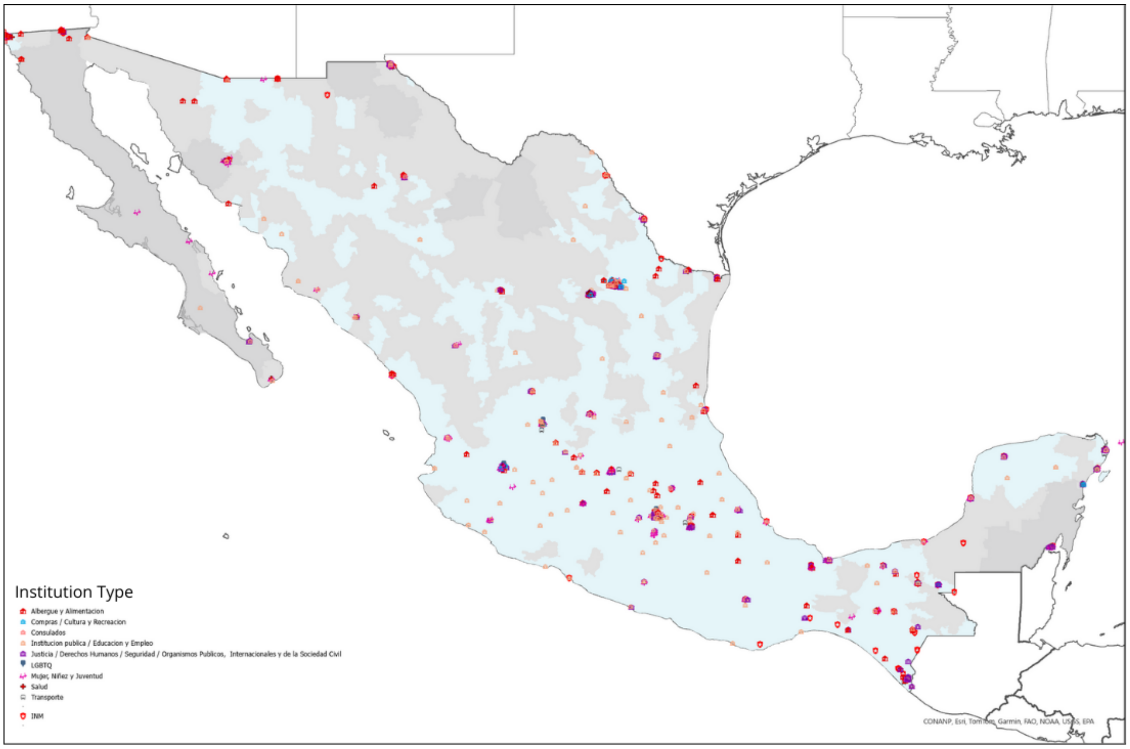

Fig 2 Facility Distribution by the type of institution, self-made

The data we will use can also be divided into the following categories of object classes. For clarity, the objects are labeled with the geospatial object they reference in the framework production and graph construction.

1. **Irregular Migration Encounter Events: Demand Data**. This data, sourced from statistical repositories managed by the INM (National Institute of Migration), serves, as discussed in the literature review, as an approximate ratio representing the relative transit in transit cities. It provides insights into detention occurrences and migration paths. Although it is limited as a feature of population flow, it is helpful to understand **demand** for institutional coverage.

2. **Infrastructure: Institutions**. This data covers the physical location of organizational facilities designed to receive and provide direct attention to migrants. It is crucial for evaluating institutional capacity and coverage. Facilities are categorized into two types:

   - INM facilities (National Institute of Migration), used to assist, detain, and process migrants. Data is sourced from the Global Detention Project 2023 directory.
   - Public institutions, including those from civil society and international organizations, supporting migrant protection. Data is extracted from directories such as those from the International Organization for Migration (IOM) and 'Redes, Migrantes Sin Fronteras'.

3. **Infrastructure: Transit Features**. This includes other important physical features of main migration routes, such as main highways, railroads, entry points, and crossing gates. This data is gathered to help draw travel paths with contextual logic. Apart from serving as a guiding object for logical directions within the network's node connections, this data also helps estimate travel costs based on the total distance traveled.

4. **Space and Environment: Terrain Characteristics**. Geostatistical data, including continental terrain descriptors and climatic data, are collected at the municipal level. This information, sourced from the National Institute of Statistics and Geography (INEGI), aids in understanding regional vulnerabilities and terrain challenges.

5. **Risk: Municipality Demographic Data**. A self-defined set of statistics for insecurity and violence exposure will be considered, aiming for all data to be consistently collected and valid for comprehensive analysis. These perspectives are retrieved from some of the main sources for statistics in the region, including Mexico's National Institute of Statistics and Geography (INEGI), the primary organization tasked with collecting and disseminating information about the country, covering aspects such as territory, resources, population, and economy. Along with, The College of the Northern Border, Migration Policy Unit, Survey on Migration at the Southern Border of Mexico (EMIF Sur), and the Executive Secretariat of the National Public Security System (SESNSP), a decentralized and autonomous body that collects statistics every month from the state prosecution offices' records. These dimensions are primarily analyzed as **risk** measurements.

To maintain statistical comparability and avoid redundancy, each measurement is set to be retrieved from a unique source unless a complementary characteristic can be found in a different data collection source, in that case, while putting the data together we'll make sure that the collection methodology does not compromise the validity of the statistical data representation.

Complementary, the **risk** measurements will be compared in a base index score, set to range from 0-1 using MinMax Scaler methods, and a similar adaptation of the method will be used for climatic and geographic data. Each risk source is cleaned, processed, and put together as follows.

3.1.1 R1: Violence and Insecurity: Women, Families, and Children

The statistics used in this **risk** measurement are consolidated into a single risk feature: "Violence and Insecurity for Women, Families, and Children," sourced from the database of the Executive Secretariat of the National Public Security System. It includes incident events in 2023, categorized by municipal division, for 'Feminicide,' 'Child Trafficking,' 'Liberty and Sexual Security Violations' (including Sexual Harassment, Sexual Abuse, Sexual Coercion, Simple Rape, Aggravated Rape), and 'Societal Violations' (including Corruption of Minors, Human Trafficking, and Other Crimes Against Society).

3.1.2 *R2: Institutional Violence*

Similarly, "Institutional Violence" aims to integrate the perception of abuse of authority and corruption, which can lead to cases where migrants are subjected to extortion, illegal toll payments, and physical aggression. While it is extremely challenging to accurately project these data, I explored several documents detailing the experiences of migrants and the importance of the "datafication[4]" of these experiences.[29]

To select the data, we first used the Migration at Mexico's Southern Border 'Emif Sur', designed to extract the migrant perspective. I filtered the columns corresponding to section P34 of the survey, which details the experiences of migrants when detained by Mexican authorities. Specifically, section P34 indicates the location of incidents, the treatment received from the authorities during processing, and the frequency of specific abuses such as mockery, disdain, insults or shouting, physical aggression, theft of belongings, and other abuses detailed by the migrants. Additionally, this section covers the conditions of the detention centers, including basic sanitary services, availability of food and water, and other related factors on 'Emif Sur'. To help prevent bias from using survey-based sources, which might exclude municipalities not appearing in the survey, I included data on 'Crimes committed by public workers' from the SESNSP dataset (data from 2023). This inclusion helps widen the scope to more municipalities within the corridor, ensuring that smaller municipalities are not overlooked.

3.1.3 *R3: Organized Crime*

Then, I employed a risk based on incident frequency rather than cartel presence. Using SESNSP data, I selected key indicators: homicide data, drug dealing, and kidnapping. Specifically, we analyzed crimes affecting 'Other legal goods' classified as 'drug dealing,' 'Intentional homicides committed with firearms,' and 'Crimes affecting personal liberty,' including extortionate and express kidnappings. This selection highlights the criminal activities most indicative of organized crime's influence within municipalities.

3.1.4 *R4: Geographic and Climatic Risk Value Calculation*

Finally, the Geographic and Climatic Vulnerability indicator assesses general terrain conditions and predominant extreme climatic conditions by municipality. Climatic vulnerability varies significantly with time; however, for long-term institutional infrastructure planning, I consider a year-long perspective of transit migration dynamics. In the R4 Geographic and Climatic Risk section,

[4]"Datafication refers to the process by which subjects, objects, and practices are transformed into digital data. Associated with the rise of digital technologies, digitization, and big data, many scholars argue datafication is intensifying as more dimensions of social life play out in digital spaces. Datafication renders a diverse range of information as machine-readable, quantifiable data for the purpose of aggregation and analysis. Retrieved from: Southerton, C. (2020). Datafication. In: Schintler, L., McNeely, C. (eds) Encyclopedia of Big Data. Springer, Cham. https://doi.org/10.1007/978-3-319-32001-$4_3 32-1$

I collected and preprocessed climatic data to evaluate temperature extremes, which are crucial for assessing potential risks to facilities that remain stationary for at least a year. The data was sourced from the INEGI database, utilizing their seasonal average extreme temperatures repository.[27] The Maximum Temperature Index (ITME) is calculated as $\mathrm{ITME} = \frac{\mathrm{TMAX} - \mathrm{media\_max}}{\mathrm{desv\_max}}$, and the Minimum Temperature Index (ITmE) is calculated as $\mathrm{ITmE} = \frac{\mathrm{TMIN} - \mathrm{media\_min}}{\mathrm{desv\_min}}$. ITME values are normalized between 0 and 0.5, with negative or zero values set to 0, and ITmE values are normalized inversely. The combined climatic risk is the sum of these normalized values.

I combined this metric with a geographic infrastructural risk measuring approach, using INEGI's geostatistical framework to differentiate rural and urban AGEBs[26] . Urban areas have higher population density and infrastructure, while rural areas are more dispersed and agriculturally focused. I calculate a rural-urban ratio at the municipal level, arguing that an urbanized municipality is more accessible regarding needs and services for traveling communities. Additionally, due to its denser demographic, it serves as a safer and more likely option for trans migrants.

3.2 Geographic Information Systems (GIS) to Represent the US-Mexican Corridor as a Permeable Network: A Graph Network Approach to Route Data Analysis.

Fig 3 Mexican Corridor: Migration Routes Network. Representation of the migration transit flow as a directed graph, illustrating the primary routes from south to north through the Mexican land borders. The map highlights key transit cities and route regions, categorized into Centro, Golfo, Pacífico, and Sur, providing an overview of the migration corridors within the country, self-made.

To achieve the structural composition of the data needed for the analysis, we first need to define the scope of our network as a platform that will host the migratory transit in our study. In this sense, as mentioned in the literature review, it is important to maintain an institutional interpretation of

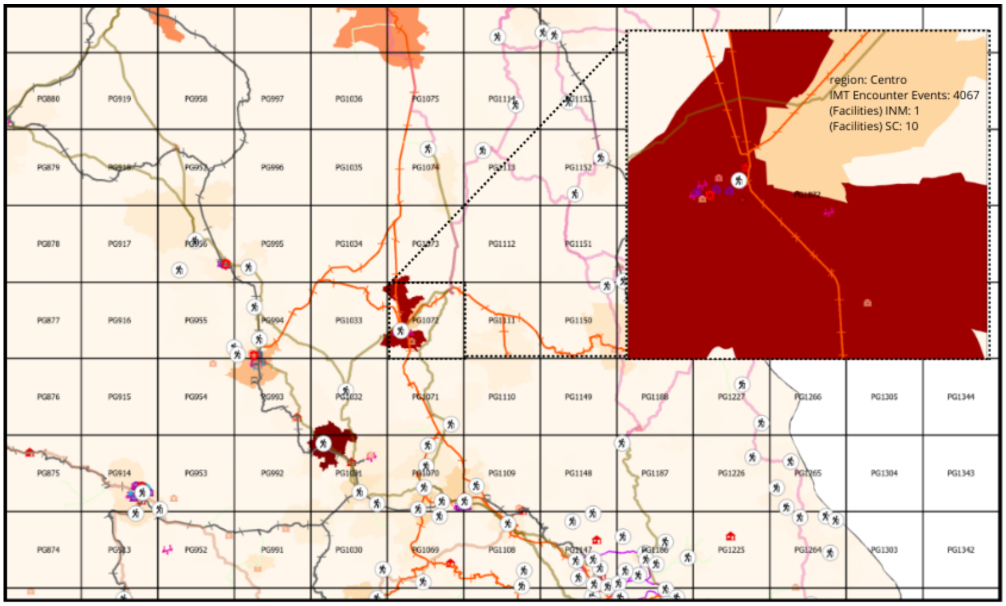

Fig 4 Visual representation of the ensembling process, Cell Id: PG-1031 in figure, self made

the network. Therefore, the decision to define our nodes was limited to only those cities with documented physical infrastructure for managing migration [5]. To maintain consistency that allows for a reproducible and verifiable exercise, we used municipalities referred to as 'transit cities' that appear in the IMT bulletin compiled by the INM regarding encounters with migrants in irregular situations, resulting in 389 nodes for 2023. These were integrated into a grid map exercise to ensure spatial consistency and logically relate the nodes based on their locations relative to the whole. This approach also helped reduce the computational load involved in creating networks on inconsistent terrain. After testing different sizes, the grid size that worked best for this case was determined to be 0.7x0.7 cardinal degrees (approximately 71.86 km x 77.92 km). These groupings led to 203 arcs or connections between points of interest for metric analysis [6].

For the analysis, the arcs are a crucial feature because they not only represent direction and distance which I included using the Google API's direction matrix. Additionally, through the arcs, we integrate a representation of the entire 'real' territory that the network traverses. The cities adjacent to each arc are considered segments, so in the network, including the 389 transit cities that compose the nodes, there are 1,507 municipalities in total, whose data are integrated for the analysis.

[5] Referring to records of irregular migration in the given year. Retrieved from www.politicamigratoria.gob.mx/es/PoliticaMigratoria/Boletines_Estadisticos

[6] In Mexico, 0.7 degrees of longitude is approximately 71.86 kilometers. For latitude, 0.7 degrees will always be approximately 77.924 kilometers due to the spherical shape of the Earth.

Finally, the corridor was divided into regions: South, Pacific, Center, and Gulf. A route code was assigned to each geographical point, representing the region to which the point belongs. This helped establish rules, barriers, and logical pathways, considering the regions' geography and infrastructural distribution, primarily involving a network limited by the main roads, railroads, and walkable routes. This conditioned filtering process resulted in 5,354 different route combinations for transit from entry cities at the southern border to final towns at the northern border.

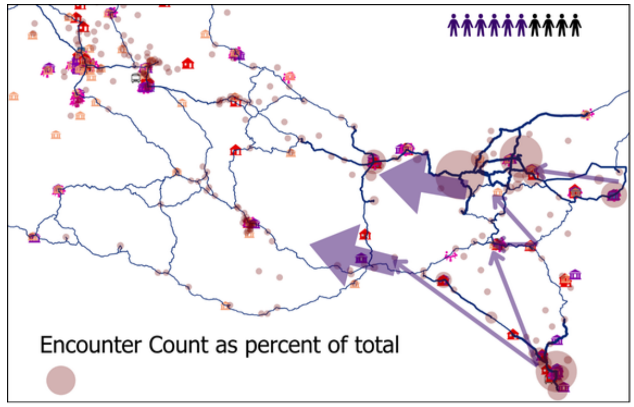

Fig 5 Arcs follow a logical path and direction to prevent for improbable route combinations

3.3 Analysis

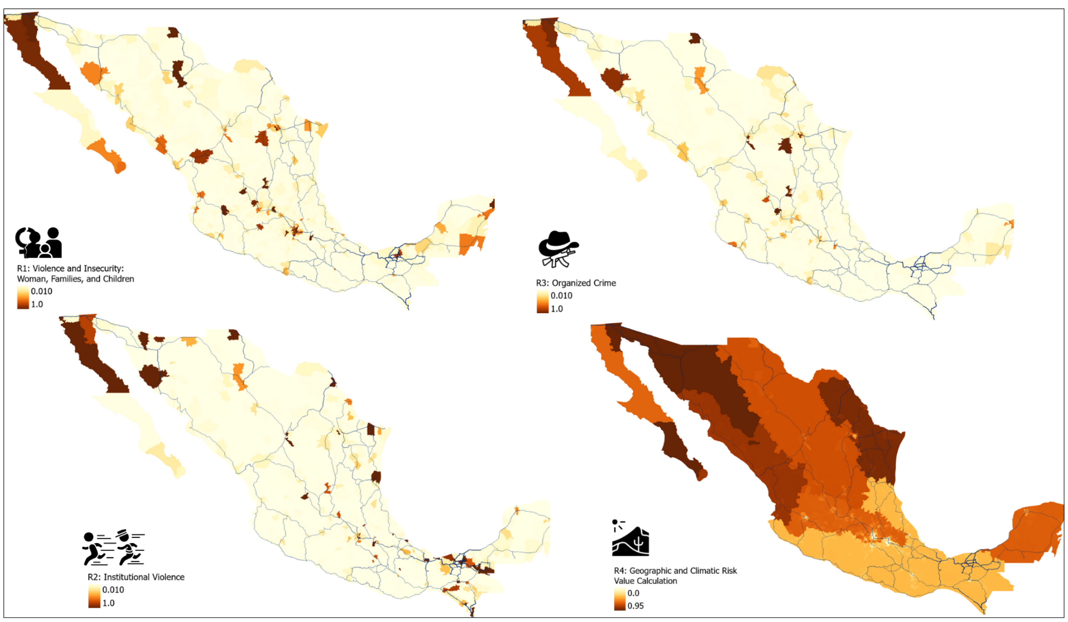

Fig 6 Encounter Events per Region (left), Maps of Each Municipal Risk Dimension Compared to "Walking" Routes or Arcs (right), self made.

While Analyzing Vulnerability at the systematical level is important to keep in mind that since the encounter events are our main indicator for demand of institutional coverage in this case, distribution of them should give us a notion of how the systems work. Also keeping a measurable track of distribution on demand enables for reproduction and comparability of results, both over time, circumstances changes, and/or in management experiments. For that, the goal is to approximate the dynamics from a status quo perspective, see how it does, and compare them with an optimized distribution exercise.

3.3.1 Vulnerability 1: Institutional Capacity

The metric **(Vulnerability 1)** uses a basic ratio between the logarithm of encounter events per transit city (node) and the number of INM stations assigned to accommodate those events. Through the logarithmic transformation, we adjust the events data to handle outliers and skewed distributions, acting upon taking into account the need to treat for -The Distance Bias for the Southern Region-, this considers the short dimensional width and the closeness to the southern border of initial regions as factors increasing the proportion of encounters, as distance advances, the territory gets wider, increasing the number of regions available for transit and the possible path combinations. The logarithm ($\log$) is used to capture the relative change in demand over these circumstances.

Complementarily, we understand that there is considerable variance between the number of Mexican Institute of Migration (INM) stations and the locations where the INM reports having processed and channeled events of encounters with irregular migrants. The proportion of locations (389) per facility (52) is much higher, suggesting the use of alternative facilities designated by the authorities of these locations to attend and register these events. Given this ambiguity, we assume each location as the base facility (1), resulting in:

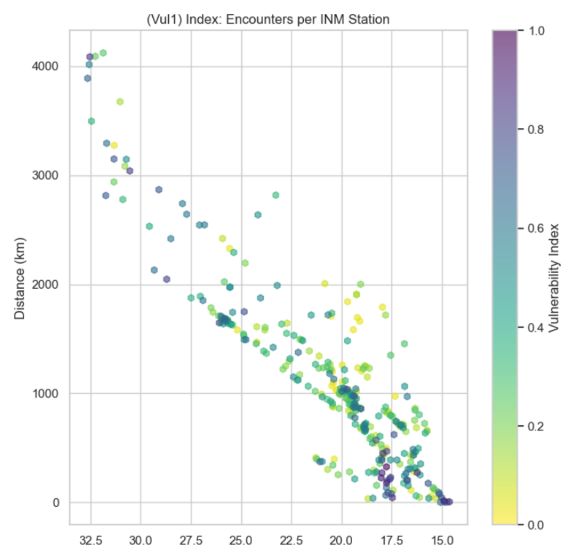

Fig 7 Vulnerability 1: Fixed Ratio of ITM Encounter Events per INM Station

$$\text{Vulnerability 1} = \frac{\log(D_i)}{F_i + 1}$$

Where:

- D_i represents the demand at Transit City(node) i
- F_i represents the facilities available at Transit City(node) i

Additionally, we perform a min-max normalization to obtain a score on a scale of 0 to 1, where values closer to 1 indicate greater vulnerability and a lower relative institutional capacity to manage migration events.

3.3.2 Vulnerability 2: Risk Mitigation Capacity

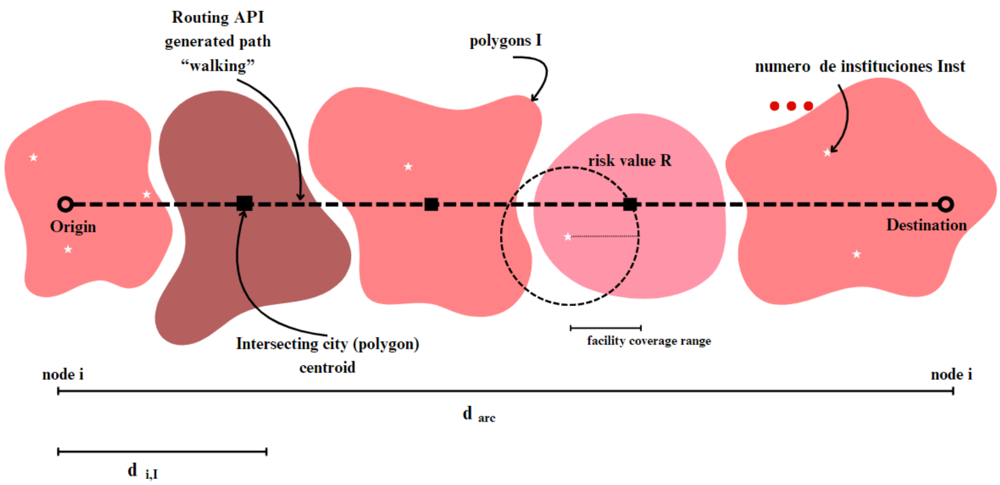

Fig 8 Risk and Distance Mitigation Capacity Index: Construction Framework

Although similar, the construction of the Vulnerability 2 metric is somewhat more complex. In this metric, we integrate risk values at the municipal level, along with direction and distance. As shown in Figure 7, we create a visual representation of how measurement objects interact to achieve this integration. The resulting metric, **Vul2**, defines vulnerability in relation to risk and travel distance, considering the available institutional infrastructure that provides coverage, protection, or shelter.

The logic is as follows: measure the exposure of transit points of interest (POIs) to high-risk zones, taking into account the distance traveled within these zones while moving between two transit POIs. Additionally, it evaluates the number of institutions within a 30 km radius of each POI, which can ideally be a source of support in cases of vulnerability. We aim to use this scheme as a way to illustrate the impacts of the aforementioned risks on general migrant vulnerability (to those risks) in the context of being in mobilization.

The notations are described as follows;

- D_i: Demand at node i.
- F_i: Facilities available at node i.
- R_i: Risk of node i (pre-calculated risk index).
- R_p: Risk of the intersecting-city p.
- $d_{p,i}$: Distance from intersecting-city p to node i.
- d_{arc}: Total distance of the arc.
- F_p: Facilities available at the intersecting-city p.
- $\sum_{k=1}^{N} d_{\text{arc},k}$: Sum of all the total distances of the arcs.
- n: Number of intersecting cities for a given node.

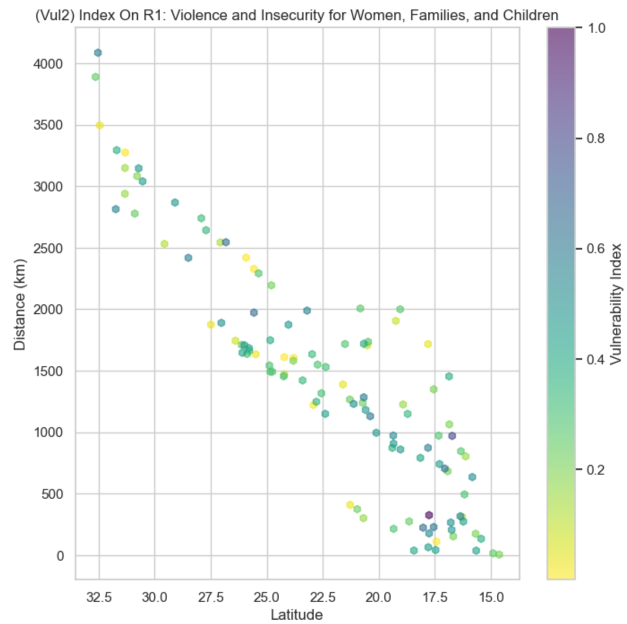

Fig 9 Vulnerability 2: Institutional Coverage in relation with insecurity of R1 ¨Woman, Children, and Families¨, self made

The initial Vulnerability 2 for each node i is calculated as:

$$V_{2i} = \frac{R_i \cdot D_i}{F_i + 1}$$

Then the length of each arc is assessed as: To adjust the initial vulnerability considering the intersecting cities of a longer arc, the following logic is used:

if (1): $d_{p,i} < \frac{d_{arc}}{2}$

$$R_p = \left(R_i \cdot \frac{d_{p,i} \cdot \frac{\sum_{k=1}^{N} d_{\text{arc},k}}{d_{arc}}}{d_{arc} - d_{p,i}} \right) \cdot \frac{1}{F_p} \cdot \frac{100}{n}$$

or if (2): $d_{p,i} = \frac{d_{arc}}{2}$

$$R_p = \frac{1}{2} \cdot \left(\left(R_i \cdot \frac{d_{p,i} \cdot \frac{\sum_{k=1}^{N} d_{\text{arc},k}}{d_{arc}}}{d_{arc} - d_{p,i}} \right) \cdot \frac{1}{F_p} \cdot \frac{100}{n} \right)$$

else if (3): $d_{p,i} > \frac{d_{arc}}{2}$

This means that no additional calculations are made for the remaining intersecting polygons

In the formulas, $\frac{1}{F_p}$ represents the inverse of the facilities available at the polygon p. It means that as the number of facilities F_p increases, the risk contribution of that polygon decreases, and vice versa. It serves to adjust the risk calculation based on the capacity of the facilities available in the intersecting polygon. The adjusted Vulnerability 2 is calculated by multiplying the initial vulnerability by the accumulated product of the risks of the intersecting cities:

$$V_{2i,final} = V_{2i,initial} \times \prod_{p \in P} R_p$$

where P is the set of intersecting polygons that meet the conditions. Finally, a vulnerability score ranging from 0-1 is given to each transit city, in consideration that these are the places that are being primarily provided with infrastructure.

3.3.3 Results: Status Quo

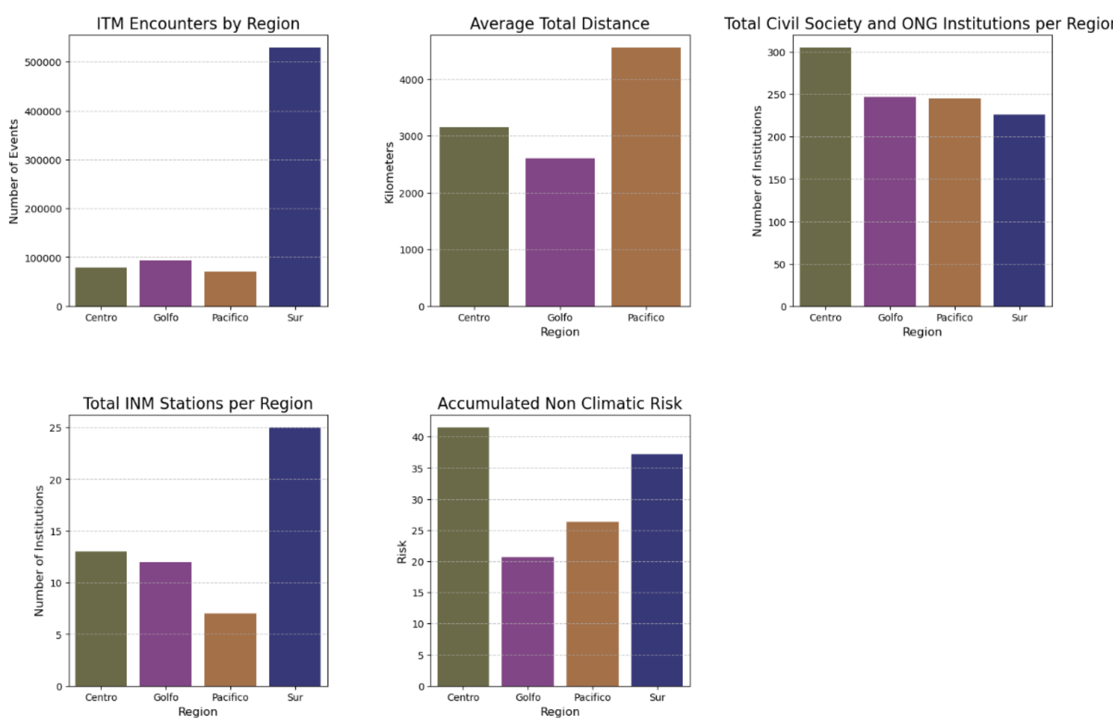

Fig 10 Transit Figures: Comparison between regions, Self-Made

In this section, we will review the status quo using the metrics obtained during the framework development as one of the project's objectives, which is to develop datafication in the corridor in the context of irregularity. Although the final part of the project will present an alternative method for deciding how infrastructure should be distributed to minimize human rights vulnerability exposure, reviewing the status quo will allow us to make a comparison.

To review the methodology, I consider it pertinent to evaluate its capacity to answer questions of interest related to the corridor's vulnerability that propose an alternative for decision-making from an institutional perspective. For example, referring to the work of the National Institute of Migration (INM) and the governments involved in managing the phenomenon: **What did we learn from Ciudad Juárez in 2023?**[7] **How could this have been foreseen? Are there any places with a high relative risk of experiencing a similar tragedy?** Vulnerability 1, discussed earlier, is a simple ratio of the number of reported encounters in a transit city against the number of INM installations, like the one that burned in Ciudad Juárez, within at least a 30 km walking distance. Figure 6 shows a relatively higher vulnerability in the 'Sur' (South) Region, as expected, but the trend continues to the west side of the corridor in the 'Pacífico' (Pacific), followed by the 'Centro' (Center) region, notably in North Pacific and North Center, where Ciudad Juárez is located. Before its closure in June, Juárez, Chihuahua, ranked as the 29th of 359 municipalities in terms of overcrowding vulnerability, according to our methodology.

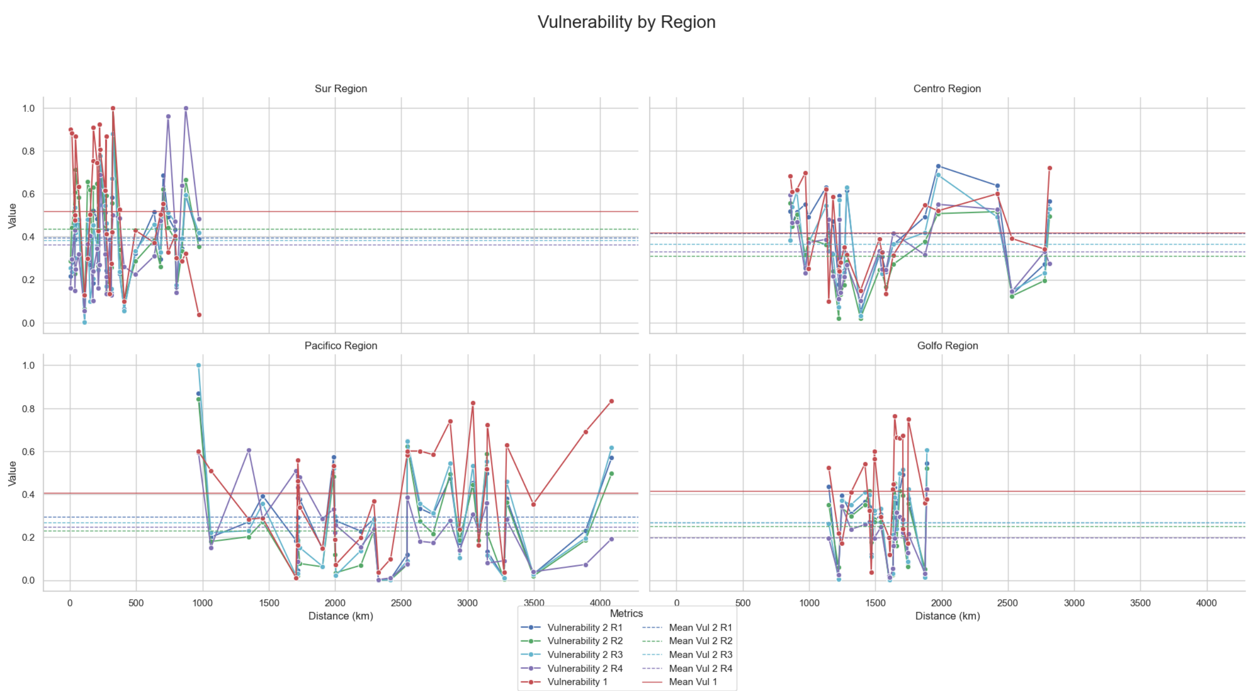

Fig 11 Results: Vulnerability Distribution Scores per Distance traveled (South to North)in Status Quo, Self-Made

From the migrants' perspective, it would be useful to know, **Which route has the overall risk to transit by (exposure risk)?** For this, while we might generally look at Figure 11, the 'non-

[7] Reports indicate that the facility was severely overcrowded, with one account stating that 68 people were confined to a cell designed for a maximum of 50 individuals. This overcrowding contributed to a lack of basic necessities, including food and water, which ultimately led to the protests by the detainees. Source: NBC News.

climate risk' graph, or even Figure 6, which might offer more granularity, in this context and with the available data, the Vulnerability 2 metric allows us to differentiate the risks transmigrants may encounter on their journeys. This can be beneficial for migrants but with very marked limitations, such as the relative need to choose which risk to face, which seems illogical considering we are discussing risks, not facts [8]. Therefore, at most, the ability to choose where more accompaniment might be needed, which can also be reviewed in Figure 11, 'SC Institutions per Region'. It seems pertinent to consider additional reasoning. For example, the argument presented in Ramos' work about the relative security of traveling in large, organized groups might be a better decision-making alternative for migrants concerned about their safety, despite being relatively recent and yet to be quantitatively proven.

However, regarding planning from the civil society organization's perspective, **Which route has the most risk by demand (relative risk)?** and based on that, **Where should I establish support missions for migrants?** Although this only comes up as an appreciation, it takes away any threshold about where and how irregular migration mostly happens. Instead, it tells us that we must be able to observe the phenomena everywhere (not just in the transit cities occupied in the networks of this exercise). Therefore, in alignment with Vulnerability 2 of this work, assessing relative risk—the number of encounters per city of transit exposure—may be our best option as it provides a closer look at the human rights vulnerability of transmigrants and the capacity to assign institutional support in strategic locations. For instance, Figure 11 illustrates that risk vulnerability is just slightly above but closer to similar in the Pacific region for example with the Gulf, but considerably lower than Center, however, the longer transit distance increases the cost and exposure time compared to the Center and Gulf regions, where distances are much shorter, and relative institutional coverage is higher. We can argue then that in the Pacific region, there is a disproportionality in coverage concerning the length of the route, mainly noticeable by the total distance traveled between one peak of Vulnerability (2) and another.

4 Discussion and Policy Suggestions

Now that we have a better understanding of the data, we need to ask ourselves, as stakeholders and decision-makers, what we aim to achieve with it. One objective may be to reduce overall vulnerability. To accomplish this, it will be necessary to deploy funds and resources to enhance institutional and governmental support, providing better coverage. This entails developing a comprehensive plan to address irregular migration, which may include institutional reforms, infrastructure

[8] To do this, we must grasp the entire panorama. While risk is generally stationary and unlikely to change drastically over time, it remains a constant concern, whether for migration transit or local residents. So we need to take a little break to figure in our analysis that, according to Lee[], transmigrants typically follow established paths, and changes are minimal. This is still true for higher-risk encounters. Another thing to keep in mind, as we previously discussed, is that it's commonly believed that most migration transit in Mexico occurs along railroads, which would be seen mostly in the 'Center' region.

development, and other measures, that may take a lot of time. However, if immediate resources are unavailable, we must explore alternative strategies.

For example, the approach illustrated in Figure 10 could offer valuable insights. Instead of focusing solely on reducing overall vulnerability, we could aim to bring all vulnerability values closer to the average. This approach may not significantly lower overall vulnerability, but by reducing extreme peak values, we can mitigate the likelihood of incidents similar to Juarez, 2023.

Now, this requires a direct examination of the factors contributing to our defined vulnerabilities. Since the origin of risk often lies beyond the migration phenomenon and is more location-specific, our ability to influence these factors is limited. Nonetheless, focusing on encounters and infrastructure can be a promising approach. The idea at this point so to be able to compare our data, in order to identify not only vulnerabilities but also areas of opportunity.

4.1 Uncapacitated Facility Location Problem (UFLP)

One option to address this is the Uncapacitated Facility Location Problem (UFLP). The UFLP is a computational problem that consists of identifying an optimal subset of facility locations by minimizing the total distance over demand, from a status quo set of facility locations. For our analysis, we adopted a similar approach to Perez Pereda, 2023.[30] While the UFLP framework provides a solid foundation, our specific requirements introduce elements that may necessitate modifications to the basic UFLP model.

The goal here is to identify demand in cities and place facilities within a range of 30km from the city centroid to best support that demand, given a limited number of facilities. The UFLP helps us allocate resources effectively to reduce vulnerabilities and improve coverage across various regions. To run this model, we will modify the basic UFLP framework by incorporating weighted demand, assignment constraints, and iterative or multi-objective approaches to create a more tailored model that effectively addresses our specific scenarios.

To run experiments, I set the data frames to represent the objects as; the demand centers are the transit cities or nodes (i), which include the city name, code, geodetic coordinates 'xy', and demand (D), as well as a 30km radius circular polygon that represents the range within reach. The facility locations, in one scenario, are the INM Detention Centers (F_a), and in another scenario, the SC and ONG Institutions (F_b), both with their corresponding coordinates.

We will review the scenarios based on the size of F_a and F_b, meaning the number of facilities available for that matter. Before continuing, we need to keep in mind some considerations about the basics of the UFLP.

While the original mathematical formulation of UFLP[31] is:

Objective Function: Minimize the total cost:

$$\text{Minimize} \quad \sum_j f_j x_j + \sum_i \sum_j c_{ij} y_{ij}$$

Constraints

Each client must be served by exactly one facility:

$$\sum_j y_{ij} = 1 \quad \forall i$$

A client can only be served by an open facility:

$$y_{ij} \leq x_j \quad \forall i, j$$

Binary constraints for decision variables:

$$x_j \in \{0, 1\} \quad \forall j$$

$$y_{ij} \in \{0, 1\} \quad \forall i, j$$

On our case study and methodology, I work with the following variations:

- In the context of limited facility availability, each transit city has a different level of demand, which suggests that not all facilities should serve all cities equally. Even though this is a departure from the traditional UFLP, for now, we'll focus on maximizing coverage without worrying about how much demand each facility can serve.
- There are no restrictions on the eligibility of facility locations within the cities since this exercise is conducted on a national scale.
- For our exercise, we assume the facilities are open 24/7, which is a completely fabricated scenario.
- Costs, such as accessibility or walking distance, are not considered in this formulation since we aim to improve coverage, not reduce costs.
- The cost of building facilities is also not necessary for this formulation due to the recurring changes in distribution over time in the past[9]

Then the approach proceeds as follows, utilizing a greedy algorithm in Python. The greedy algorithm prioritizes the assignment of facilities to transit cities with the highest demand first,

[9] Government of Mexico, National Institute of Migration. "INM reports on transformation work in migration stations to prevent repetition of incidents like the one in Cd. Juárez on March 27, 2023." https://www.gob.mx/inm/prensa/inm-informa-de-trabajos-de-transformacion-en-estaciones-migratorias-para-no-repeticion-de-hechos-como-el-de-cd-juarez-el-27-de-marzo-2023.

ensuring that each facility is within a 30km range of the assigned cities. By doing so, we aim to maximize coverage and minimize the distance over demand. This method involves iterating through the transit cities, assigning available facilities to those with the highest unmet demand, and then re-evaluating the remaining demand and available facilities. This iterative process continues until all facilities are optimally assigned.

4.2 Government Institutional Capacity: Current vs Optimal

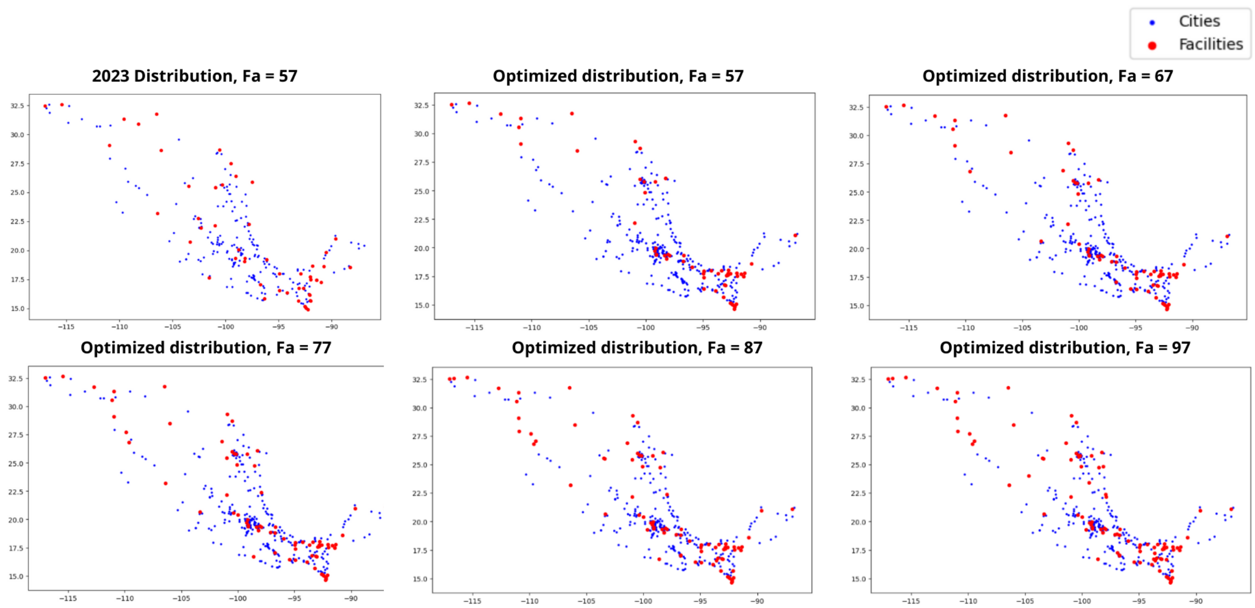

Fig 12 Optimal Institutional Distribution: INM Detention Centers, Self Made

For our case, it helps prioritize the assignment of facilities to transit cities with the highest demand first, ensuring that each facility is within a 30km range of the assigned cities. By doing so, we aim to maximize coverage and minimize the distance over demand. This method involves iterating through the transit cities, assigning available facilities to those with the highest unmet demand, and then re-evaluating the remaining demand and available facilities. A adaptation that I made, is that while itearating a facility assignation at its given time, the algorithm looks to cover as much demand (Di) on the colateral, this approach effectively captures the essence of the greedy algorithm. This iterative process continues until all facilities are optimally assigned by keeping track of which cities are covered by which facilities, and aiming for next optimal spot available.

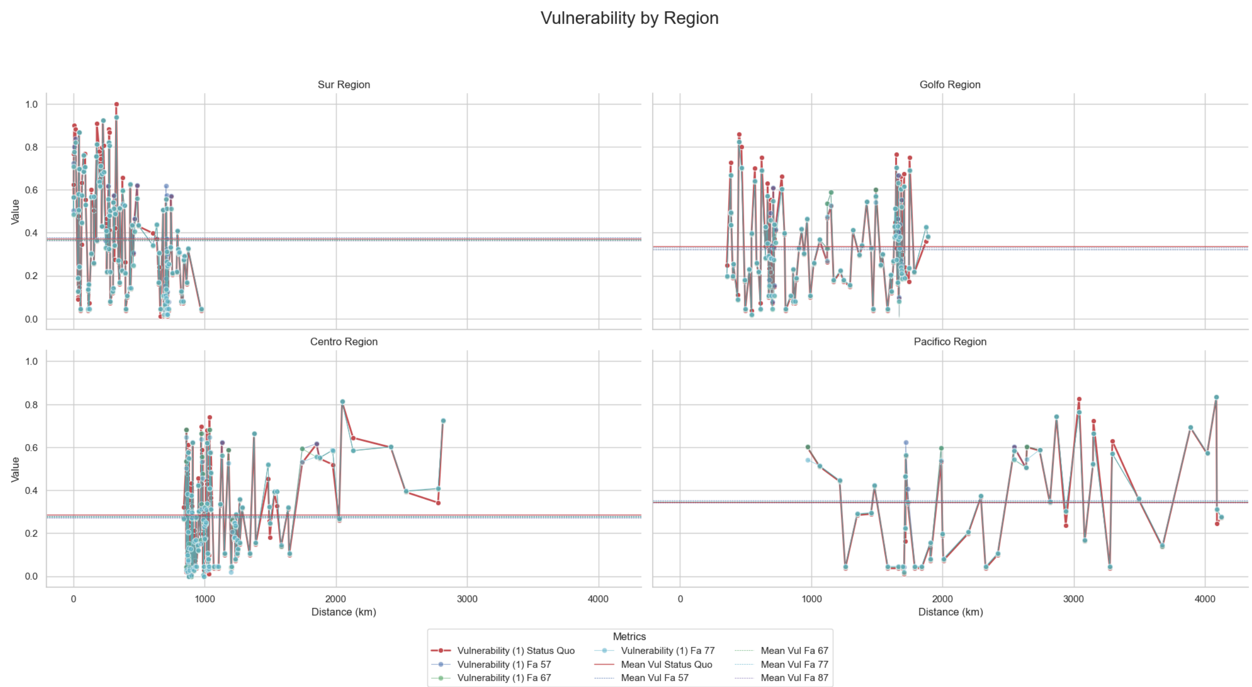

Fig 13 Optimal Institutional Distribution: INM Detention Centers, Self Made. The first thing to observe is the level of variability of the different results between the regions, most changes are seen in the South, while the Pacific looks more unified with the Status Quo result, indicating the need for facilities.

This scenario, which involves optimizing the distribution of the current number of INM Detention Centers (F_a) and increasing the number of these facilities until all locations are satisfied, multiple experiments will be conducted and tracked for comparison. In this problem, each transit city has a varying demand (D_i). Facilities (F_a) should be assigned to the most needing locations first, meaning that locations with the highest demand max(D_i) should be prioritized, while assignments should also aim to intersect with other nearby locations within the range to cover as much demand (D) as possible. I ran some experiments to identify bigger vulnerable areas, by considering an incrementation of ten in the total facilities available for assignment for each experiment from the original fifty-seven. Even from the experimental distribution of the same fifty-seven of 2023, there is a considerable diminution of the peaks, this does not imply that existing facilities should change locations, due to the cost of changing the current organization, but rather aims to show where new facilities are needed. In Figure 13, see how there are way more nodes above the average un 'Sur' compared to the rest of the regions, Figure 12, shows that as availability increases, first-served locations are located in the 'Sur' region.

5 Future Work

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