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Criticality assessment and cascading effects: impacts of COVID-19 disruptions in public transport on marginalized groups in Dortmund, Germany, São Paulo, Brazil, and Cape Town, South Africa

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Abstract

The COVID-19 pandemic has underscored the interconnectedness of critical infrastructure systems and their profound impact on marginalized communities. This study investigates the cascading effects of reduced mobility and infrastructure disruptions caused by COVID-19 response strategies on marginalized households across three diverse urban settings: Dortmund, São Paulo, and Cape Town. Employing a criticality assessment, we examine disruptions in healthcare, food and nutrition, social work, education, and childcare sectors, highlighting interdependencies and their implications for marginalized communities. Our findings reveal that disruptions in one sector, such as public transportation, can trigger adverse consequences across interconnected systems, amplifying vulnerabilities and exacerbating social inequalities. Furthermore, limited digital accessibility compounds these challenges, particularly for marginalized groups who may lack access to necessary technologies or digital literacy skills. Addressing these disparities in digital access is crucial for ensuring equitable access to essential services and



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support networks, especially in times of crisis. The study underscores the importance of mobility and accessibility in addressing systemic vulnerabilities and advocates for comprehensive resilience strategies that prioritize the needs of marginalized communities. Recommendations for policymakers, urban planners, and community stakeholders are provided to enhance infrastructure resilience and mitigate the indirect effects of disruptions on marginalized groups. The study contributes to a deeper understanding of cascading effects within critical infrastructure networks and informs future research and policy initiatives aimed at building resilient communities in an interconnected world.

Keywords: Critical infrastructure, criticality assessment, cascading effects, marginalized communities, COVID-19 disruptions, accessibility, social inequalities

INTRODUCTION

In an era marked by unprecedented global crises, the intricate interplay between spatial mobility, societal structures, and the ramifications of disruptions has come to the forefront. The COVID-19 pandemic, caused by the novel coronavirus SARS-CoV-2, emerged as a global health crisis in late 2019, swiftly transcending national borders and affecting people from all walks of life^[1]. As a recent and stark example of such a crisis, the pandemic brought into sharp focus the vulnerabilities of marginalized groups^[2-4]. While each crisis is distinct in its origins, this study uses the pandemic as an example to shed light on the effects of restricted mobility such as a disruption of public transport. Contact restrictions and curfews shaped and changed accessibility and the way we interact with each other. In many countries, public transport systems were influenced, which has particularly affected those relying on them and unable to switch to private vehicles or online alternatives. The impact varies depending on the restrictions imposed by the government and the existing public transport network. Disrupted mobility can have crucial effects on other areas of life, as spatial mobility is essential for reaching critical infrastructures and services^[5].

Thus, this research delves into the multifaceted impacts of disruptions caused by COVID-19 response strategies on marginalized groups in Dortmund, Germany, São Paulo, Brazil, and Cape Town, South Africa. The overarching research question probes into the indirect effects of critical infrastructure and service disruptions on the livelihoods of marginalized households, analyzing the three periods before, during, and after the pandemic. This research aims to navigate this complex terrain by focusing on critical sectors essential for societal well-being, including healthcare, food and nutrition, social work, education, and childcare, employing a criticality assessment approach. Additionally, the study explores the potential of virtual mobility and online services as substitutes for in-person services during disruptions, acknowledging the evolving dynamics of a digitally connected world.

Through the analysis of cascading chains, the study anticipates the ripple effects of disruptions in each field and interconnections between them. These cascading chains were validated through expert workshops in the respective case study areas, which included various actors and experts from academia, city administration, social infrastructures, and non-governmental organizations (NGOs). By using the pandemic as a concrete example, involved experts were able to remember a specific event and did not have to make assumptions about possible effects. At the same time, the effects of restricted public transport can also be triggered by a range of events, encompassing, for example, technical issues, adverse weather conditions, labor strikes, or financial challenges. This way, the paper contributes to the existing body of knowledge by exploring the indirect effects of COVID-19-induced disruptions in critical infrastructure on marginalized groups. By employing a cascading effects model, the study provides a nuanced understanding of how interconnected systems amplify vulnerabilities, offering valuable guidance for policymakers and urban planners to enhance resilience and equity in critical infrastructure services.

Although the pandemic was a global phenomenon, governments reacted differently in terms of restrictions. In Germany, the first COVID-19 case was reported on January 27, 2020. In the following weeks, the number of infections in Germany and the rest of the world continued to rise. In March 2020, the then-chancellor Angela Merkel appealed to the population to avoid social contact and stay home as far as possible^[6]. During the first lockdown, schools and non-essential businesses had to close^[7,8]. The government imposed restrictions on social gatherings and travel, encouraged remote work, and promoted hygiene practices such as handwashing and mask-wearing^[7]. From June to mid-October 2020, the federal government decided to ease the measures. These included returning to schools, opening certain types of businesses and services, and ending strict social distancing^[9,10]. Incidence-based measures were introduced depending on the number of cases per 100,000 inhabitants in the respective municipalities^[11]. With a rising number of infections again in autumn and winter, a renewed lockdown was imposed from mid-October 2020 to March 2021^[12], and in the spring and summer of 2021, measures were eased again based on incidence and individual vaccination status^[13]. In April 2023, over three years after the first lockdown, Federal Minister of Health Karl Lauterbach announced the end of all federal measures^[14]. Overall, Germany saw fluctuating infection rates with significant stress on the healthcare system, but the mortality rate was relatively lower compared to some other European countries, partially due to early and decisive action and widespread testing and vaccination campaigns^[15,16].

As a federal state, the lockdown in Brazil was not a centralized national measure, but rather a series of coordinated actions between the different levels of government: federal, state and municipal. In the beginning of the COVID-19 pandemic, the federal government issued general guidelines, such as international travel restrictions and social isolation measures, through the Ministry of Health^[17]. However, the implementation of quarantine measures was mainly driven by state and municipal governments, which had the autonomy to establish their own policies by considering the local epidemiological situation and health system capacity. The Supreme Court ratified this autonomy in light of the federal government's refusal to adopt more restrictive measures. This resulted in a variety of approaches across the country, with some regions implementing stricter measures and others adopting more flexible strategies. In the specific case of the state of São Paulo, as of June 2020, the *Plano São Paulo* was implemented as an additional strategy for dealing with the pandemic developed by the state government^[18]. This plan established criteria for easing and relaxing social isolation measures, taking into account the epidemiological situation in each region of the state^[19]. As a strategic tool in the management of the COVID-19 crisis in São Paulo, it provided clear and transparent guidelines for decision-making and actions to deal with the pandemic. However, there are reservations about its effectiveness and the implications of using algorithms and data in decision-making during the COVID-19 pandemic^[20]. Brazil faced significant challenges with high infection and mortality rates, particularly in densely populated areas and among marginalized communities^[21]. The fragmented response and disparities in healthcare infrastructure exacerbated these outcomes^[22].

South Africa implemented one of the strictest lockdown measures globally during the initial phase in response to the pandemic. South Africa had five alert levels of lockdown, with level one imposing the least stringent and level five the most severe restrictions^[23]. These alert levels were declared nationally, provincially, or in a district. As the pandemic progressed, measures were gradually adjusted following the number of infections, the health system capacity in a specified area to respond to the disease burden and other factors that would influence the level of infection, hospitalization, and mortality. The government imposed a nationwide lockdown that included restrictions on movement, closure of schools and non-essential businesses, and a ban on alcohol and tobacco sales^[24]. Additionally, the government implemented widespread contact tracing efforts to identify and isolate infected individuals^[25]. Schools, offices, and non-essential businesses were closed, and mobility within the city nearly came to a halt with strict curfew

hours^[26]. The national state of disaster was lifted in April 2022. South Africa's response was marked by high compliance initially, but high-density living conditions in informal settlements make it difficult for people to self-isolate^[27]. Despite efforts to manage the pandemic through strict measures and extensive contact tracing, the country experienced high levels of infection and mortality, particularly affecting marginalized populations^[28].

These measures, while aimed at protecting public health, have also led to social, economic, and socioeconomic hardships, necessitating responses that go beyond immediate crisis management to consider long-term resilience building. The pandemic has laid bare vulnerabilities and inequalities ingrained within societies, amplifying existing disparities and leaving marginalized people susceptible to the multifaceted consequences of the crisis.

Marginalization refers to the process through which certain groups are pushed to the edge of society, limiting their access to resources, opportunities, and rights available to more dominant groups^[29]. This exclusion often results from systemic inequalities and discrimination based on various social identities. The disparities extend across various dimensions of marginalization, which include aspects of race, class, age, gender, sexual identity, disability, and the intersectionality of these factors^[30,31]. Numerous studies globally and in specific countries have highlighted the stark disparities in the impact of COVID-19 on different groups^[2,32,33]. Individuals living in poverty or facing socioeconomic disadvantage faced heightened risks, racial and ethnic minority groups experienced disproportionate impacts, and those from lower socioeconomic backgrounds encountered challenges in accessing healthcare services^[3,4,34].

Beyond health impacts, economic repercussions have been far-reaching, disproportionately affecting vulnerable populations. Job losses, income instability, food insecurity, and, in extreme cases, the loss of homes have become prevalent issues, particularly for already marginalized communities^[1]. The pandemic has also deepened social divides, exacerbating isolation, mental health challenges, and limited access to education^[35,36].

Urban planners now face the task of adapting swiftly to address immediate challenges while considering the long-term impacts on urban form, mobility, and social cohesion. This research aligns with the imperative to plan urban spaces that promote public health, equitable access to essential services, and overall well-being, recognizing that the resilience of critical infrastructures is intertwined with the societal mobility patterns that underscore the lived experiences of marginalized populations. It seeks to illuminate the multifaceted challenges marginalized communities face, delving into the economic, social, and spatial dimensions of their experiences during the pandemic. Examining the specific ways in which marginalized groups have been disproportionately affected, this research aims to uncover underlying structural inequities and develop targeted strategies to mitigate adverse effects and foster more inclusive and resilient systems for societal well-being.

THE ROLE OF INDIRECT EFFECTS OF THE PANDEMIC

Existing studies have explored the direct effects of the pandemic on marginalized groups, such as increased health disparities, economic hardship, and access to essential services focusing on the immediate health impacts and economic vulnerabilities exacerbated by the pandemic^[37,38]. However, these studies predominantly concentrate on the immediate consequences without examining the broader, indirect effects. Notably, there is a gap in literature concerning the exploration of indirect effects resulting from disruptions in critical infrastructure and services, as demonstrated by Barouki *et al.*^[39], indicating emerging research needs. The cascade of impacts triggered by such disruptions has yet to be comprehensively examined,

posing an interesting avenue for a more nuanced understanding of the challenges faced by marginalized communities during the pandemic.

The European Union defines critical infrastructure assets or systems essential for maintaining vital social functions, health, safety, security, and economic or social well-being^[40]. They play a pivotal role in amplifying risks within an entire system, whether a region, a country, or even on a global scale, despite physical damages often being localized to specific areas. While the physical damage may be restricted to a limited area, the economic and societal effects can reverberate across regions and countries, highlighting the interconnectedness of critical infrastructures.

Criticality, defined as the relative measure of the importance of an infrastructure in terms of the consequences of its disruption or loss of function, underscores the significance of safeguarding essential services for societal well-being^[41]. Cross-cutting criteria are employed to determine criticality, including the number of users relying on the essential service, the interdependencies between sectors, the potential impact on economic and societal activities, and the geographic reach of potential incidents^[40]. These criteria provide a comprehensive framework for assessing the criticality of infrastructural assets and guiding resilience efforts. Assessing systemic criticality requires a network-wide, trans-sectoral perspective^[42-44]. The systemic criticality of critical infrastructures introduces complexities not adequately addressed by traditional place-based risk concepts, as they tend to disregard functional interdependencies between sectors and do not consider cascading effects that may take place outside directly exposed areas^[45,46].

Systemic criticality, as an emerging concept in a globally interconnected world, gauges the relative importance of an infrastructure in relation to the consequences of a disruption or failure for the security of the supply of important goods and services to society. It defines infrastructure as highly important based on structural, functional, and technical considerations within an overall system^[45]. Understanding systemic criticality becomes paramount in addressing the challenges of risk assessment and management^[47].

Past approaches of a criticality assessment often revolved around describing the impacts of a singular event, such as an extreme weather event, including a flood, on the disruption of a specific critical infrastructure and the subsequent interconnected effects. This starts a domino effect characterized by a chain reaction of similar events triggered by a single occurrence, highlighting the interconnected nature of critical infrastructures^[43]. Limited to a single infrastructure sector, such as the spread of a disturbance within the power network, the domino effect underscores the vulnerability of interconnected systems to localized disruptions.

In contrast, cascading effects encompass a broader scope, extending beyond individual sectors to encompass disruptions in essential services. Even a localized disturbance in one sector can lead to far-reaching and long-term negative impacts on service delivery across multiple sectors. For example, disrupted transport links can precipitate cascading effects in sectors vital for societal functioning, including food and nutrition, education, healthcare, and social services^[48]. These cascading effects underscore the systemic vulnerabilities inherent in critical infrastructure networks and emphasize the importance of resilience planning to mitigate their impact.

Moreover, studies often look at the interconnectivities between the respective critical infrastructures^[46,49] but do not adequately address the nuanced interplay between the effects and the vulnerabilities of marginalized groups. The COVID-19 pandemic also did not solely affect a singular place-based facility such as a health care facility or school, but rather influenced every aspect of life. Its effects transcended the traditional

boundaries of critical infrastructure disruptions, presenting a unique challenge in understanding and assessing the systemic repercussions of a non-physical, global event, necessitating a systemic risk perspective.

Therefore, it is essential to investigate the specific effects of diverse COVID-19 response strategies from a systemic criticality perspective. This approach enables the estimation of case-specific indirect effects on livelihood and accessibility, considering the complex interdependencies among critical infrastructures.

CONCEPTUAL FRAMEWORK

The study employs a cascading effects model to investigate the multifaceted impacts of disruptions in critical infrastructures caused by COVID-19 response strategies on marginalized households. This model posits that disruptions in one sector can trigger adverse consequences across interconnected systems, amplifying vulnerabilities, reducing livelihoods, and exacerbating social inequalities. The starting point of these disruptions lies in restricted mobility resulting from COVID-19 response measures. Whether due to decreased availability of public transport, lockdown strategies mandating people to stay at home, or voluntary decisions to avoid public spaces for fear of infection, the restriction of mobility initiated a chain reaction of disruptions in critical infrastructure sectors. By examining the cascading effects of disruptions in healthcare, food and nutrition, social work, education, and childcare sectors, the study seeks to elucidate the intricate interdependencies within critical infrastructure networks and their implications for marginalized communities. While disruptions in critical infrastructure sectors touch all individuals, marginalized groups are disproportionately affected due to the lack of alternatives and safety nets available to them^[50,51]. The sectors are chosen due to their fundamental role in the daily lives and well-being of marginalized households and, unlike critical infrastructures such as electricity or water, they require physical accessibility by users. Marginalized communities often rely heavily on public services and have limited access to private resources, making them more vulnerable to disruptions. For example, while a transportation disruption might be an inconvenience for more affluent individuals who can afford alternative means of travel, it can severely hinder marginalized individuals' access to these essential services^[52]. This exacerbates existing inequalities and underscores the necessity of focusing on these sectors to understand and mitigate the broader societal impacts on these vulnerable populations.

Selected sectors

Access to healthcare: The healthcare sector plays a fundamental role in ensuring the physical well-being of individuals and communities. Disruptions in healthcare services can have profound implications for marginalized households, including limited access to medical treatment, preventive care, and essential medications. Vulnerable populations often face barriers to healthcare access due to socioeconomic disparities, exacerbating existing health inequalities^[32,53].

Access to and supply of food and nutrition: Access to nutritious food is essential for maintaining overall health and well-being. Food insecurity, inadequate nutrition, and limited access to fresh produce contribute to health disparities and socioeconomic inequalities among marginalized populations^[54]. Furthermore, disruptions in institutions that distribute food, such as schools, daycare facilities, or shelters, can significantly affect marginalized households reliant on these services for daily meals.

Access to and availability of social work: Social work services play a vital role in providing support and assistance to marginalized individuals and families. Disruptions in social work infrastructure, including advice centers, charities, and community resources, can exacerbate social and economic disparities, further marginalizing vulnerable populations^[33]. Additionally, it can mean the loss of shelter for those in need of

rescue from discrimination, harassment, or violence. Limited access to social services hinders individuals' ability to address their needs and navigate challenging circumstances, perpetuating cycles of poverty and marginalization^[36]. Non-marginalized individuals, who might have more resources and alternative support networks, were less affected by these disruptions.

Access to education: Education is a cornerstone of social mobility and economic opportunity. Disruptions in the education sector, such as school closures and remote learning challenges, disproportionately affect marginalized students who may lack access to necessary resources and support systems such as digital learning tools, technical devices and a stable internet connection^[55], while non-marginalized individuals, who might have more resources and alternative support networks, were less affected by these disruptions. Learning gaps, academic setbacks, and increased dropout rates further entrench existing inequalities, hindering marginalized individuals' ability to achieve their full potential.

Access to and availability of childcare: Affordable and accessible childcare services are essential for enabling parental workforce participation and promoting child development. Disruptions in childcare infrastructure, including daycare facilities and early childhood education programs, can pose significant challenges for marginalized families, particularly single parents, and low-income households^[55]. Limited access to childcare services impedes parents' ability to maintain employment and secure stable incomes, exacerbating financial instability and social exclusion.

The selection of these sectors is grounded in their critical importance to marginalized households' overall livelihoods. Healthcare, food and nutrition, social work, education, and childcare services are essential components of societal infrastructure, providing foundational support for vulnerable populations. By examining the cascading effects of disruptions in terms of accessibility in these sectors, the study aims to identify key vulnerabilities, challenges, and opportunities for enhancing resilience and mitigating the impact of critical infrastructure failures on marginalized communities.

METHODS

This study employs a qualitative research design to provide a nuanced exploration of the indirect effects of disruptions to infrastructure and services during the COVID-19 outbreak, particularly focusing on marginalized groups. Studies showed how disruptions of infrastructure and services resulting from the COVID-19 outbreak had an impact on marginalized groups in the form of limited access to employment, increased financial burdens, social isolation, reduced opportunities, and disrupted access to essential services^[1,35,36]. Qualitative research is chosen for its capacity to capture the complex and interrelated experiences within the selected critical sectors. Five sectors were selected where service disruption would directly impact marginalized groups: the health sector, nutrition, social work, education, and childcare.

Data collection

Literature research and expert interviews: Initial insights into cascading effects were drawn from an extensive literature review encompassing studies that elucidate the repercussions of disruptions on marginalized groups. To enrich the understanding, qualitative interviews were conducted with key experts who provided valuable insights. Initially, public transport operators were interviewed to determine the extent to which public transport collapsed during the pandemic and which groups of people were particularly affected. The unequal impact of the pandemic was also discussed with public health department employees. Furthermore, social workers from various sectors were consulted to gain insights into the lives of various marginalized people during the pandemic: Homeless individuals, people with disabilities, poor people, those with a migration background, and older adults.

Cascading effects development: The development of the cascading effects framework involved an iterative process that integrated insights from both literature review findings and expert interviews. Initially, the framework was conceptualized based on a synthesis of relevant literature pertaining to critical infrastructure disruptions and their impacts on marginalized communities. Subsequently, insights and perspectives gathered from expert interviews were incorporated into the framework, allowing for a comprehensive understanding of the interconnected challenges faced by marginalized communities. This approach ensured that the cascading effects framework accurately reflected the complex dynamics and interdependencies within critical infrastructure systems. The structure of the cascading effect chains can be seen in [Figure 1](#). The chains start with the possible dependencies of a critical infrastructure sector on public transport and follow the impacts a disruption potentially has on employees and on the users of the respective infrastructure. Furthermore, possible interdependencies with other sectors are indicated.

Validation workshops: To fortify the validity and reliability of the developed cascading effects, validation workshops were conducted in each of the three case study areas: Dortmund, Germany, São Paulo, Brazil, and Cape Town, South Africa (see [Figure 2](#)). The workshop participants constituted experts from diverse sectors, ensuring a multidimensional perspective. For each workshop, around fifty experts, selected based on their recognized expertise and experience in their respective fields, were invited with at least ten invitations per sector to ensure enough participants from different fields. The workshops then constituted of around ten experts with two people per sector. The composition of participants was approximately 40% from practice and administration, 40% from academia, and 20% from local NGOs. This distribution provided a balanced and comprehensive view of systemic dependencies and the deliberate formation of interdisciplinary groups encouraged rich discussions, emphasizing the interconnected nature of disruptions across sectors^[56].

However, it is important to acknowledge the potential for self-selection bias, as participation was voluntary and those who attended were likely those with a keen interest and available time^[57,58]. Recognizing the challenges faced by some participants, particularly those from NGOs and social workers with limited resources and heavy workloads, we supplemented the workshops with individual interviews. This approach ensured that their critical insights were included despite their constrained availability.

Guiding questions in workshop

The experts were presented with the research question of *What are the indirect effects of disruptions of infrastructure and services resulting from COVID-19 outbreak on the livelihoods of marginalized households before, during and after the pandemic?* looking through the lens of mobility and public transport. While COVID-19 was used as an example, it was made clear that disruption can happen again during future crises, e.g., extreme weather events or strikes. Thus, the experts drew from their lived experience during the pandemic but could also add potential effects that they saw might happen in the future.

While the experts discussed their own areas of expertise, it was also important to look at interdependencies between the sectors. Working in small interdisciplinary groups to develop an understanding of systemic dependencies, talking to each other, and passing on existing knowledge, they were also provided with guiding questions.

1. Plausibility and interconnections: The validation process scrutinized the presented cascade chains and interconnections with other sectors to ensure their plausibility and accuracy.

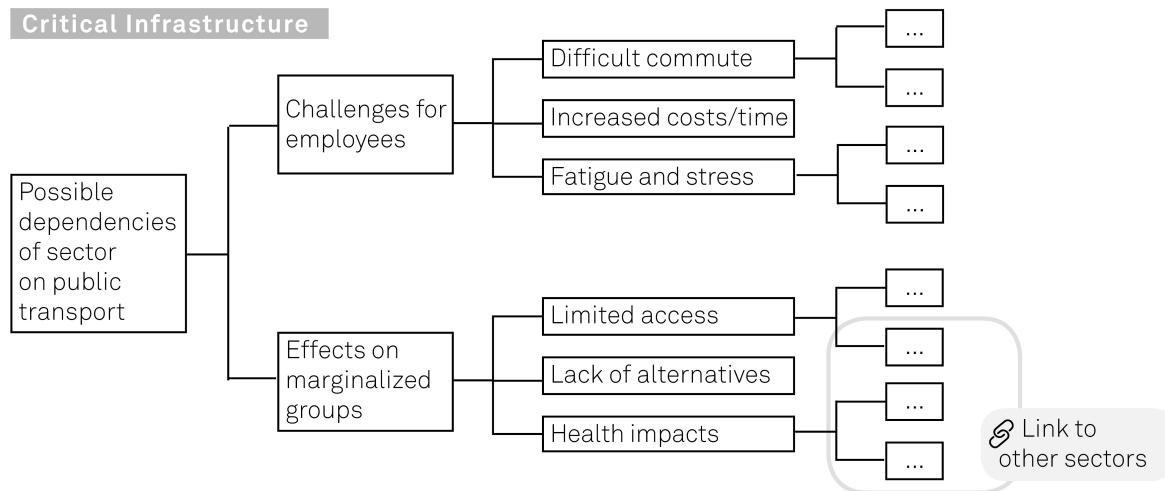


Figure 1. Exemplary structure of the cascade effect chains.

2. Unconsidered effects: Experts were prompted to consider and identify any additional effects not yet contemplated in the initial drafts, ensuring a comprehensive evaluation.

3. Temporal dimension: The workshops delved into the temporal dimension of cascading effects, exploring how suddenly these effects take place and their persistency over time.

4. Spatial considerations: Spatial aspects were considered, assessing specific locations of critical failures, affected infrastructures/services, and alternative/redundant sites.

5. Cross-border impact: The workshops also explored the cross-border challenges and opportunities associated with the cascading effects, recognizing the global nature of the disruptions.

Limitations and sampling considerations

While the research team diligently sought to secure a diverse range of experts, including representation across sectors and divergent perspectives within each sector, the final outcomes are inevitably influenced by participant acceptance and willingness to engage in the workshops. Recognizing potential biases, the set of leading questions and effective moderation was employed. This approach fostered an inclusive environment, ensuring that all voices, including those of quieter participants, were heard and considered.

The iterative nature of the methodology, combining literature research, expert interviews, and validation workshops, enhances the depth and reliability of the findings, contributing to a comprehensive understanding of the impacts of disruptions on marginalized communities.

RESULTS

The results chapter presents a comprehensive analysis of the cascading effects of disruptions in critical infrastructure sectors on marginalized communities. Focusing on Dortmund, São Paulo, and Cape Town, it examines the interplay between healthcare, food and nutrition, social work, education, and childcare systems during the COVID-19 pandemic. This chapter begins with an overview of cascading effects across critical sectors, then delves into specific narratives from each case study area, illustrating the complex

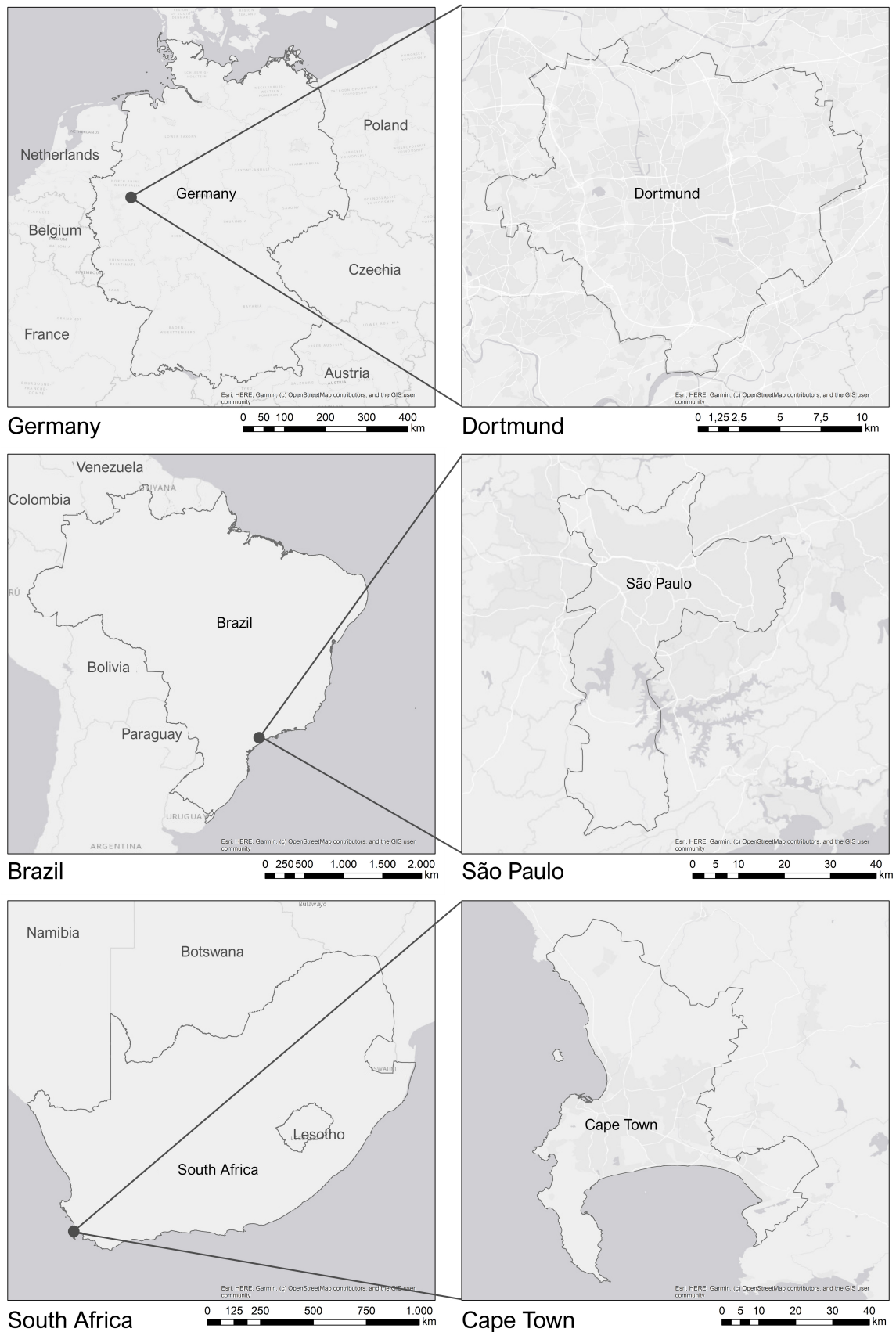


Figure 2. Case study areas (based on Esri, HERE, Garmin, OpenStreetMap contributors, and the GIS user community).

challenges these communities face. The complete and detailed cascade effects are provided as [Supplementary Figures 1-5](#).

Cascading effects across critical infrastructure sectors

Healthcare: Disruptions in healthcare infrastructure, such as limited access to medical facilities and resources, have profound implications for marginalized communities. Reduced healthcare access leads to delayed treatments, exacerbating health conditions and increasing healthcare disparities among vulnerable populations. While non-marginalized individuals also faced challenges, their access to private transportation and financial resources mitigated some of the adverse effects.

Food and nutrition: Supply chain disruptions and closure of food distribution centers affect access to nutritious food, particularly for children reliant on school feeding programs. This scarcity of food exacerbates malnutrition and heightens vulnerability to health complications, perpetuating cycles of poverty and food insecurity.

Social work: Disruptions in social work infrastructure, including advice centers and community resources, exacerbate social and economic disparities among marginalized populations. Limited access to support services hinders individuals' ability to address their needs and navigate challenging circumstances, perpetuating cycles of poverty and marginalization.

Education: School closures and limited access to educational resources exacerbate learning inequalities among marginalized students. Lack of access to technology and educational support systems further widens the education gap, hindering academic progress and future opportunities for vulnerable youth. Greater access to digital resources allowed non-marginalized families to better cope with remote learning.

Childcare: Closure of childcare facilities and limited access to childcare services disrupt parents' ability to work and provide for their families. The absence of structured childcare programs also hampers child development and exacerbates socioeconomic inequalities among marginalized households. Access to private childcare options and the ability to work from home allowed non-marginalized families to better navigate the closure of public childcare facilities.

In addition to the cascading effects observed across critical infrastructure sectors on marginalized communities, it is crucial to highlight the impact on staff working within these sectors. Increased commuting costs and times emerge as a notable challenge, particularly when alternative transportation options are limited or expensive. This translates to higher commuting costs and longer travel times, which can strain finances, disrupt work-life balance, and influence job satisfaction. Moreover, longer or more strenuous commutes resulting from public transportation disruptions contribute to heightened fatigue and stress among workers. This, in turn, adversely affects their mental well-being, work performance, and the quality of care provided to those in need. Given their reliance on in-person meetings and the difficulty in substituting these interactions online, disruptions to transportation pose significant risks. During the pandemic, these risks are exacerbated by the higher likelihood of exposure to illness, leading to staff shortages and increased workloads for those remaining.

In-depth exploration of cascading chains

The cascading effects on marginalized groups are often similar across the three case study areas. However, certain effects are particular to specific case study areas, due to unique location-specific conditions, e.g., load shedding in South Africa or marginalization in Germany often being based on language barriers. These effects are highlighted as such in the supplementary figures. While our study provides a comprehensive overview of cascading effects across the five critical sectors, we will delve deeper into one particularly intriguing aspect of the cascading chains observed in each case study area.

Dortmund

In Dortmund, the impact of COVID-19 disruptions on marginalized communities was particularly pronounced within the education sector. School closures resulted in the loss of crucial support systems for vulnerable students, including intensive teacher guidance and access to educational resources. Children from migrant backgrounds, in particular, faced challenges compounded by language barriers, hindering their ability to engage in remote learning activities effectively. Moreover, the shift towards remote work and homeschooling placed additional burdens on caregivers, often resulting in unequal distribution of labor and reinforcing traditional gender roles.

Additionally, the closure of social facilities and support services posed significant challenges for marginalized individuals and families. The lack of access to advice centers, charities, and community resources deprived vulnerable populations of essential support networks, exacerbating social and economic disparities. The increased demand for psychological support and counseling further strained already stretched resources within the social work sector, underscoring the need for innovative solutions to address the growing mental health crisis. Limited mobility brought challenges for those in need to reach the facilities and also made it more difficult for social workers to conduct outreach activities. The economic and organizational costs associated with coping with homelessness surged, further amplifying social inequalities and threatening the livelihoods of marginalized communities.

Even after lockdown measures and mobility restrictions were eased, for some residents, there was a notable reluctance to resume their use of public transportation due to the perceived fear of contracting infections. This voluntary self-restriction resulted in individuals refraining from accessing essential services, such as healthcare and social services, despite their potential need or significant benefit from such support. This reluctance further exacerbated pre-existing issues that arose prior to or during the pandemic, continuing to affect communities in the post-lockdown period. The hesitancy to utilize public transport not only hindered individuals' access to vital resources but also underscored persistent concerns regarding safety and infection risk, highlighting the enduring impact of the pandemic on mobility patterns and service utilization.

São Paulo

The case study in São Paulo shed light on the unique challenges faced by marginalized women, particularly concerning increasing gender-based violence and mobility^[59]. Train and subway stations emerged as critical public spaces for accessing support services for victims of violence against women, highlighting the importance of transportation infrastructure in addressing gender inequalities. The unequal distribution of resources and opportunities between downtown areas and the outskirts of São Paulo further underscored the complex interplay between socioeconomic factors and mobility. This also marks a shift in the work of social services as facility-based operations transitioned to unconventional settings such as subway stations, aiming to bring support services closer to communities, acknowledging the importance of accessibility and proximity in times of crisis. Furthermore, it underscores a new utilization of mobility hubs as multipurpose spaces, serving not only as transportation nodes but also as vital community resources.

Moreover, disparities in life expectancy and access to healthcare highlighted the entrenched inequalities within the city, with residents of downtown areas enjoying better access to essential services compared to those in peripheral neighborhoods. However, efforts to enhance public spaces and improve connectivity, such as providing health services at train stations, have sought to address some of these disparities and improve access to vital resources for marginalized communities.

Cape Town

The case study in Cape Town illuminated intricate interdependencies between critical sectors, particularly highlighting the cascading effects and intersections of the food sector with healthcare and education. One of the narratives emerging from the data was the profound impact of COVID-19 disruptions on children from marginalized communities, particularly concerning their access to nutrition and education.

Access to food, especially for children reliant on school feeding programs, became severely restricted with the closure of schools and daycare facilities. Approximately one-third of learners in the Western Cape province depended on these programs for their daily meals, making the sudden cessation of services a critical concern. Moreover, the closure of informal food vendors, which are prevalent in townships and other low-income neighborhoods, further exacerbated food insecurity issues, as these vendors were often the primary source of fresh produce for many residents.

The absence of access to nutritious food posed immediate challenges and had long-term ramifications, including intra-household triage, such as reliance on alternative food networks through practices of sharing^[60] and potential intergenerational impacts on child development. Malnutrition emerged as a pressing concern, with implications extending beyond the food sector to affect healthcare delivery. For instance, malnourished individuals may not be suitable candidates for certain medical procedures or surgeries, thereby straining healthcare resources and exacerbating existing vulnerabilities.

Furthermore, the disruption to education resulting from school closures had multifaceted effects on children's well-being and future prospects. Learning gaps and academic setbacks were commonplace, with some students dropping out of school altogether. The absence of recreational and after-school programs during the pandemic further heightened the risk of negative outcomes, including increased substance abuse, involvement in criminal activities, and unintended pregnancies.

Cross-cutting themes

Several common themes emerged across all case study areas, underscoring the profound impact of COVID-19 disruptions on marginalized groups. Increased incidents of gender-based violence and child abuse, compounded by social isolation measures, highlighted the critical role of schools as safe havens for vulnerable individuals. The absence of digital alternatives further exacerbated existing inequalities, particularly concerning access to essential services and support networks.

Furthermore, the dependence on technology as an alternative means of accessing resources highlighted the digital divide and unequal access to technology among marginalized populations. In response, various initiatives were implemented to bridge this gap, including efforts by institutions in Dortmund to provide tablets to marginalized groups and initiatives in Cape Town where residents in affluent neighborhoods donated mobile data to residents in townships for digital schooling. Addressing these disparities and building resilience within critical infrastructure systems will require comprehensive and inclusive strategies that prioritize the needs of marginalized communities.

DISCUSSION

Reflecting on the results in the context of our research question, the profound impact of disruptions in critical infrastructure sectors on the livelihoods of marginalized households is illuminated. It is demonstrated that seemingly isolated disruptions, such as those in public transportation, can trigger cascading effects with far-reaching implications across various sectors of daily life. For instance, the closure or limitation of public transport systems not only impedes individuals' ability to access essential services but also exacerbates existing inequalities by disproportionately affecting marginalized communities as these are, compared to non-marginalized groups, more reliant on these services for mobility. Additionally, reduced mobility and confined daily routines further compound the challenges faced by these communities. Social distancing becomes particularly difficult in densely populated informal settlements, where the density of people limits the effectiveness of preventive measures^[26,61]. The inability to commute also restricts residents' access to necessary services that might not be available in their residential area.

Therefore, one key implication of these disruptions is the critical importance of mobility and accessibility in sustaining livelihoods, particularly for vulnerable populations. The findings underscore the essential role of public transportation in facilitating access to healthcare, education, employment opportunities, and social services. When transportation systems are disrupted, marginalized households face increased challenges in meeting their basic needs and accessing vital resources, further exacerbating socioeconomic disparities. Tariverdi *et al.*^[62] proposed a new methodology for computing urban accessibility to essential public services such as healthcare and analyzing the criticality of infrastructure components in relation to the services they provide, such as transport, based on open data. This methodology enables the identification of isolated locations and populations regarding the studied public service and could be a useful tool for further urban planning in a case as presented in this study.

Moreover, the study contributes to a deeper understanding of the broader societal impacts of critical infrastructure disruptions. Studies like the one conducted by Sunio *et al.*^[63] showed the impact of public transport disruption on access to healthcare facilities during the pandemic but have not looked at the subsequent impacts on other sectors yet. By uncovering the interconnectedness between different sectors, it is revealed how disruptions in one sector can have ripple effects across others, creating complex and intertwined challenges for marginalized communities. For example, we showed how disruptions in transportation can affect access to education, influencing child care and access to food, which can affect the sectors of healthcare and social work, highlighting the interconnected nature of critical infrastructure systems.

Furthermore, the findings emphasize the importance of considering intersections between critical infrastructure sectors in resilience planning and risk management strategies. By identifying how disruptions in one sector can amplify risks and vulnerabilities in others, the study underscores the need for integrated approaches that address the interdependencies between infrastructure systems. For instance, efforts to enhance transportation resilience should consider the implications for healthcare delivery, education access, and social support services, ensuring a holistic and coordinated response to disruptions.

RECOMMENDATIONS

The observed cascading effects underscore the critical importance of inclusive policies and effective governance mechanisms in mitigating the indirect impacts of infrastructure disruptions on marginalized communities. Policymakers should prioritize the development of resilient infrastructure systems that can withstand and recover from shocks while ensuring equitable access to essential services. Lessons learned from the diverse case study contexts, including the interplay between critical sectors and their implications

for vulnerable populations, should inform policy formulation and decision-making processes.

Policymakers must recognize the heightened vulnerabilities of marginalized groups and prioritize interventions that address these disparities. While measures aimed at the general population can provide broad benefits, targeted support for marginalized communities is crucial for promoting equity. For instance, maintaining and enhancing public transportation services during emergencies, ensuring equitable access to digital learning tools, and supporting community food programs can help mitigate the disproportionate impacts on marginalized groups. Mobile healthcare units and social workers can also bring support directly to underserved areas, reducing the dependency on disrupted public transportation.

Building on the insights gained from the case studies, urban planners must adopt a holistic approach to infrastructure development that considers the interconnectedness of critical sectors and their potential ripple effects. Investments in infrastructure resilience should prioritize underserved areas and address systemic vulnerabilities, such as food insecurity and limited access to healthcare and social services.

For this, community engagement is essential for building resilience and fostering social cohesion in the face of infrastructure disruptions. Stakeholders should leverage the strengths and resources of local communities to develop tailored interventions that address their specific needs and vulnerabilities. Empowering marginalized groups to participate in decision-making processes and co-design solutions can enhance the effectiveness and sustainability of resilience initiatives. The case study differences offer valuable insights into the diverse needs and priorities of communities, highlighting the importance of context-specific approaches to community engagement and empowerment.

In order to this, education plays a crucial role in raising awareness about the cascading effects of infrastructure disruptions and the importance of resilience planning. By providing training and educational resources to policymakers, planners, and community members, stakeholders can enhance their understanding of complex interdependencies and build capacity for proactive risk management.

CONCLUSIONS

The findings from our case studies shed light on the profound impact of COVID-19 disruptions on marginalized households across different geographic and socioeconomic contexts. Our research question aimed to explore the cascading effects of disruptions in critical infrastructures on the livelihoods of marginalized communities, with a focus on the intersections between different sectors and the broader societal implications. Through the lens of these case studies, we can discern the intricate ways disruptions in critical sectors, such as healthcare, food supply, social work, education and childcare caused by restricted mobility have exacerbated existing vulnerabilities and inequalities, further underscoring the systemic challenges marginalized populations face during the pandemic. Our findings further underscore the importance of considering cascading effects in assessing infrastructure resilience and developing strategies to mitigate the indirect impacts on marginalized groups.

Key findings and contributions

Our research has illuminated the intricate dynamics of infrastructure disruptions and their ripple effects across critical sectors and marginalized communities. In Cape Town, the closure of schools and daycare facilities disrupted children's access to essential food services, exacerbating food insecurity and nutritional deficiencies. In Dortmund, school closures and limited access to social services highlighted the challenges faced by vulnerable students and families, particularly those from migrant backgrounds. In São Paulo, there are reports of gender-based violence and disparities in access to healthcare, underscoring the need for

inclusive infrastructure planning and community engagement.

Importance of considering cascading effects

The cascading effects observed in our study highlight the interconnectedness of critical infrastructures and the need for holistic approaches to resilience planning. By understanding the systemic vulnerabilities and interdependencies between sectors, policymakers, urban planners, and community stakeholders can develop targeted interventions to address the needs of marginalized populations and enhance infrastructure resilience. Integrating cascading effects into resilience assessments can provide valuable insights into the potential consequences of infrastructure disruptions and inform evidence-based decision-making processes.

Need for future research

While our study has shed light on the cascading effects of infrastructure disruptions, several avenues remain for future research in this area. Further investigation is needed to understand the long-term impacts of infrastructure disruptions on marginalized communities and to develop comprehensive resilience strategies that address systemic vulnerabilities. An important aspect refers to the impact on different groups based on gender, race, age, and ethnicity. Looking within these groups, it is also possible to identify other strategies, such as communities, alliances, and collaboration, to build a resilient network in the face of disruptive events. Collaborative research efforts that leverage interdisciplinary expertise and engage with local communities are essential for advancing our understanding of cascading effects and enhancing infrastructure resilience in an increasingly interconnected world.

Research exploring the role of technology and digital infrastructure in mitigating the indirect effects of disruptions on marginalized groups can provide valuable insights into innovative resilience solutions. It is essential to acknowledge the growing role of emerging technologies in addressing these challenges. Technologies such as AI and blockchain have shown significant potential in enhancing pandemic control and infrastructure resilience^[64]. Further research could therefore examine how privacy-preserving contact tracing like P2B- and BU-trace can be integrated with existing public health infrastructure to improve tracing accuracy while maintaining user privacy^[65-67]. Additionally, developing AI algorithms that forecast the spread of infections could help identify vulnerable infrastructure nodes, and recommend proactive measures to prevent system-wide failures^[68].

In conclusion, our study highlights the importance of considering cascading effects in assessing critical infrastructures' resilience and developing strategies to mitigate the indirect impacts on marginalized groups. By understanding the complex interactions between critical sectors and their implications for vulnerable populations, we can build more resilient and inclusive infrastructure systems that promote a sustainable livelihood for all members of society.

DECLARATIONS

Authors' contributions

Methodology, formal analysis, investigation, resources, writing - original draft preparation, visualization: Schnittfinke T

Methodology, writing - reviewing and editing, supervision, project administration, funding acquisition: Greiving S

Writing - review and editing, investigation, validation, supervision, project administration, funding acquisition: Zuidgeest M, Behrens R, Rink B, Momm S

Writing - reviewing and editing, supervision, project administration, funding acquisition: Scholz W

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

The authors conducted expert interviews in accordance with the ethical guidelines for good research practices as outlined by TU Dortmund University. The research adhered to research organization's guidelines, which does not require formal ethical committee approval for expert interviews and workshops of this nature. The participants were fully informed about the nature and purpose of the research prior to their participation. They were informed about the use of the information they provided and agreed to participate voluntarily.

Consent for publication

Not applicable.

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