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

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Highlights

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- Migrants' vulnerability on human rights is tied to institutional and infrastructural capacity.
- The framework exposes flaws in migration management through the North American corridor.
- Infrastructure redistribution optimization reduces vulnerability across regions.

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Abstract

Irregular migration is a pressing global issue causing human suffering and economic losses. One challenge in addressing it is the difficulty in measuring and quantitatively understanding the phenomenon. Migrants are especially vulnerable to criminal networks, remaining 'institutionally' invisible due to their irregular status. Authorities' lack of action or willingness to intervene worsens the situation. Regions like Southern and Central Mexico show greater vulnerability due to punitive enforcement and inadequate infrastructure. Current facility placements fail to meet demand, leading to human rights risks, as seen in Ciudad Juárez in 2023. This work aims to visually and quantitatively differentiate the vulnerability of migrants related to institutional capacity and risks to their basic rights and dignity. Through computational analysis, key findings emerge about migratory transit dynamics that are of public interest. The goal is to develop a scalable framework that can help in optimizing migration management by integrating data models with social and humanitarian efforts. The framework highlights critical variables such as socio-environmental risks (e.g., climate, transportation, demographics, language barriers, abuse, and migrant motivations). The framework demonstrates previously documented flaws in managing migration, often noted through case studies and migrant experiences. By applying the Uncapacitated Facility Location Problem (UFLP), this study proposes infrastructural optimizations that redistribute vulnerabilities, reducing extreme conditions. The study concludes that effective and humane public policies are essential to safeguard human dignity, as the existing approach leads to poor resource planning and worsens the invisibility of vulnerable migrants.

Keywords: irregular migration, migration institution, infrastructure distribution, human rights vulnerabilities, migration policy, migration routes, transnational migration

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1. Introduction

Many communities face complex challenges that are incompatible to address with mainstream approaches or are simply left unaddressed. In some of these cases, the effect of these challenges becomes so unsustainable that communities end up establishing connections with the "underworld" or the informally and semi-undocumented "in the shadows-like" schemes of crime and corruption networks.

For example, data related to the vulnerability of migrant communities is difficult to collect and access through official platforms, leading to a lack of proactive policies to prevent or mitigate risks. Institutions often find it easier to react to the effects of these risks than to identify them in advance. Many authors consider the lack of proactive policies detrimental in irregular migration, especially for migrants who were, directly or indirectly, forced into performing risky mobility, mostly due to misinformation or lack of economic means[22, 49, 50]. 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 [1], some using high-risk methods like stowing away on trains or relying on coyotes[2]. Gilodi et al. (2024) discuss how there is a link between irregular migration and corruption, as migrants often depend on criminal networks[3]. This increases their exposure to risks and distrust of institutional approaches[1]. This phenomenon is very concerning, due to the increasing numbers of families, the elderly, and women with children traveling these routes annually[3]. Where, many migrant women, refrain from reporting crimes of sexual nature such as rape, abuse, and kidnapping[3, 4, 5]. Simultaneously, the number of trafficking victims worldwide has been growing at an alarming rate in recent years, Rubio & Guadiana (2021) accurately explain how migrant women in irregular status are extremely vulnerable to being forcefully recruited in human trafficking networks[6].

This work adopts a resilience engineering approach, influenced by the research of Ramirez-Marquez & Rocco (2012)[52], to understand the vulnerability of migrant communities. It presents a framework for visualizing vulnerability in geographic and spatial dimensions by analyzing how migrants interact with the infrastructural resources that make up the migratory corridor in Mexico. The objective is to assess vulnerability and quantify the risks and challenges migrants face. As Gilodi et al. (2024) mentions, "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."[3] 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 where institutions manage operations and dynamics. Originally introduced before World War I, primarily in education and public health[8], by the 60s and 70s, more rigorous models were developed for urban planning, as seen in Freeman (1977) work [9]. 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 Roman, C. G., & Moore, G. E. (2004) [10].

This work aims to develop a bi-sectoral evaluation model involving both government and civil society, with a focus on irregular migratory transit (IMT). While complex, this approach is necessary due to the significant community vulnerability associated with migration irregularity. Community organizations play a critical role as "mediating structures that facilitate the emergence and maintenance of values," and "strong institutions have implications for increasing public safety and reducing levels of violence," as noted by Roman and Moore (2004)[10]. Strengthening institutional capacity in one sector can benefit the other, as effective decision-making relies on inputs from both 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, this work 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 [11, 12].

There are three additional sections in this work: **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 methods and data used, presenting descriptive results of the 'current' reality with 2023 data. Finally, **Section 4** discusses result interpretation, offering comparative analysis through the uncapacitated facility location problem, and includes public policy proposals.

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 [13]. This review examines the complexity added to mobility while interacting to all those factors and, focusing on IMT challenges in the Mexico-U.S. corridor.

Most of the mainstream discussions on Irregular Migration focus on its causes and consequences, the public debates highlight the economic costs for the hosting community to support transit. Others review the integration or exclusion discussions raising 'cultural' concerns, many aligned with forms of xenophobia and racism[14, 15]. Policy agendas worldwide have yet to provide clear and implementable 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 community resilience, then, often become secondary in the discussion [13, 20]. 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 [15, 16, 7]. Thus, harsher, more exclusionary, and coercive policies complicate the management of IMT as a social issue and could be particularly harmful to vulnerable communities. Unfounded or poorly implemented policies (by all countries involved) can negatively affect efforts to make the phenomenon visible, keeping it invisible in informality[17, 19] and the migration corridor.

As this work addresses systematic injustices from migrant data underrepresentation [20] it is important to note: IMT injustices manifest as violence received by migrants in the form of informal labor schemes, corruption networks, inadequate policies, and racism and xenophobia in hosting regions[21]. Leading organizations struggle to develop comprehensive data sources, increasing community vulnerability [22], and governmental institutions often inaccurately portray IMT dimensions with unspecific, ambiguous data collection, leaving research reliant on approximations[23].

In addition to the lack of representation problem, IMT circumstances vary considerably based on the regional development, so understanding mobility phenomena of this nature requires addressing it as a unique 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. Thus, this work's case study focuses only on the Mexico geographic area, as a 'terrestrial' multi-node pathway 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 are as characteristic in modern times as those taking place 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 [37].

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 migration dynamics 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 IMT. 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 [24], and trends of political destabilization in origin societies [25]. 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 [26]. A stark example is the atrocities occurring within the informal train railroad transportation system for migrants across Mexico [27], exacerbated by criminal organizations engaging in sinister activities such as trafficking networks, kidnappings, and prostitution [3, 5].

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 [28, 29].

2.2. Literature Review

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 [30].

In recent years, researchers studying irregular migration have increasingly emphasized the need for a more granular and migrant-focused visualization of the phenomenon [27, 23, 1, 22]. Despite this call, reports, bulletins, and publications from organizations like the International Organization for Migration (IOM) struggle to establish a consistent methodology for dimensionalizing 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 [31]. 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'.

In the case study corridor, 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 pioneer theory from 1966, which suggests that "migration tends to occur largely within well-defined paths," indicating that, while planning and logistics are important, they are secondary to the existing migration streams and the information available about them (Lee, 1966, p. 54)[47]. This aligns with Casillas' (2008) observations about the transit corridor in Mexico, where he notes that "migrants from Central America do not create paths; they make existing ones their own" (p. 7)[23]. 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

Given the previous discussion, 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 community 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 transmigrantes en México" (2006) [1], adapted using object-oriented techniques as described in Glennon, A. (2010) [11]. Casillas' pioneering work in Mexico has served as a foundation for other studies, including Llanos, 2021, 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. [32], 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 [33], where instead we used the Direction Matrix API from Google Maps. Finally, a grid segmentation similar to that used by Ali Mostafavi, and Chao Fan, 2022 [34] 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 [35], 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 Roman, C. G., & Moore, G. E. (2004)[10], 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) [33]. The previously mentioned demand will be given by irregular migration 'encounter events' records per city that will be discussed further in the data 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[1].

Additionally, previous studies tend to generalize 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 and granularly. To address such gap, this approach fragments 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 IMT to delve into granular detail to adequately address community vulnerability and thus, 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 anecdotal 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. For example, Primary data sources include Mexican immigration authorities and U.S. southern border officials, with information often fragmented, inaccessible, and inconsistently reported [51]. The Missing Migrants Project, has improved data on deaths and disappearances, especially concerning gender and age, which are 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. Methodology Approach

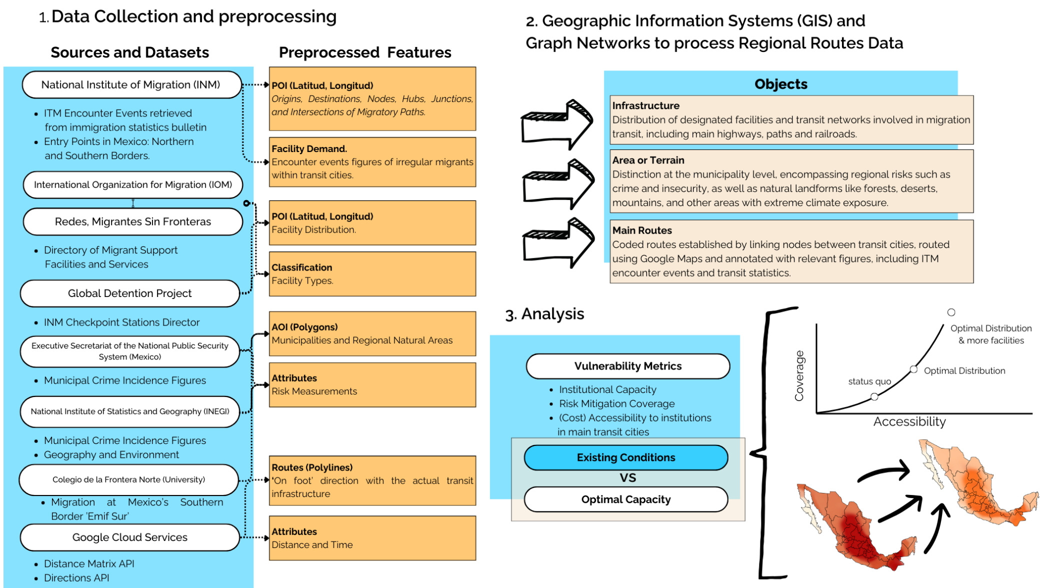

Figure 1: Methodology Framework

The framework developed consists of three main parts. In addition to offering a comprehensive vulnerability analysis, it also breaks down the complexity of the phenomenon into distinct areas of observation and requirements.

1. **Data Collection:** This section 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 that will be analyzed.
2. **GIS Systems and Network Construction:** This section 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 section 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 pert of the framework will allows to quantify vulnerabilities and propose data-driven recommendations for improving the well being of migrants. Additionally, this section targets flaws in the structural management of infrastructure and institutions, focusing on two aspects, which, in alignment with our literature review, will enable for the computation of vulnerability:

- **Institutional Coverage Index:** Measures the ratio of migrant encounters to available institutions to host the migrants. This first metric is identified as Vulnerability 1: Capacity over demand of government-designed facilities used to host and process migrants in irregular situations.
- **Risk Mitigation Capacity:** Evaluates 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 delivers a testing procedure to identify and rank the severity of risk for migrants' well-being related to the availability of facilities during their journeys across regions and 'transit cities' within.

3.1. Data Collection, Preprocessing, and Risk Index Formulation

The data collected 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 development 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 an approximate ratio representing the relative transit in transit cities as discussed in the literature review. 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[37].
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:

Figure 2: Facility Distribution by the type of institution

- INM facilities (National Institute of Migration), used to assist, detain, and process migrants. Data is sourced from the Global Detention Project 2023 directory[37].
- 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)[40] and 'Redes, Migrantes Sin Fronteras'[41].[1]

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[43, 44].

[1] 'Maps throughout this book were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit www.esri.com.'

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[39].
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. The data is retrieved from The College of the Northern Border, Migration Policy Unit, Survey on Migration at the Southern Border of Mexico (EMIF Sur)[38], 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[45]. 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 it has to be made 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[45]. 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).

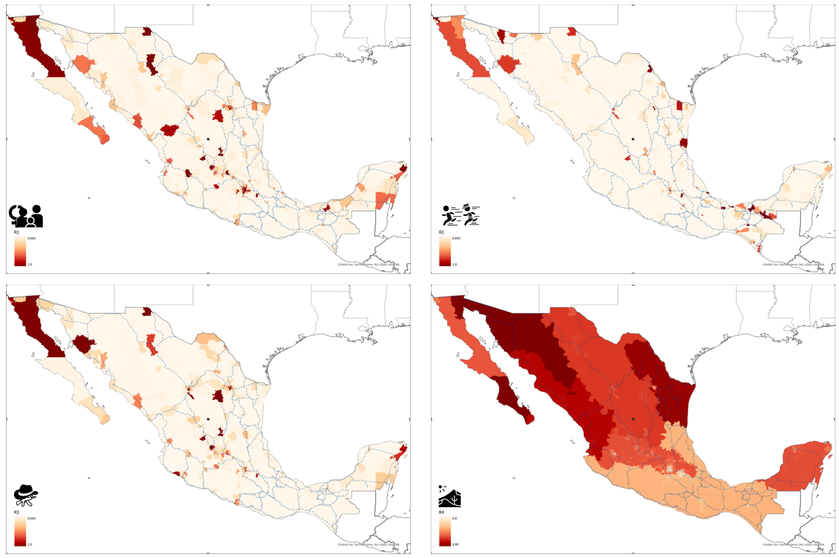

Figure 3: Maps of Each Municipal Risk Dimension Compared to "Walking" Routes or Arcs

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. The selected data included, the Migration at Mexico's Southern Border 'Emif Sur'[38], is designed to extract the migrant perspective. Data corresponding 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, data on 'Crimes committed by public workers' from the SESNSP dataset (data from 2023)[45] is included. 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

The framework also employed a risk based on incident frequency rather than cartel presence. Using SESNSP data[45], and selects key indicators: homicide data, drug dealing, and kidnapping. Specifically, the methodology analyzes 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 over time; however, for long-term institutional infrastructure planning, a year-long perspective of transit migration dynamics was considered. In the R4 Geographic and Climatic Risk section, data was collected and preprocessed for 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[39], utilizing their seasonal average extreme temperatures repository[39]. The Maximum Temperature Index (ITME) is calculated as $\text{ITME} = \frac{\text{TMAX}-\text{media\_max}}{\text{desv\_max}}$, and the Minimum Temperature Index (ITmE) is calculated as $\text{ITmE} = \frac{\text{TMIN}-\text{media\_min}}{\text{desv\_min}}$. 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.

The framework also combines this metric with a geographic infrastructural risk measuring approach, using INEGI's geostatistical framework to differentiate rural and urban AGEBs[39]. Urban areas have higher population density and infrastructure, while rural areas are more dispersed and agriculturally focused. A rural-urban ratio is calculated at the municipal level, with the argument that a more urbanized municipality is more accessible in terms of needs and services for traveling communities. Additionally, due to its denser demographic, it is considered 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.

Figure 4: 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

To achieve the structural composition of the data needed for the analysis, the scope of the network was first defined as a platform that will host the migratory transit in the study. In this sense, as mentioned in the literature review, it is important to maintain an institutional interpretation of the network. Therefore, the decision to define the nodes was limited to only cities with documented infrastructure for managing migration by the Mexican authorities in the given year[37].

To maintain consistency for a reproducible and verifiable exercise, municipalities referred to as "transit cities" that appear in the IMT bulletin compiled by the INM regarding encounters with migrants in irregular situations were used, resulting in 389 nodes for 2023. These nodes were integrated into a grid map exercise to ensure spatial consistency and to 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 determined to work best for this case was 0.7x0.7 cardinal degrees (approximately 71.86 km x 77.92 km). These groupings resulted in 203 arcs or connections between points of interest for metric analysis.

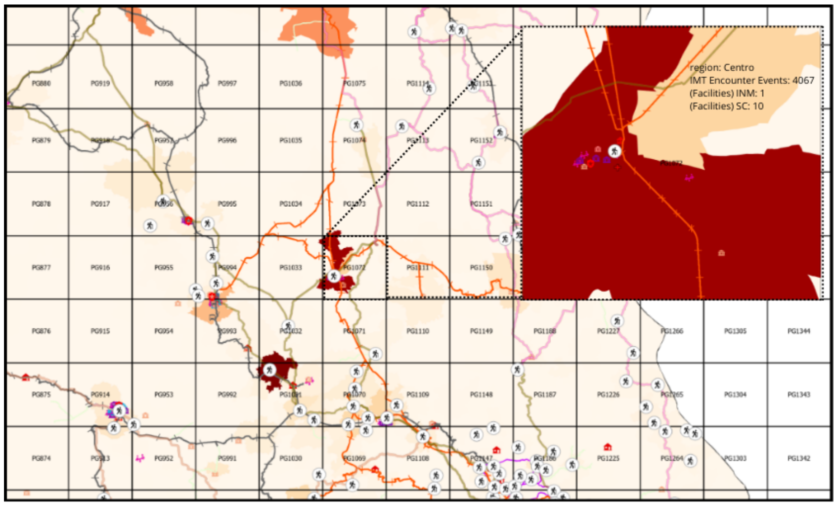

Figure 5: Visual representation of the ensembling process, Cell Id: PG-1031 in figure

For the analysis, the arcs are a crucial feature as they not only represent direction and distance, which were included using the Google API's direction matrix[46]. Additionally, the arcs 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 a total of 1,507 municipalities, whose data are integrated into the analysis.

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.

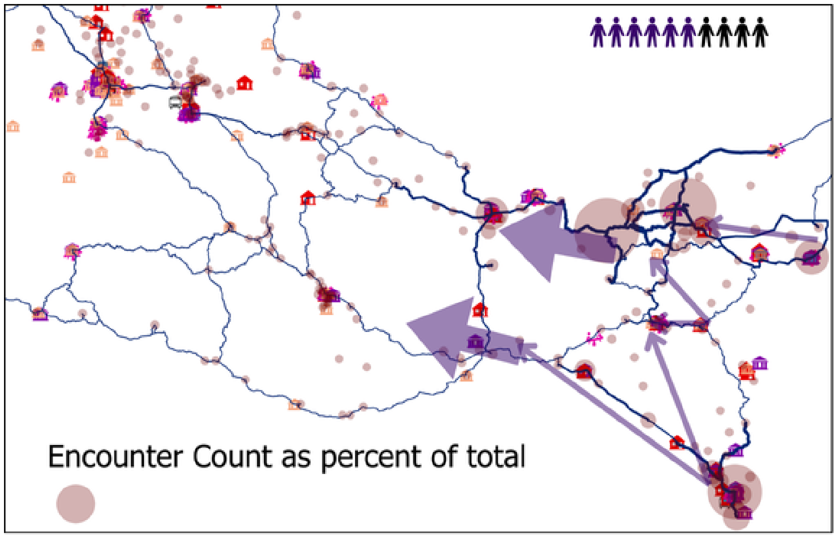

Figure 6: Arcs (edged by cities that recorded IMT events) follow a logical path and direction to prevent improbable route combinations

3.3. Analysis

The encounter events are our main indicator of demand for 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, the events data are adjusted to handle outliers and skewed distributions. This adjustment accounts for the need to address the -Distance Bias for the Southern Region-, which considers the short dimensional width and the proximity to the southern border of initial regions as factors increasing the proportion of encounters. As distance advances, the territory becomes 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 under these circumstances.

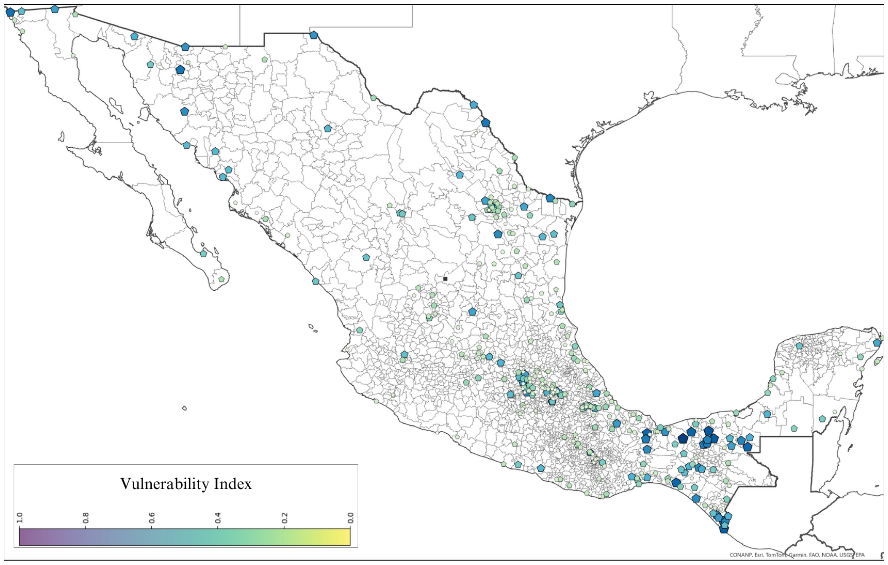

Figure 7: Vulnerability 1: Ratio of ITM Encounter Events per INM Station

Complementarily, it is understood that there is considerable variance between the number of Mexican Institute of Migration (INM) stations and the locations where the INM reports processing and channeling 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 in these locations to attend to and register these events. Given this ambiguity, each location is assumed to be the base facility (1), resulting in:

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

Where:

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

Additionally, a min-max normalization is performed 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.

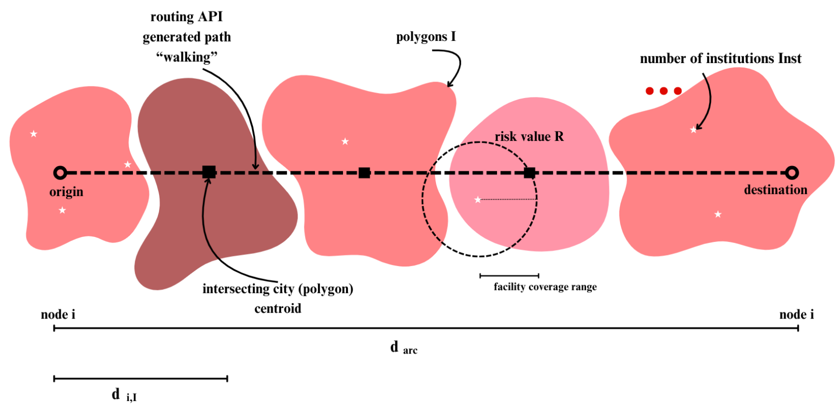

Figure 8: Risk and Distance Mitigation Capacity Index: Construction Framework

3.3.2. Vulnerability 2: Risk Mitigation Capacity

Although similar, the construction of the **Vulnerability 2** metric is somewhat more complex. In this metric, risk values at the municipal level are integrated along with direction and distance. As shown in Figure 8, a visual representation is created to illustrate how measurement objects interact to achieve this integration. The resulting Vulnerability 2 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: the exposure of transit points of interest (POIs) to high-risk zones is measured by taking into account the distance traveled within these zones while moving between two transit POIs. Additionally, the number of institutions within a 30 km radius of each POI is evaluated, which can ideally be a source of support in cases of vulnerability. This scheme, as represented in Figure 8, is intended 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.

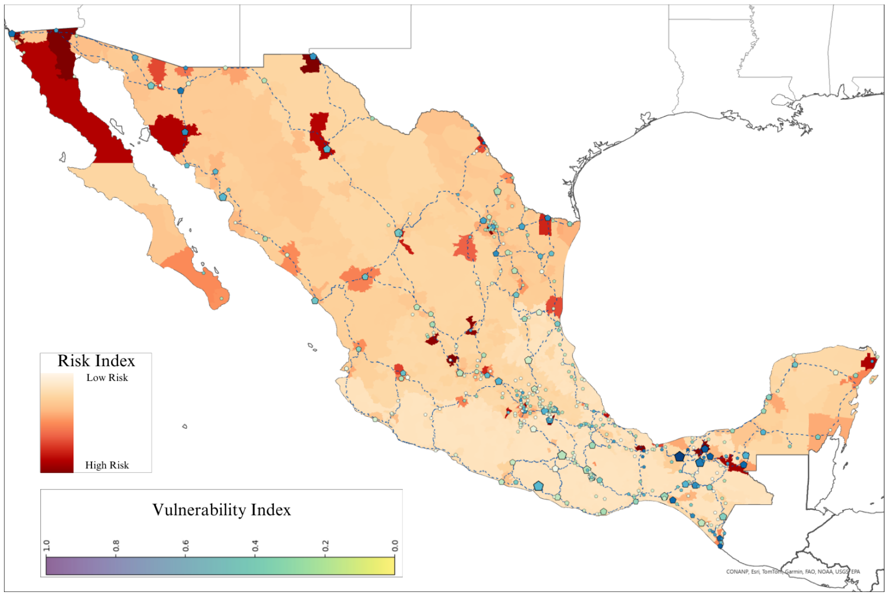

Figure 9: Vulnerability 2: Institutional Coverage Over Total Risk

- $d_{p,i}$: 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.

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: Existing Conditions

In this section, the status quo is reviewed using the metrics obtained during the framework development, which is one of the project's objectives 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 allows for a comparison.

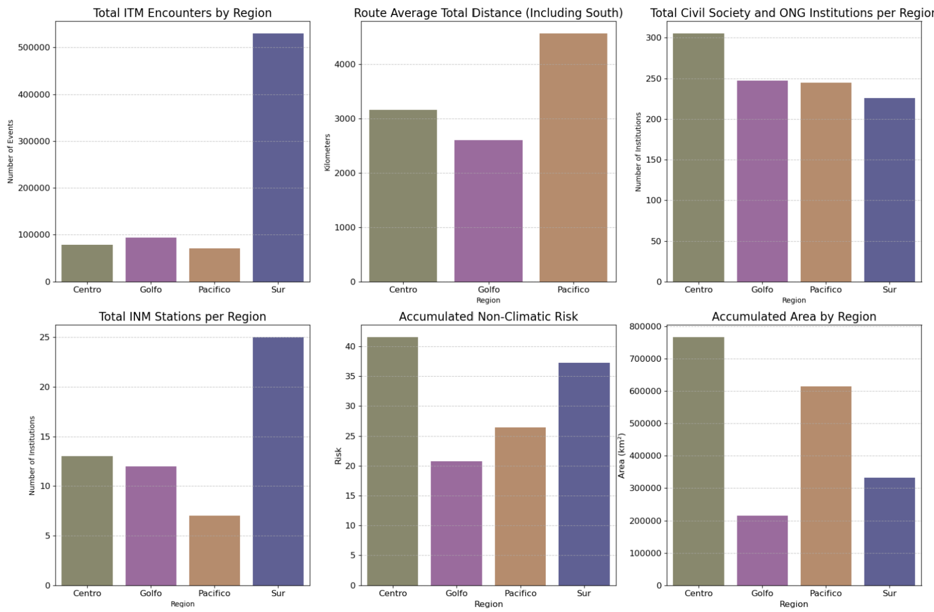

Figure 10: Transit Figures: Comparison between regions

To review the methodology, it is pertinent to evaluate its capacity to answer questions of interest related to the corridor's vulnerability, which proposes 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 was learned from Ciudad Juárez in 2023, where over 40 migrants died due to overcrowding of the detention facility?[28], 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, such as the one that burned in Ciudad Juárez, within at least a 30 km walking distance. Figure 6 shows relatively higher vulnerability in the 'Sur' region, as expected—due to 'The Distance Bias for the Southern Region' and the corridor's bottleneck effect—but the trend continues to the west side of the corridor in the 'Pacífico' region, followed by the 'Centro' region, notably in North Pacific and North Center, where Ciudad Juárez is located. Before its closure in June, Juárez, Chihuahua, ranked 29th out of 359 municipalities in terms of overcrowding vulnerability, according to the methodology.

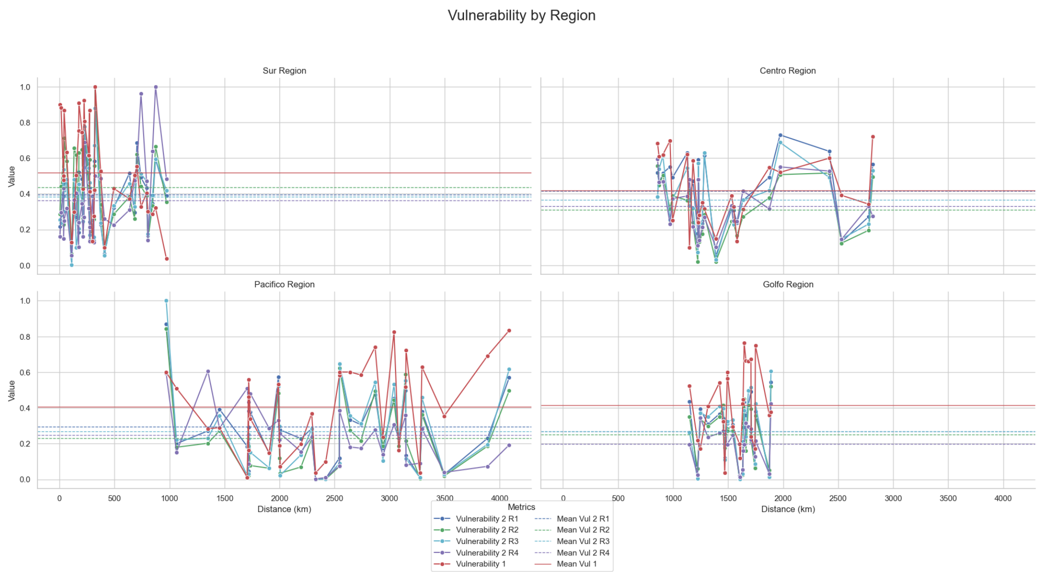

Figure 11: Results: Vulnerability Distribution Scores per Distance traveled (South to North)in Status Quo

From the migrants' perspective, it would be useful to know, Which route has the overall risk to transit by (exposure risk)? For this, while Figure 11, the 'non-climate risk' graph, or even Figure 6, might offer a broader perspective, the Vulnerability 2 metric allows for a more detailed differentiation of the risks migrants may encounter on their journeys. This can be beneficial for migrants, but with marked limitations, such as the relative need to choose which danger to face, which may seem illogical given that the discussion revolves around risks rather than facts. For instance, while risk is generally stationary and unlikely to change drastically over time, it remains a constant concern for migrants while in transit. According to Lee's theory (1964), "migrants typically follow established paths, and changes to new paths are unlikely" [47]. This holds true even for higher-risk encounters. As previously discussed, most migration transit in Mexico is commonly believed to occur along railroads, particularly in the 'Center' region.

For migrants' decision-making, choosing where more accompaniment might be more suitable can also be reviewed in Figure 11, 'SC Institutions per Region.' However, it seems pertinent to consider additional reasoning. For example, Sanchez, Rubio Campos, and Sumano Rodríguez (2021) suggested that the relative security of traveling in large, organized groups may be a better decision-making alternative for migrants concerned about their safety [7], despite being relatively recent and yet to be quantitatively proven.

From the perspective of civil society organizations, this metric may be more useful for planning. Answering questions like Which route carries the highest risk based on demand (relative risk)? and Where should support missions for migrants be established? can provide valuable insights for decision-making. While this is an observation, it challenges the notion that irregular migration is concentrated in specific areas. Instead, it emphasizes the importance of monitoring the phenomenon across all regions, not just the transit cities analyzed in this study. Therefore, in alignment with Vulnerability 2 in this work, assessing relative risk—the number of encounters per transit city in relation to risk exposure—may provide 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 slightly higher, but comparable, in the Pacific region compared to the Gulf region, yet considerably lower than in the Center region. However, the longer transit distances in the Pacific region increase the cost and exposure time compared to the Center and Gulf regions, where distances are shorter and relative institutional coverage is higher. It can be argued that in the Pacific region, there is a disproportionality in coverage relative to the length of the route, as evidenced by the total distance traveled between peaks of Vulnerability 2.

3.4. Uncapacitated Facility Location Problem (UFLP)

One option to address the current state of the corridor 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, based on a status quo set of facility locations.

For this analysis, a similar approach to Perez Pereda (2023) [33] was adopted. While the UFLP framework provides a solid foundation, the specific requirements of this study introduce elements that may necessitate modifications to the basic UFLP model.

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

To run experiments, the data frames are set to represent the objects as follows: 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 30 km 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.

The scenarios will be reviewed based on the size of F_a and F_b, meaning the number of facilities available for each case. Before proceeding, some considerations regarding the basics of the UFLP must be kept in mind.

The original mathematical formulation of UFLP[36] 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:

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

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

In the case study and methodology, the following variations are considered:

- In the context of limited facility availability, each transit city has a different level of demand, suggesting that not all facilities should serve all cities equally. Even though this is a departure from the traditional UFLP, the focus remains on maximizing coverage without concern for how much demand each facility can serve.

- There are no restrictions on the eligibility of facility locations within the cities, as this exercise is conducted on a national scale.

- For this exercise, it is assumed that the facilities operate 24/7, a completely hypothetical scenario.

- Costs, such as accessibility or walking distance, are not considered in this formulation, as the goal is to improve coverage rather than reduce costs.

- The cost of building facilities is also not factored into this formulation.

The approach proceeds by utilizing a greedy algorithm in Python. The greedy algorithm prioritizes the assignment of facilities to transit cities with the highest demand first, ensuring that each facility is within a 30 km range of the assigned cities. This method aims to maximize coverage and minimize the distance over demand. The algorithm iterates through the transit cities, assigning available facilities to those with the highest unmet demand, and then re-evaluates the remaining demand and available facilities. This iterative process continues until all facilities are optimally assigned.

3.5. Government Institutional Capacity: Current vs Optimal

For the case study, solving the UFLP prioritizes assigning facilities to transit cities with the highest demand, ensuring that each facility is within a 30 km range of the cities it serves. This approach aims to maximize coverage and minimize the distance over demand. The method iterates through the transit cities, assigning available facilities to those with the highest unmet demand, and then re-evaluates the remaining demand and available facilities. As an adaptation, the algorithm also seeks to cover as much collateral demand (D_i) as possible during each facility assignment, effectively capturing the essence of a greedy algorithm. This process continues until all facilities are optimally assigned, while tracking which cities are covered by which facilities and selecting the next optimal location.

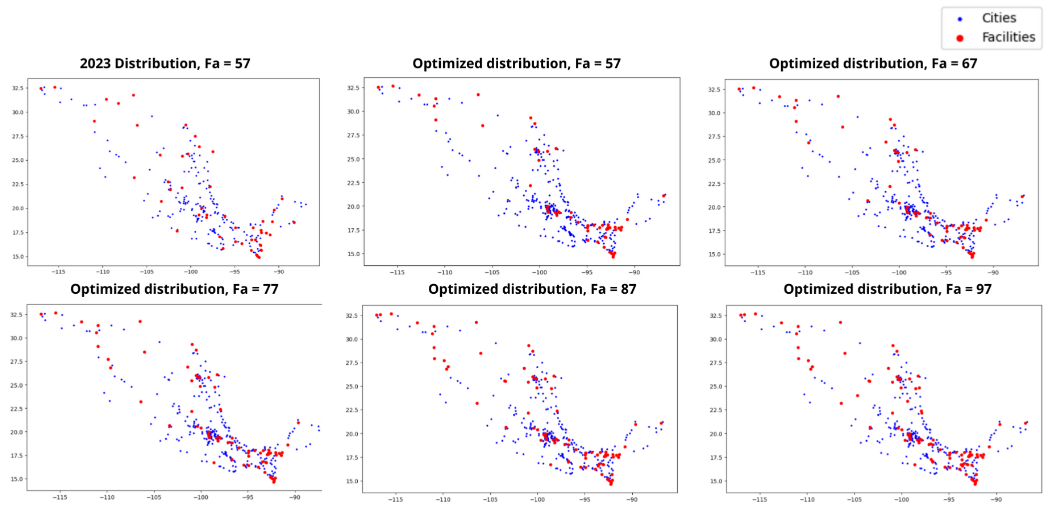

Figure 12: Optimal Institutional Distribution of INM Detention Centers using different facility availability counts

In this problem, each transit city has a varying demand (D_i). Facilities (F_a) are assigned to the locations with the highest demand, max(D_i), while also aiming to cover nearby locations within range to maximize demand coverage. For comparative purposes, the UFLP was used to optimize the distribution of the current number of INM Detention Centers (F_a). The number of available facilities was then gradually increased across different scenarios, and the results were tracked for comparison.

By increasing the total number of facilities available for assignment in increments of ten in each scenario, starting from the original fifty-seven, larger vulnerable areas that emerged with each subsequent scenario were identified. The first noticeable aspect in Figure 12 is the variability of results across different regions, with the most significant changes observed in the South and Center—particularly in the early stages of the increasing scenarios. In contrast, the Pacific region appears more consistent with the Status Quo result, even as the number of available facilities increases.

However, the most immediate need for placing facilities in the south and center regions, as suggested by Figure 12 (Optimized distribution, F_a = 57), does not imply that the other regions are optimally satisfied. Rather, it highlights the existence of other important factors that warrant policy review and future planning. First, authoritarian detention activities, as shown in Figure 10, are heavily concentrated in the south. Although, as shown in

Table 1: **Top Facility Need per City, Based on UFLP Solving with 57 Facilities**

City	Original INM in 30km	INM in 30km (after optimization)	Difference
Jalapa, Tabasco	0	4	4
Ecatepec, Estado de Mexico	0	3	3
Tacotalpa, Tabasco	0	3	3
Teapa, Tabasco	0	3	3

Note: This table illustrates the cities that the UFLP algorithm identified as most in need of facilities, and how the availability of facilities changes after optimization.

Table 2: **Top Facility Decreases, Considering UFLP Rearrangement with 57 Facilities**

City	Original INM in 30km	INM in 30km (after optimization)	Difference
Frontera Comalapa, Chiapas	2	0	-2
Bacalar, Quintana Roo	2	0	-2
Comitan de Dominguez, Chiapas	2	0	-2
La Trinitaria, Chiapas	2	0	-2

Note: These are the top four cities that would have their facilities relocated to a city with greater need based on the UFLP algorithm.

Figure 11, these detentions are not evenly correlated with the infrastructural capacity, as the south still shows the highest peaks of Vulnerability 1. This can be attributed to previously discussed phenomena, particularly the harsh and strategic deployment of migration authorities.

These deployments, referring to illegal and unfounded checkpoints as well as harsh persecutions—documented in various reports—are further supported by the data in Figure 13, which explicitly confirms that authorities exploit the territorial characteristics of the regions. In the south, this is evident through the bottleneck effect due to its narrow geography, as illustrated in Figure 10 (Total Area). In the Gulf, a similar effect is demonstrated by the extensive coverage relative to the short regional distance, as shown in Figure 10 (Average Total Distance). In the Center, raids are commonly conducted in strategically important transportation locations, such as bus stations and train hubs, which are characteristic of Estado de México, where vulnerability also peaks, as shown in Figure 11. The train line "La Bestia," which starts in the Central Region, is a notable example of this situation. This suggests that aggressive authoritarian behavior directly penalizes transit migration by decreasing transit cost/effectiveness. Rather than spreading enforcement evenly across zones, efforts are concentrated in strategic captive locations, which may have the collateral effect of pushing migrants to riskier transportation means.

Furthermore, it is evident that current institutional planning, particularly regarding facility distribution in the southern region, is highly inefficient. As shown in Tables 1 and 2, the first optimal facility rearrangements predominantly occur in this region, with facilities being both relocated within and added to the same area. Although unrelated to governmental planning, the lack of civil society and NGO representation in the region, as seen in Figure 10, exacerbates the institutional distribution problem that is compromising migrant safety in the south.

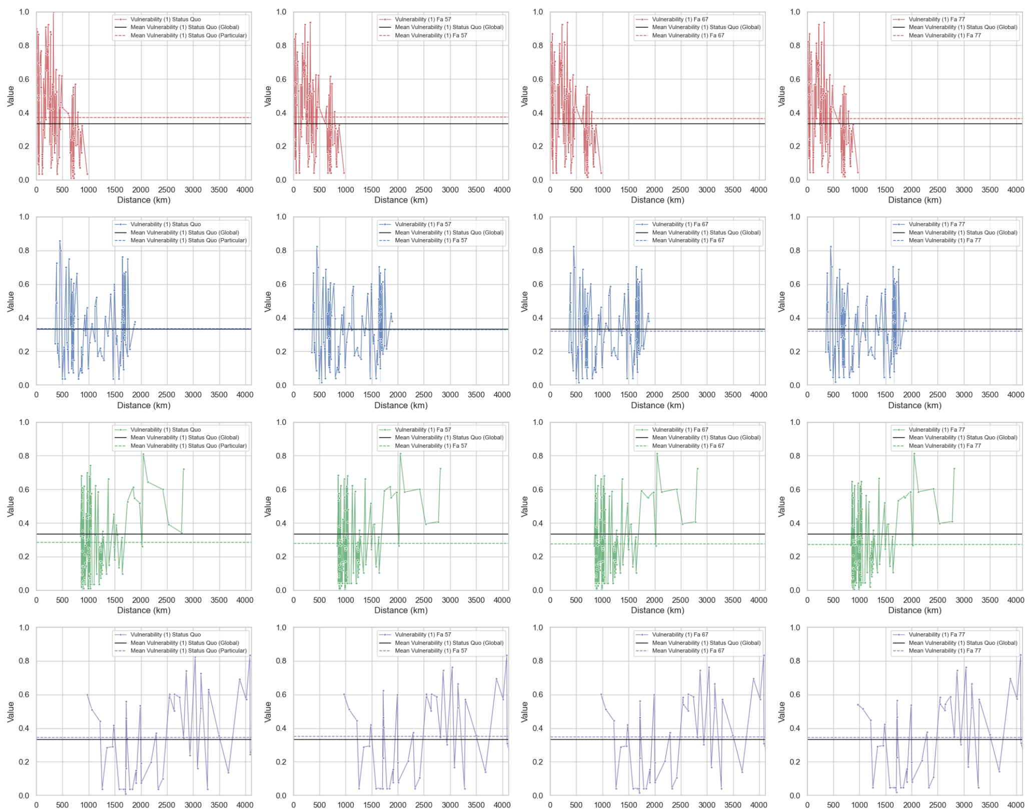

Figure 13: Vulnerability 1: Comparison of Optimal Scenarios versus Status Quo Distribution (Top to Bottom: South, Gulf, Center, Pacific)

Figure 13 also illustrates for all regions there are a significant average amount of vulnerability between nodes. This uneven distribution of vulnerability suggests that within the corridor, there is a permeability of vulnerability, this condition reinforces the idea that route planning could improve safety, and reduce exposure to unfair cost/effectiveness transit trade off that comes with the harsh authoritarian policies.

On another hand, even from the experimental distribution of the same fifty-seven facilities from 2023, there is enough evidence to suggest that improvements to infrastructural planning could be made, even with the same number of facilities as in the Status Quo. The considerable reduction in the count of extreme peaks, as shown in Figure 13, indicates this potential.

This does not imply that existing facilities should change locations due to the costs associated with reorganizing the current structure. Logically, the UFLP, in the scenario with the same 57 facility count, redistributes vulnerability to reduce extreme concentrations in specific regions. Instead, it highlights where new facilities are most needed. Table 3 shows how, from a Status Quo to an Optimal Scenario with the same number of facilities, vulnerability increases in the South and Pacific regions, while it decreases in the Center and Gulf regions.

	Average Vulnerability				**Vulnerability per Kilometer**			
Metric/Region	**South**	**Gulf**	**Center**	**Pacific**	**South**	**Gulf**	**Center**	**Pacific**
Vulnerability (1) Status Quo	0.37267	0.33669	0.28674	0.34471	0.04370	0.01764	0.01111	0.00393
Vulnerability (1) Fa 57	0.37644	0.33002	0.27893	0.35278	0.04414	0.01729	0.01081	0.00402
Change from Status Quo	+0.00376	-0.00666	-0.00781	+0.00807	+0.00044	-0.00035	-0.00030	+0.00009
Vulnerability (1) Fa 67	0.36554	0.32220	0.27779	0.34829	0.04286	0.01688	0.01076	0.00397
Change from Fa 57	-0.01089	-0.00782	-0.00114	-0.00450	-0.00128	-0.00041	-0.00005	-0.00005
Vulnerability (1) Fa 77	0.36732	0.32219	0.27495	0.34671	0.04307	0.01688	0.01065	0.00395
Change from Fa 67	+0.00177	-0.00001	-0.00284	-0.00157	+0.00021	0.00000	-0.00011	-0.00002

Table 3: Vulnerability Results: Comparison of Scenarios

Naturally, having as many facilities as possible would reduce vulnerability evenly. However, Table 3 demonstrates that significant improvements in vulnerability can be achieved by increasing the number of facilities from 57 to 67, coupled with optimal relocation, without redistributing vulnerability from any region to another. This would represent an ideal scenario while relying solely on optimal relocation by adding new facilities to most need cities is realistically the second-best option.

4. Discussion

First, as Casillas (2008) [23] pointed out, the challenges associated with irregular migration flows remain highly relevant today, as there is still no reliable data to quantify how many migrants are transiting through specific corridors. Much of their movement remains invisible, leading studies on migration flows to rely largely on approximations. This reliance complicates the understanding of how these corridors function and hinders effective policy design in anticipation of these movements.

In line with Lee's (1966) [47] theory, which posits that "migration tends to occur largely within well-defined paths," these ideas are connected to graph theory, as discussed by Llanos (2021) [48]. From this perspective, migrants traverse established routes but do so within a system that allows them to choose from diverse directional combinations, forming multiple routes within the network.

By constructing the framework of this paper, it is confirmed that the connection of these ideas provides a robust approach to bridging the gap between approximations and actual mobility flows. However, rather than viewing this network as a simple series of connections between cities similar to Llanos (2021) [48], it is argued that the corridor must be analyzed as a complex system—or more specifically, a network system. The level of detail in this analysis is contingent upon the researcher's area of interest, which shapes the system's complexity.

For this study, which focuses on governmental institutional capacity, the network granularity was represented by major terrestrial roads, highways, and railroads. In other contexts, the network might include rivers or trails, particularly in regions like Chiapas or Tabasco, where walking is a significant mode of travel. The key takeaway is that the system's scope shapes the dimensions of the network. In this case, the network was defined by detentions carried out by governmental institutions within an institutionally scoped network system. Other network compositions may coexist, but each will vary depending on the specific focus of the research.

Taking the previously described approach brought significant benefits to the current state of knowledge. For instance, it allowed the addressing of one of the main challenges associated with vulnerable communities, which is the lack of representative data. As mentioned earlier, studies in this field often rely on observations and interpretations of experiences. However, through the construction of this framework, many previously undocumented events were quantitatively demonstrated. For example, the results revealed that aggressive authoritarian policies, including harsh enforcement measures, disproportionately affect certain regions. This evidence could be highly beneficial in supporting policy changes aimed at addressing these issues.

In line with this, the analysis also indicated that the current distribution of institutional facilities, particularly in the southern region, is inefficient. This inefficiency is underscored by the need for optimal facility relocation within the same region, as highlighted by the vulnerability assessments. These findings suggest that a more strategic allocation of resources is necessary, with a focus on reducing institutional gaps that heighten risks for migrants.

Finally, the findings call for a comprehensive review of institutional policies related to irregular migration. The observed gaps in infrastructure, particularly in high-risk areas, indicate that both government and civil society organizations must collaborate to create more resilient systems. Policies should prioritize not only immediate infrastructural improvements but also long-term strategies to enhance institutional capacity and safeguard migrants' human rights.

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