Project number 875022

SmartHubs

Smart Mobility Hubs as Game Changers in Transport

WP5. Impact assessment of SmartHubs Living Labs

T5.4. SmartHubs resilience and vulnerability assessment

Deliverable 5.4

Resilience and vulnerability assessment

Version: 1.1

Date: 22/12/2023

Responsible partner: University of Bologna, Italy (UNIBO)

Authors: Caterina Malandri (UNIBO), Roberto Patuelli (UNIBO), Michele Rabasco (UNIBO), Aura Reggiani (UNIBO), Rebecca Rossetti (UNIBO)

This project is supported by the European Commission and funded under the Horizon 2020 ERA-NET Cofund scheme under grant agreement Nº 875022

DOCUMENT CHANGE RECORD

Version	Date	Status	Author	Description
1.0	27/11/2023	Draft	Unibo Team	First draft
1.1	22/12/2023	Complete	Unibo Team	Final version

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EXECUTIVE SUMMARY

This document describes the SmartHubs Resilience Tool, developed within the SmartHubs project. The tool analyses the accessibility and network connectivity impacts of mobility hubs on the resilience of urban public transportation networks.

The development of the task described in this deliverable comprises three phases: (1) the methodological development of a study combining spatial interaction, accessibility and network analysis; (2) the development of the SmartHubs Resilience Tool, by integrating the three approaches, and (3) the application of the tool to the urban areas where SmartHubs Living Labs are located, including scenario analyses based on potential changes in the wider transport network.

The tool, which relies on public transport and bike sharing data, is made up of two components: a first one providing network analysis-based indicators, such as efficiency and betweenness; a second one allowing to compute accessibility indicators – emerging from conventional spatial interaction/transport models – for the geographical area under analysis.

Transport connectivity and area accessibility are two concepts that are closely intertwined, as both influence the ease with which individuals can reach specific locations. A well-connected transport network can facilitate the movement of people (or goods), thereby reducing travel times and increasing efficiency, and in turn, improving area accessibility.

In this report, an evaluation of the cities associated to each of the SmartHubs Living Labs is provided, using the above-mentioned indicators. A network representation of the local urban public transport supply is developed, to which origin-destination (OD) matrices (when available) containing flows of mobility throughout each city is coupled. Flows are distributed over the public transport network, allowing us to observe more in detail potential critical aspects of the network. Moreover, station-based sharing services (shared bikes) are added to this network, further enriching the representation of mobility options through the cities.

Finally, scenarios are developed where, for each city, different types of disruptions or more generally changes to service (e.g. the introduction of further bike stations) are simulated. For each scenario, network and accessibility metrics are re-computed, therefore allowing to measure the effect of such disruptions on the network, with or without the presence of bike sharing services.

The general finding of the simulations carried out is that bike-sharing stations located in correspondence of public transport stops can be of great help in improving the general resilience of urban mobility to disruptions (i.e. they increase the global efficiency of the network). Furthermore, we show that the effect of disruptions – in terms of the induced reduction in the efficiency of the network – is significantly reduced when bike-sharing services are available, compared to when they are not.

The research reported in this report lays the foundation for more work in urban mobility taking into account the importance of network resilience and accessibility, in particular towards guiding local policymakers and urban/transport planners in critical decisions regarding the integration of public transport and micromobility (e.g., mobility as a service) and the authorization of alternative (and sustainable) transport modes.

1. INTRODUCTION

In the SmartHubs project[1], Work Package 5 (WP5) is comprised of a comprehensive impact assessment of the (actual or potential) mobility hubs in the SmartHubs Living Labs. Task 5.4, which is described in this deliverable, aims to develop the SmartHubs Resilience Tool (SHRT) to examine the impacts of mobility hubs on urban accessibility and transport resilience building on earlier research (Caschili et al., 2015; Reggiani et al., 2015; Martin et al., 2018).

Providing a single definition of a mobility hub is not an easy task, as there is a wide variety of cases that all fall under the concept of a mobility hub. Accepting the indications provided by Deliverable D2.1, we define it as follows:

"*a mobility hub is a physical location where different shared transport options are offered at permanent, dedicated and well-visible locations and public or collective transport is available at walking distance*." (Geurs et al., 2022).

If we consider urban mobility to take place over an interrelated network in which different transport options are available, we can recognize that the functionality of its elements also depends on the interconnection between transport modes, that is, the interconnection between Public Transport (PT) and Shared Transport (ST). In this context, mobility hubs integrate the PT network with the more innovative, sustainable, and flexible ST.

Increasing literature is emerging on the role of multimodal transport connections as essential feature for passengers because of improvements in the journey experience, and in case of disruptions to a single transport mode (Elshater and Ibraheem, 2014).

The integration of ST with PT is crucial, as it enlarges the choice set of users, and is expected to cover the inefficiency of PT, to improve first- and last-mile movements and to generally facilitate trips (Garritsen, 2022). In this context, mobility hubs might have a significant role in assessing transport network resilience, because of the availability of different mobility options and of the strategic role of their location in enabling connections between different transport modes, even in case of disruptions. In order to mitigate the effects of these latter events on urban mobility, the transport network must be resilient.

Although a definition of the resilience for transport networks is not universally agreed upon, it can be regarded as the ability of a system to be adequately prepared (ex-ante), to respond, mitigate and adapt (ex-post) to a shock, and to restore performance (Hollnagel, 2014).

In the context of transport networks, we refer to resilience as their ability to withstand and recover from disruptions, shocks, or adverse events while maintaining their essential functions.

Since urban mobility is sensitive to unexpected changes in transport networks, increased attention is being given to the analysis of such disturbances, disasters, or disruptions (Bešinović, 2020). In recent years, urban mobility has increasingly been developed around mobility hubs, whose presence provides opportunities through diversity of sharing mobility choices (bikes, scooters, electric cars, etc.) which also could increase the resilience of the system during disrupted periods. In particular, it is interesting to investigate when and at which conditions the hub remains connected to the network, allowing continued connectivity between different modes. In this regard, we measure resilience under two perspectives: connectivity and accessibility. We intend connectivity as the weighted measure of network linkage of a given node. Accessibility, in the context of transport networks, refers to the ease with which individuals (or goods) can reach desired destinations, services, or resources within a transport system. It encompasses concepts like physical proximity, affordability, connectivity, and the availability of

[1] The SmartHubs project examines mobility hubs, dedicated on-street locations where citizens can choose from different shared and sustainable mobility options. For more information, please visit the website https://www.smartmobilityhubs.eu/.

transport options, ensuring that people can efficiently and equitably access essential services, employment opportunities, education, and recreational activities (Delmelle and Casas, 2012).

Although shared mobility offers many options, in this document we focus only on bike-sharing. The reasons are: 1) the importance of this mode in terms of the number of installations, and 2) the easy availability of data for this mode with respect to other sharing methods, such as electric cars, or e-scooters.

More precisely, we deal with a specific kind of mobility hub, composed of at least a PT stop and a bike-sharing station, whose relevance has been pointed on by several authors as an effective method for urban transportation development (Radzimski et. al, 2021; Saltykova et. Al, 2022).

Bike-sharing works by providing bicycles for hire to the public, usually for short periods of time. There are two types of service use: station-based and dockless (also known as free-floating). In the first case, bicycles must be borrowed and returned at specific docking stations; in the second case, bicycles are not subject to a physical dock, but can be returned anywhere (within the territorial boundaries provided by the providers) after use.

Bike sharing (as well as other shared modes) can provide several benefits, for urban transport and for society. From a transport point of view, bike-sharing adds an additional option for urban mobility, for instance for underserved areas (industrial zones) or at night when PT frequencies are lower. In addition, locating bike-sharing stations close to public transport stops increases the complementarity between different modes of transport, as bike sharing can be seen as an incentive for modal interchange between different public transport services.

Station-based systems can be especially useful in making public transport more connected, while a dockless model can be particularly attractive for the first and last kilometers of a journey, because it is not depending on docking stations (which makes it more versatile). However, dockless systems are much more difficult to model, and present several issues, such as higher vehicle vandalization rates and frequent vehicle drop-offs in inconvenient locations.

Moreover, bike-sharing can provide an alternative mode of transport in case of disruptions to the public transport network (PTN), such as strikes, delays, or cancellations (Cheng et. al, 2021).

Since the focus of the present Deliverable is the role of bike-sharing in complementing a PTN by providing a convenient and flexible mode for multimodal trips in case of network disruptions, we consider only the bike-sharing station-based system in our analysis. To conclude the introduction, Figure 1.1 shows the main steps of T5.4. Resilience and Vulnerability Assessment.

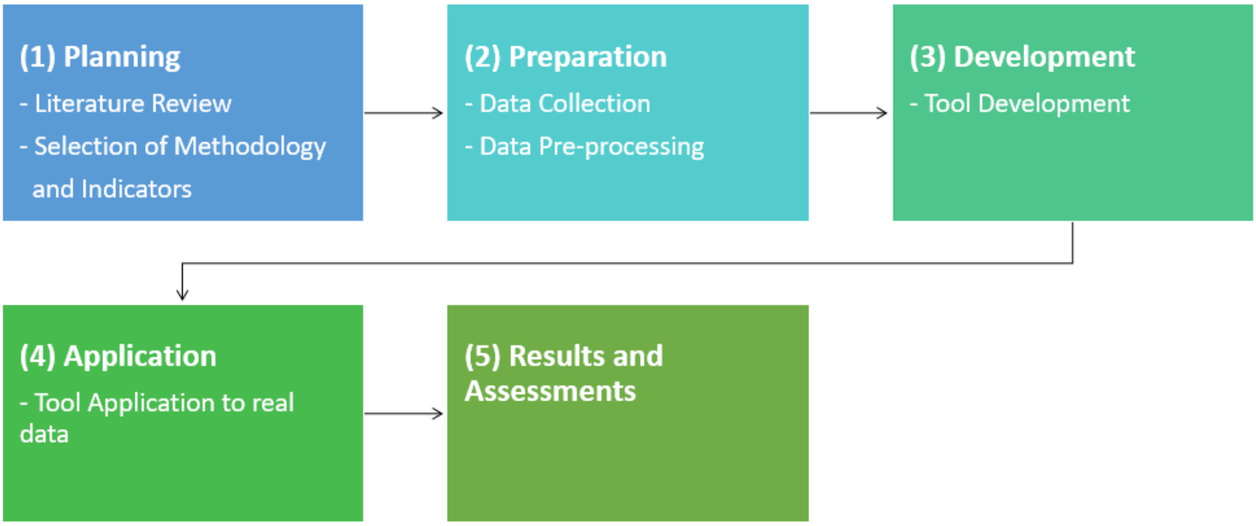

Figure 1.1. T5.4. Resilience and Vulnerability Assessment: the main steps

This Deliverable is the result of a process that involved five steps 1) planning, 2) preparation, 3) development, 4) application, and 5) results and assessments.

The planning step involved two aspects, the first being a review of the literature on the topic of resilience, in order to identify the metrics and indicators to be implemented within the SHRT. The second aspect was related to the design of the software tool. The preparation step primarily involved data collection and preprocessing activities, with the aim of making the data conform to the standards required by the SHRT. Step 3, which involved the development of the tool using R code, was the step that required the most effort in terms of time. This is often the case in many projects, as the development phase involves coding, testing, debugging, and ensuring that the code functions as expected. Step 4 consisted of applying the SHRT to the four study areas (Living Labs) of the project: the Brussels Capital Region, Munich, Vienna, and the Metropolitan Region Rotterdam-The Hague (MRDH). Specifically, the effects of disruptive scenarios on urban public transport networks and the removal/implementation of bike-sharing stations were investigated.
Jointly with Step 2, Step 4 required a significant effort in terms of coordination with the other project partners, given the vastness and diversity of the data sources and the selection of scenarios to which the SHRT is applied in the various case studies. Finally, Step 5, which concludes this Deliverable, aims to provide: a) the illustration of the previous steps, and b) a report for each case study, containing the main results obtained and a list of general conclusions.

This document is organized as follows: Section 2 defines the fundamental concepts for reading the document, also providing a brief review on the resilience of urban public transport and on the accessibility of urban areas. Section 3 illustrates the methods and metrics used, drawn from the literature, which are used to provide a quantitative analysis of urban resilience, from a transport perspective Section 4 shows, in detail, provides an overview of the functioning of the SHRT. Section 5 shows the application of this tool in two cities, namely Munich, and Vienna, and in the geographical areas defined as the Metropolitan Region Rotterdam-The Hague, and the Brussels Capital Region. It consists of four reports, one for each case study, where the results of the scenario analyses are presented. Section 6 concludes this report.

2. DEFINITIONS

This section introduces the key concepts employed in the document. These are: resilience, connectivity and accessibility. In this study, the resilience of a geographical area represents the measure we aim to capture, through the connectivity of a PTN and the accessibility of the sub-areas within the aforementioned zone.

2.1.Resilience

The definition of resilience comes from Latin verb "resilire", that is, to rebound, to spring back, or to resist (Rose, 2009). The term first appeared in academia with Holling (1973), who defined it as the property of evolution of ecological systems. Resilience in the context of transport networks refers to the system's ability to withstand and recover from disruptions, shocks, or adverse events while maintaining its essential functions. It involves the capacity to absorb, adapt to, and rapidly bounce back from disruptions, ensuring that transport services remain available and reliable even in the face of challenges such as natural disasters, accidents, or infrastructure failures (Turnbull, 2016). As it can be inferred from the previous definition, resilience concepts can be divided into two main categories: static and dynamic.

Static resilience refers to the ability of a transportation network to resist external disturbances, maintain its original equilibrium state, or ensure that any external disturbances have negligible impacts on the system's performance. This involves measuring the system's ability to persist or maintain function during a disruption (Liao et.al., 2018).

On the other hand, dynamic resilience refers to the ability of the system to adapt and recover from disruptions over time. It involves the system's capacity to reorganize and evolve in response to changes and shocks, ensuring the continuity of operations even under adverse conditions (Deloukas and Apostolopoulou, 2017).

In this Deliverable, the term resilience refers to static resilience.

2.2. Connectivity

In a transport network, connectivity measures the extent and quality of physical and operational links between different components of the network, enabling a seamless flow of people and goods. A detailed definition of this concept is given in Reggiani et al. (2015, p. 5): "*connectivity is the ability to create and maintain a connection between two or more points in a spatial system*". Thus, graph theory and network analysis are also concerned with connectivity, because of the metrics it involves, such as nodes "centrality" measures (de Stasio, 2011). Furthermore, it encompasses factors like the density of transport links, the availability of transfer points, and the ease of intermodal connections (Hensher, 2008).

2.3. Accessibility

Accessibility evaluates how easily people can access essential services, job opportunities, educational institutions, and other regional facilities. Factors like transport options, travel times, and infrastructure influence it. In the context of transport network, accessibility analysis is considered to understand the needs and behaviour of people (Reggiani et al., 2011). This concept deals with spatial interaction models (SIMs), aiming at catching interactions between nodes and areas of the network. Accessibility analysis provide a complete measurement of resilience (Östh, 2015). High accessibility means the possibility to reach a good number of spatially distributed activities within a reasonable commuting cost/time (Östh et al., 2015).

3. METHODS AND METRICS

In this section, we outline the methodology employed to calculate the variation in connectivity and accessibility, along with the metrics that capture these variations, implemented within the tool.

3.1. Network Analysis

In the context of transport networks, network analysis (NA) is an application of the theories and algorithms of graph theory. Mathematically, a transport network is a graph in geographic space, describing an infrastructure that permits and constrains movement or flow.

In graph theory, a graph is a pair $G = (V, E)$, where V is a set, whose elements are called nodes (vertices), and E is a set of paired vertices, whose elements are called edges (links). To each edge corresponds an adjacent or neighbours' pair of nodes (i,j) with $i \neq j$, and $i, j \in V$ and $i, j = 1, \dots, n$. Node degree (d_i) is the number of adjacent of a node i. We refer to hubs when nodes have large degree, which means that they have many connections with other nodes in the network.

Among the metrics developed in NA, the first one we consider in our study is *betweenness centrality (B_c)*. It is used to describe and give a meaning of importance to the nodes of a network, quantifying how many shortest paths between two given nodes j and k (σ_{jk}) pass through a node i:

$$B_c(i) = \frac{1}{n(n-1)} \sum_{j \neq i \neq k} \frac{\sigma_{jk}(i)}{\sigma_{jk}}. \tag{3.1}$$

The other metric we consider is network efficiency. It is a measure used to obtain an indication of a network's ability to exchange information. In the case of a PTN, this information concerns how easily a passenger can move from a node to a node. The basic idea is that the further apart two nodes are in the network, the less efficient their communication will be. Efficiency can be applied to both the local and global scale of a network; on a global scale, it refers to the entire network; on a local scale, it characterises the quality of information between a node and its neighbours.

A more informative metric in this context is weighted global efficiency, that refers to how effectively a transport system moves passengers. It is computed as efficiency weighted by the number of passengers moving between each pair of nodes.

In this Deliverable, we consider global efficiency in both its unweighted and weighted versions. The formula for global efficiency is:

$$GE = \frac{1}{N(N-1)} \sum_{i \neq j} \frac{1}{d_{ij}}, \tag{3.2}$$

where d_{ij} is the distance between nodes i and j. GE is a value equal or comprehended between 0 and 1 (Latora and Marchiori, 2002). The change in network efficiency is intended as a change in network connectivity, thus in network resilience under the topological perspective.

In its weighted version, the formula is as follows:

$$WGE = \frac{1}{N(N-1)} \sum_{i \neq j} \frac{F_{ij}}{d_{ij}}, \tag{3.3}$$

where F_{ij} represent the estimated flow between stops (Zhang et al, 2021).

3.2. Spatial Interaction Models and Accessibility

The second perspective to assess transport network resilience is accessibility, which refers to spatial interaction and related properties (Reggiani et al., 2011). Spatial interaction modelling is an analytical framework that describes and analyses the spatial organization and the degree of connectivity of various elements within a geographic area, such as a city, region, or metropolitan areas. This model helps in understanding how different locations within the area analysed interact with each other and are interdependent in terms of transport networks, economic activities and passengers' flow.

Thus, accessibility can be assessed by means of spatial interaction models (SIMs) using, e.g., commuting data, and taking into account different impedance functions (e.g., exponential, exponential-normal, exponential-square root, log-normal, and power form).

From the theoretical viewpoint, SIMs are related to entropy theory, utility maximization and discrete choice modelling (Reggiani, 2004). They are useful in analysing trip generation and trip distribution. The most general (unconstrained) formulation of a SIM is as follows:

$$T_{ij} = KO_jD_jf\ (\beta, c_{ij}), \tag{3.4}$$

where T_{ij} is the number of trips modelled from origin zone i to destination zone j, K is a multiplicative constant, O_j are the trips produced from zone j, D_j are the trips attracted to zone j, and $f(c_{ij})$ is deterrence function, which is a function of c_{ij} that is the distance (or other interaction costs, like travel time) between zone i and zone j (Geurs et al., 2012; Reggiani et al., 2011). β is the cost sensitivity parameter, i.e. an exponent describing the effect of cost/travel time between zones (Hansen, 1959).

From the unconstrained formula for SIMs, the analytical expression for accessibility can be extracted. Accessibility has been defined as the potential of opportunities (Hansen, 1959). It is formulated as follows:

$$ACC_i = \sum_j D_jf\ (\beta, c_{ij}), \tag{3.5}$$

where ACC_i defines the accessibility of zone i. Hansen suggests that the value of the cost sensitivity parameter in Eq. (3.5) must be the same as the one estimated in a SIM (Hansen, 1959). Usually, researchers fix this value between 0.5 to 3.0, on the basis of empirical assumptions. As a novelty in the field of research on accessibility, we followed Hansen's suggestion and we determined the value of β through the calibration of the SIM as described below. By means of this procedure, the resulting accessibility ranking can be considered methodologically correct.

In our case, we adopted a doubly constrained SIM [Eq. (3.6)]. The flow from i to j is a function of the potential at each origin, the attractiveness of each destination, and the cost (c_{ij}) of overcoming the separation between them.

$$T_{ij} = A_iO_iB_jD_j \exp\left(-\beta c_{ij}\right); \tag{3.6}$$

$$A_i = \left(\sum B_jD_j \exp\left(-\beta c_{ij}\right)\right)^{-1}; \tag{3.7}$$

$$B_j = \left(\sum A_iO_i \exp\left(-\beta c_{ij}\right)\right)^{-1}. \tag{3.8}$$

In Eq.(3.6),the Ai and Bj components are interdependent balancing factors that ensure that totals are preserved in the predicted flows and need to be computed iteratively. The cost-decay exponential function is usually used (Wilson, 1967). Alternatively, the power decay function, representing a logarithmic form of transport costs, can be used (Fotheringham and O'Kelly, 1989).

The SIM methodology allows us to derive the accessibility measure. When data for origin (O_i)-destination (D_j) and costs are available, the β parameter of the impedance function may be calibrated (estimated),[2] summarizing the effect that each component contributes towards explaining the system of flows. The emerging value of β can then be used to calculate the *indicator of accessibility* [Eq. (3.5)] for each area:

$$ACC_i = \sum_j D_j f(\beta, c_{ij}). \quad (3.9)$$

The higher the value of β, the lower the accessibility of area i; in other words, the value of the exponent β decreases as trips become more important.

The calibration of the SIM in Eq. (3.6) allows us to obtain the value of the β parameter and, consequently, to calculate the accessibility [Eq. (3.9)] of each area, as well as the accessibility loss that contributes to assessing transport network resilience when we remove stops or links.

[2] Here, the Newton-Raphson method is used to calibrate the SIM.

4. SMARTHUBS RESILIENCE TOOL

This section provides a detailed description of the operation of the SHRT. Furthermore, it indicates the types of data required and illustrates the procedures for generating an PTN, integrating it with a bike-sharing network. Finally, it shows how this (integrated) network is weighted through an assignment procedure.

4.1. Overview

The SHRT allows for resilience analysis through the examination of PTN connectivity and local accessibility.

The tool consists of two separate components: a) one, developed in the form of R code for connectivity analysis, and b) SpinModel, which works as an interactive webpage,[3] for accessibility analysis using SIMs. Within the scope of the SmartHubs project, the tool was designed to provide suggestions to urban planners, policymakers, and stakeholders about: a) the most suitable sites where to locate mobility hubs, b) the potential impact of mobility hubs on urban resilience.

In this Deliverable, we provide an example of the tool's application, considering public transport stop/stations equipped with a bike-sharing station. To do that, we integrate the PTN with the bike-sharing network. The resulting network is modelled as a graph, using empirical data, wherein the nodes represent PT stops and the edges denote the connections between two successive stops or stops equipped by a bike-sharing station. Each edge is attributed a weight that indicates the time needed to traverse the distance between two nodes (*in-vehicle time*). When a journey includes transfers within the same mode of transport or to other modes of transport, the *transfer time* and the *waiting time* at the stop are considered. In the model underlying the tool, given the information on in-vehicle time, transfer time, and waiting time, individuals will always choose the fastest path to reach their destination.

Figures 4.1–4.5 show the modelling employed in this Deliverable to represent the urban PT.

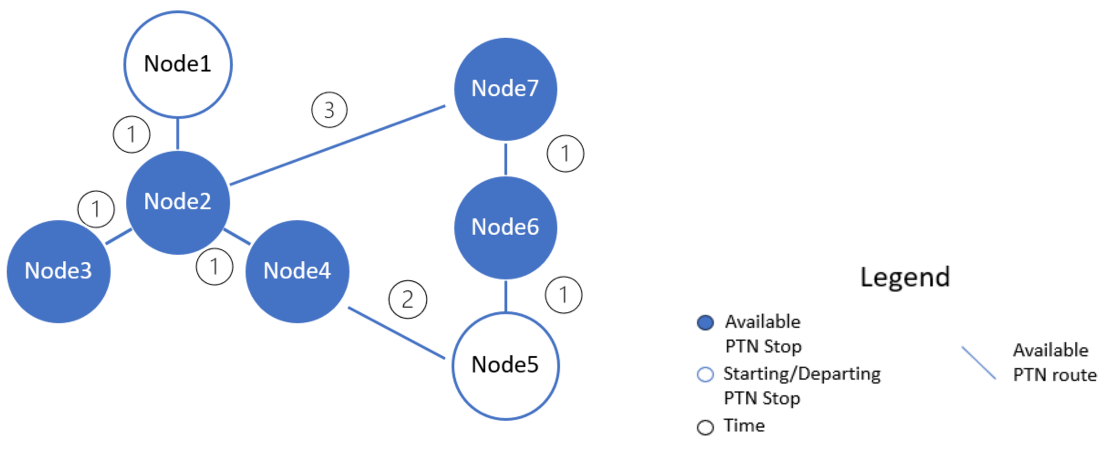

Figure 4.1. Representation of a PTN

Firstly, let us examine the scenario where there are no mobility hubs. In Figure 4.1, nodes 1–7 represent stops within a PTN. The edges connecting these nodes form a set of potential routes for moving from one node to another. The labels on the edges indicate the *in-vehicle time* in minutes. For instance, if a passenger is traveling from Node 1 to Node, two scenarios are possible. In the first scenario, the options

[3] The webpage is in development at the time of finalizing this deliverable, but will be available by the end of the project.

for moving from Node 1 to Node 5 include: Node 1 → Node 2 → Node 4 → Node 5 (with a travel time of 4 minutes) or Node 1 → Node 2 → Node 7→ Node 6 → Node 5 (with a travel time of 6 minutes). The fastest option is the first one, therefore the passenger will opt for it.

Now, if we consider that the passenger must transfer at Node 4 to complete the same journey, a *waiting-time* and a *penalty* (in terms of time) accounting for the inconvenience of the transfer are added to the *in-vehicle time* calculated above. If the travel time required to complete the journey using the path Node 1 → Node 2 → Node 4 → Node 5 now exceeds 6 minutes, the passenger will opt for the path Node 1 → Node 2 → Node 7 → Node 6 → Node 5.

We define the time to move from node i to node j as *travel time*, and the fastest route from node i to node j as the related *shortest path*.

Let us now consider a scenario where the passenger wants to travel from Node 3 to Node 5, and both these nodes are equipped with a bike-sharing station[4] at the PTN stop. We define this new multimodal network as Aggregated Public Transport Network integrated with Bike-sharing (APTNB) (Figure 4.2).

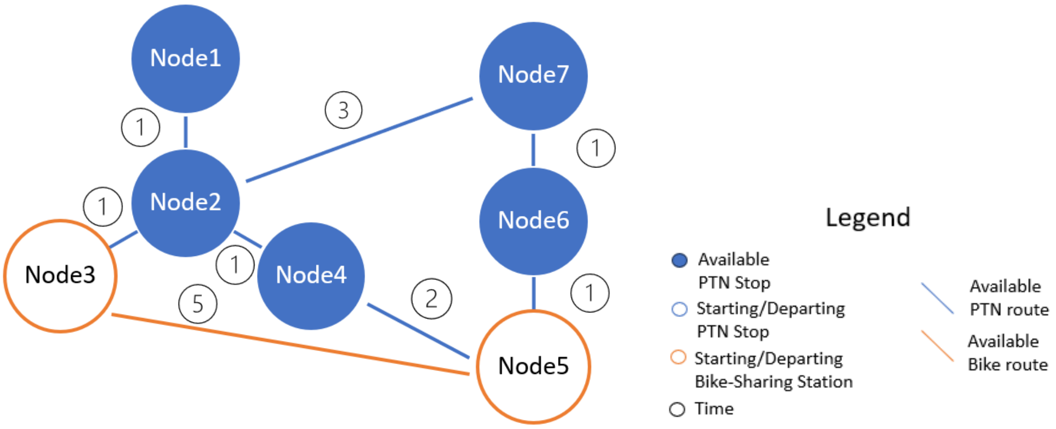

Figure 4.2. Representation of an APTNB

In this case, the passenger has an additional mobility option, which is to complete the journey by bike (represented by the orange edge). This option will be chosen if it is faster than the one provided by PT. For instance, the passenger would opt for bike-sharing if the time required to move from Node 3 to Node 5 by PT exceeds 5 minutes. However, in this example, this is not the case, as the travel time for the path Node 3 → Node 2 → Node 4 → Node 5 via the PT is 4 minutes.

Once the APTNB graph has been constructed, the first step of the SHRT is to calculate the shortest path among all possible combinations of nodes. The set of nodes, edges, and travel times represents the *status quo* of the urban PTN integrated with bike-sharing.

To study urban resilience, disruptions and additions/removals of bike-sharing stations were applied. These events are referred to as *scenarios*. A disruptive event is defined as any event that may affect the planned/regular functionality of a PTN. It's important to note that we are referring to unplanned events occurring at stops, whose effects (closures, interruptions, etc.) are temporary, i.e., such that they do not require the implementation of additional and/or replacement mobility services. Figure 4.3 provides a schematic representation of the main causes of disruptive events that can involve urban transport systems.

Examples of external disruptive events are severe weather events involving temporary closures or damages to the stops. An example of a temporary consequence after a natural event is the closing of a

[4] We recall that the bike-sharing system is the only sustainable mobility mode we consider in this Deliverable. In other terms, a bike-sharing station, closely connected to a PT stop, represents a proxy for a mobility hub.

subway stop after local flooding. Moreover, transport networks can also be the object of terrorist attacks or strikes. Examples of internal disruptive events are mechanical/technical failures of the rail facilities and equipment. Finally, accidents happen in all transport systems due to both internal and external causes (Janić, 2018).

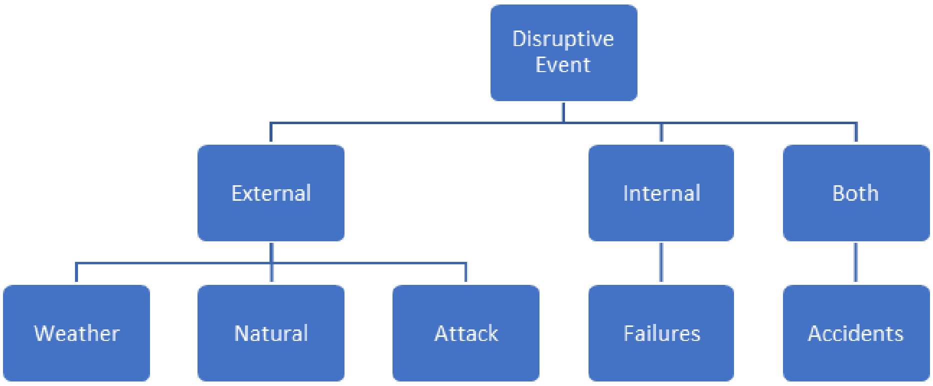

Figure 4.3. Schematic representation of disruptive events on a PTN

The consequences of disruptive events on a APTNB may vary. Here, we define three types of consequences: 1) limited, involving one or more stops, due to random events such as breakdowns or accidents; 2) extensive, involving one or more stops, because of random events such as flooding of a large area of the city; 3) very extensive, involving one or more major stops within the network, due to events such as terrorist attacks or protests.

A disruption on the PTN results in the removal of the nodes affected by the event and the connected links. The removal of a bike-sharing station reduces the number of available travel options. The addition of a bike-sharing station produces the opposite effect. In all cases, the APTNB structure changes. Figure 4.4 provides an example of what happens to the travel time after a node removal.

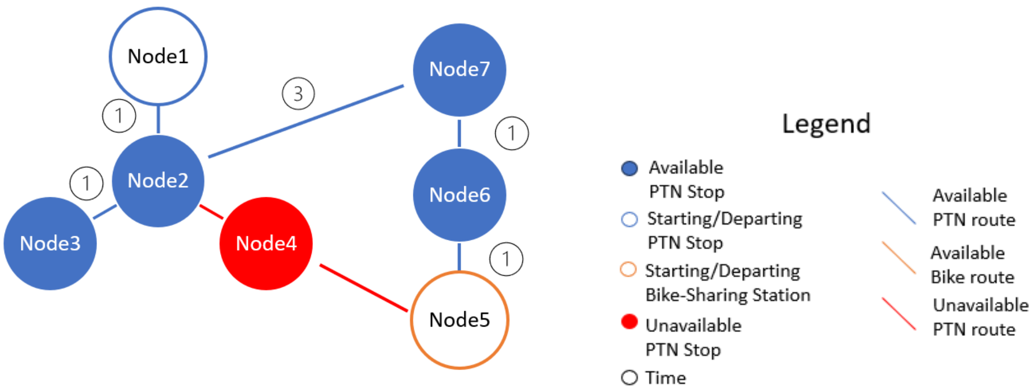

Figure 4.4. Representation of an APTNB after a disruption

Let us now consider a disruptive event that renders Node 4 temporarily inoperative. This means that a passenger who wants to move from Node 1 to Node 5 cannot use the path Node 1 → Node 2 → Node 4 → Node 5 anymore. He/she must use the path Node 1 → Node 2 → Node 7 → Node 6 → Node 5. The travel time required to complete such a journey will be 6 minutes, while the travel time in the status quo, to move from Node 1 to Node 5 was 4 minutes. The inaccessibility of Node 4 led to an increase in travel time.

Moving from the example to the general case, we can affirm that the removal of a node z entails an increase in the travel time from node i to node j, if node z is part of the shortest path that goes from node i to node j.

Adding a bike-sharing station at one node, can cause the opposite effect: reducing the travel time between two nodes. Let's imagine the situation in Figure 4.5.

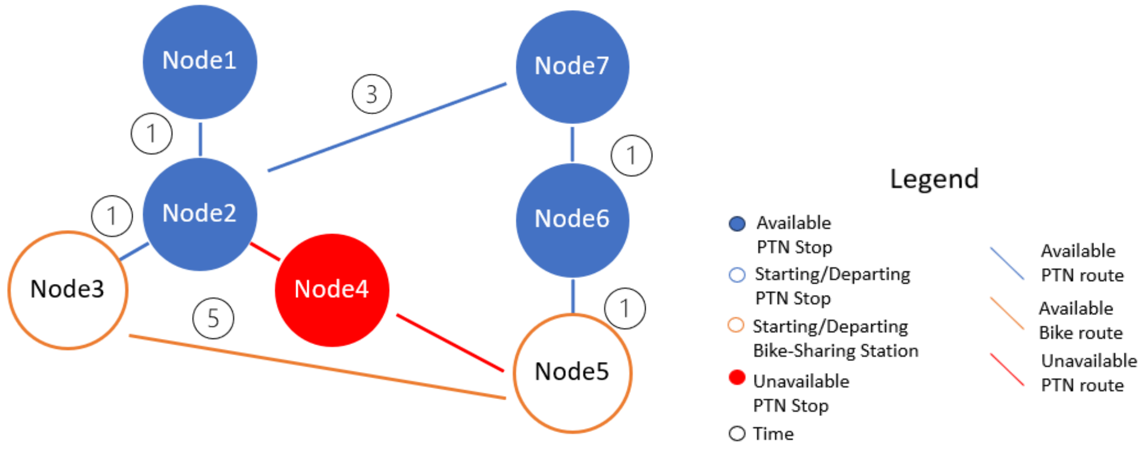

Figure 4.5. Representation of an APTNB after a disruption, with a new bike station

Again, the passenger needs to move from Node 3 to Node 5, in which there are bike-sharing stations. Since Node 4 becomes unavailable, the fastest route using the PTN is the follows: Node 3 → Node 2 → Node 7 → Node 6 → Node 5 in 6 minutes. Assume now, that a new bike share station is added to Node 3 and the time on the vehicle (in this case a bike) required to travel between Nodes 3 and 5 is 5 minutes as descripted in Figure 4.5. In this case, since the travel time by bike is less than PT, this would result in a decrease in the average shortest path.

The main purpose of the present Deliverable is to quantify the change caused by disruptions and bike-sharing station additions/removal that were applied, based on suggestions by the Living Lab leaders, in terms of resilience. Based on the literature (see Section 1), we study resilience under two perspectives: connectivity and accessibility.

More specifically, we measure urban resilience, following disruptive events, in terms of the change in connectivity of the PTN (integrated with bike sharing) and the change in accessibility of urban areas.

To do this, we use four metrics: global efficiency, weighted global efficiency, betweenness centrality, and area accessibility, which have been described in Section 3.

Global efficiency is a valuable indicator for PTNs because it measures how efficiently passengers can travel across the network. A high global efficiency indicates that passengers can travel between any two points in the network with relatively few transfers.

Weighted global efficiency provides a more nuanced understanding of the network's performance, by taking into account the varying strengths of connections between nodes. Routes with higher weights (e.g., higher demand) will have a greater impact on the network's efficiency.

Nodes with high betweenness centrality are often critical for the robustness of the network. If such a node is disrupted, it can significantly impact the network's functionality and the travel time of passengers.

The remaining sections of this section illustrate the data and procedures used, common to each case study. In Section 5, each case study will be illustrated separately. In this Deliverable, the case studies addressed are the Brussels Capital Region, Munich, Vienna and the RMDH.

4.2. Data Typologies

The SHRT uses three distinct kinds of data as input: general transit feed specification (GTFS), geographic information systems (GIS), and origin-destination (OD) data.

- The GTFS is an open standard used to distribute relevant information about transit systems. The SHRT uses the GTFS Schedule that contains (static) information about routes and schedules, and geographic transit details.
- GIS consists of integrated computer hardware and software that store, manage, analyse, edit, output, and visualize geographic data. The SHRT uses GIS data to delimit the area of study, to connect bike-sharing with PTN, and for visualization purposes.
- OD data show the movement of people from one place to another. These data are usually organised in the form of a $n \, x \, n$ matrix in which each row and column represents an area/neighbourhood, and each cell represents the flow of people moving from one area to another.

GTFS data allow the construction of single-mode public transport networks (metro, tram, bus, etc.). This network is comprised of a series of nodes (stops), and the edges between each pair of nodes (connections), arranged in accordance with a predetermined sequence.

Unfortunately, the network does not contain intra-network connections (those that allow for line changes) or inter-network connections (those that allow for changes in transportation mode). This is significant for connectivity analysis, as PT modelling through GTFS data results in individual networks of different transport modes that are disconnected from each other. One way to overcome this issue is to aggregate the stops and consequently the connections between them, in order to obtain a joint PTN. The method used in this Deliverable is illustrated in Section 4.3.

The departure and arrival times between each pair of nodes enable the computation of in-vehicle time. The frequency of PT at a given node is determined by the number of vehicles passing through it. GTFS data also include information on PT routes and modes, which allows for the assignment of a transfer penalty.[5]

4.3. Public Transport Network Generation

As anticipated in the previous section, the SHRT returns an ordered list of nodes and edges, the latter weighted for in-vehicle time, for each public transport network. These modes can be bus, tram, metro, train, and so on. From now on, we refer to these networks as single mode networks (SMNs).

To construct a joint PTN, an aggregation method for stops is needed. The logic here is to aggregate those stops that, being within a short walking distance from each other, allow for the facilitation of transitions between different lines or modes of transportation.

To do that, we aggregated stops that have the same name, whether they belong to the same or different modes of transport.[6] Then, the underlying hypothesis of this choice is that transit stops sharing the same name are in proximity of each other is validated by a quantitative check for each case study, as described in Section 5. This choice has the advantage of eliminating the need for a predefined radius within which stops must be considered for aggregation, thereby removing the necessity for an arbitrary parameter in the aggregation process. Figure 4.6 illustrates our procedure.

[5] More information regarding GTFS data can be found at https://developers.google.com/transit/gtfs.

[6] When the name is followed by suffixes or prefixes that serve solely to determine the mode, these are not considered, and the stops are also aggregated.

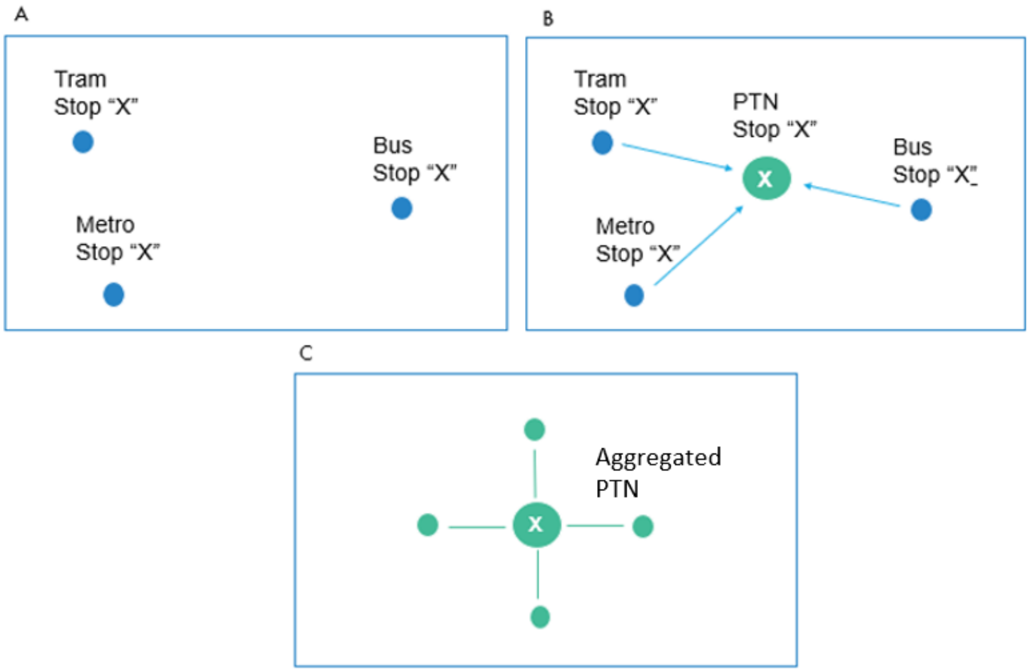

Figure 4.6. Procedure for aggregating stops with the same name

In Figure 4.6A, the individual stops (blue nodes) all have the same name "X", but belong to three different transport networks (metro, tram, and bus). In order to study the connectivity of the urban transport network, these are aggregated. In in Figure 4.6B, the individual stops converge into a single stop (green node) whose geographical coordinates fall at the geometric centroid of the set of points identified by the geographical coordinates of the individual stops.[7] The network in Figure 4.6C is the result of aggregating all nodes with the same name-and represents the generation of the aggregated PTN.

4.4. Integration of Public Transportation and Bike-Sharing

Once the PTN has been constructed, the next step is to integrate it with the bike-sharing system. In this case, we are not dealing with a traditional PTN, as there is no predetermined sequence of nodes. Shared bikes can move almost freely within the urban road network, with the only constraint being that bikes must be picked up and dropped off at a fixed station if they are part of a station-based service.

We modelled shared-bike mobility by constructing a "bike-sharing" network and then connecting it to the PTN.

This procedure was carried out in two steps: (1) *Bike-PTN nodes integration* – the bike-sharing stops are aggregated to those of the PTN if the former is within a circular buffer with radius less than or equal to 200m (Aultman-Hall and Kaltenecker, 1999; García-Palomares et al., 2012); (2) *Bike-PTN edges integration* – stops resulting from the integration between PTN and bike-sharing are connected if they are within a circular buffer with radius less than or equal to 3km (Böcker et al., 2020). Finally, the edges between PTN stops integrated with a bike-sharing station are weighted using travel time. The latter is calculated as distance/speed where the value of speed is 15km/h (Fishman et al., 2013). Figure 4.7 illustrates these two steps. To calculate the distance between PTN stops integrated with bike-sharing stations, the `R` package `osrm` was used, which is a routing service based on 'OpenStreetMap' data.

[7] In a given Cartesian reference, the geometric centroid of a set of points is the result of the arithmetic mean of the respective coordinates of the points.

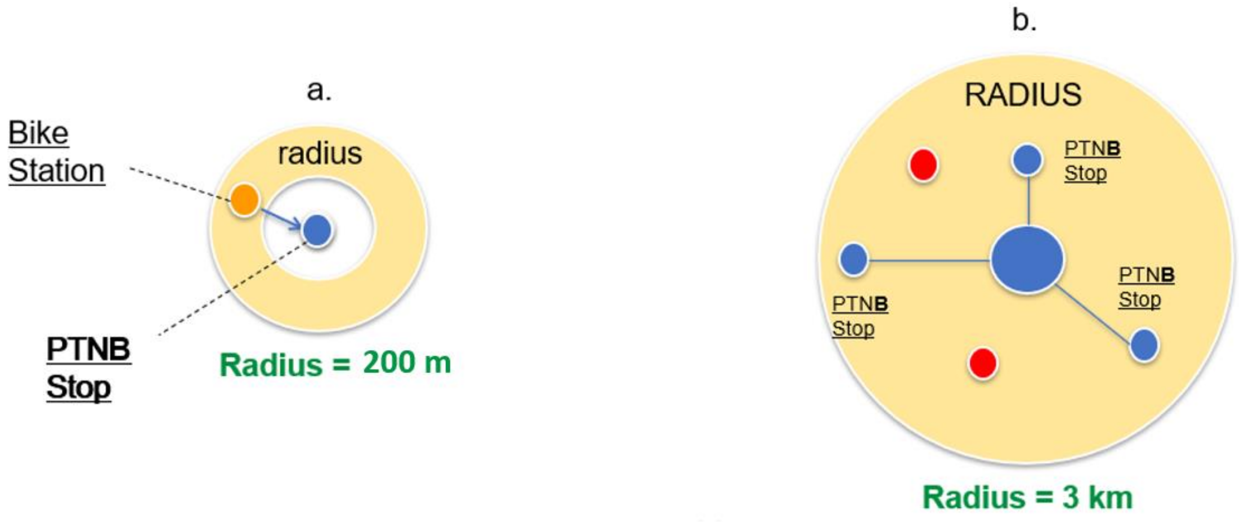

Figure 4.7. Procedure to construct a bike-sharing network

Note. Box A: The orange node is a bike-sharing station, the blue node is the result of the aggregation of the station with the public transport stop. The circle represents the area within which the station is to be integrated. Box B. Blue nodes are public transport stops integrated with a bike-sharing station, blue links are links between them, red nodes are public transport stops without a bike-sharing station. The circle represents the area within which stops with stations must be connected.

4.5. Shortest Paths, Travel Times Evaluation and Assignment

As specified in previous sections, both efficiency and accessibility of a network depend on the passenger travel times between origin and destination stops and between districts, respectively (Eqs 3.2–3.9). Travel times derive from the paths chosen by the passengers to reach the desired destination. In the context of transportation systems, passenger path choice behaviour is traditionally modelled in the framework of random utility theory (Cascetta, 2013). Each path is assigned a cost, and a passenger rationally chooses the minimum cost alternative, under the assumption that every traveller is a rational decision-maker. Random utility models allow to express the probability of selecting an alternative instead of the others.

Generally, in a transportation system, a passenger chooses between the various routes available before starting the trip (*pre-trip* choices), based on expected attributes and characteristics of the supply. However, in some cases, the route is defined only during the trip as some choices can be made adaptively (*pre-trip/en-route* choices). Such path choice behaviour is relevant especially in the case of urban public transport systems with high frequency and low reliability, and if travellers are not completely informed regarding vehicle arrival times (Nuzzolo et al., 2003). In fact, in the case of high frequency transportation services, a fully pre-trip choice behaviour may induce a passenger to unrealistically consider as mutually exclusive two equivalent lines connecting the same pair of stops. In reality, a passenger going from stop A to stop B may choose to board the first vehicle that allows her to come closer to the destination, independently of the line.

In this work, it is assumed that users do not have complete information regarding vehicle arrival times. Under this hypothesis, to include en-route choices in the analysis, the user does not choose a path, but rather a travel strategy, which can be defined as a set of rules that travellers follow during the trip (Spiess and Florian, 1989; Gentile and Nökel, 2016). In particular, passengers choose their departing stop a priori (*pre-trip)*, while at certain stops (*diversion nodes*), they can make en-route decisions which consist in boarding the first vehicle belonging to one of the attractive lines.

From a topological point of view, travel strategies can be represented by using hyperpaths (Nguyen and Pallottino, 1988; Gallo et al., 1993), which are acyclic subgraphs of the network containing one or more diversion nodes. Hyperpaths can be considered as the combination of elementary paths, where multiple links (i.e. lines) exit only from diversion nodes. At each diversion node i of hyperpath k, the probability of using a line l depends on the frequencies φ of the set of attractive lines $L_{i,k}$ departing from the node:

$$prob(l|i,k) = \frac{\varphi_l}{\sum_{n \epsilon L_{i,k}} \varphi_n}. \tag{4.1}$$

Among the set of available hyperpaths, a passenger chooses the minimum cost one. In this project, the cost associated with an hyperpath coincides with the travel time of a passenger using such alternative.

As described in Section 4, the network is composed of public transport links and bike links. Therefore, the generic hyperpath k is made up of public transport and/or bike links as well. Regarding public transport links, travel time TT_{PT} is decomposed into three components, related to different trip phases: on-board travel time T_{ob}, waiting time T_w and transfer time T_t. Considering a public transport link a going from stop i (initial stop) and j (final stop), the total travel time is evaluated as:

$$TT_{PT}^{a} = T_{ob}^{a} + T_{W}^{a} + T_{t}^{a}. \tag{4.2}$$

On-board travel time of transit links T_{ob}^{a} have been assumed to be equal to the scheduled in-vehicle travel time retrieved from GTFS data, representing the difference between the scheduled departure times at two consecutive stops. We do not consider congestion with respect to the flow of transit users, as it is assumed that transit services are designed with some extra capacity.

Transfer time T_t^a is modelled in the form of a penalty which is equal to 5 minutes (Guo and Wilson, 2011), added when the lines used to arrive and depart from stop i are different, that is, when passengers must transfer from one line to another.

At a stop, the waiting time represents the average time between passengers and vehicles arrivals and depends on the frequencies of the "attractive lines", that is, lines that a passenger can use indifferently to reach her destination. Even if waiting links are not explicitly modelled in the network, they are included in the travel time associated with each public transport arc. Waiting time of arc a is expressed as:

$$T_W^a = \frac{\theta}{\sum_{n \epsilon L_{a,k}} \varphi_n} = \frac{\theta}{\phi_{ak}}, \tag{4.3}$$

where ϕ_{ak} is the cumulative frequency of the attractive lines (belonging to hyperpath k) departing from the initial stop of arc a. θ depends on the regularity of the service; in this case, we take θ = 0.5, as we assume a perfectly regular service and passengers' arrivals at a stop described by a Poisson process with constant arrival rate (Cascetta, 2013). If the set of attractive lines contains more than one option, a passenger waits for and board the first vehicle belonging to such alternatives that arrives at the diversion node. Otherwise, if only one line at the stop allows the passenger to reach its destination, she must wait until the vehicle of the desired line arrives.

Bike travel times T_{bike} on bike links are obtained as the ratio between the length of the link L_{bike} (real distance retrieved from OpenStreetMap) and an average cycling speed v_{bike} assumed to be equal to 15 km/h (Fishman et al., 2013).

Finally, travel time of hyperpath k is given by the sum of link travel times multiplied by the probability of using each link when following that route (diversion probability). The choice among available hyperpath alternatives k' can be expressed as the probability $p(k)$ that hyperpath k is the one of maximum perceived utility U_k:

$$p(k) = prob(U_k > U_{k'}) = prob(V_k + \varepsilon_k > V_{k'} + \varepsilon_{k'}), \forall k' \neq k. \tag{4.4}$$

In this project, we assume that the maximum utility corresponds to the minimum travel time, and we adopt a deterministic choice model (ε = 0) in which all users choose a maximum average utility (minimum travel time) alternative. Shortest paths evaluation has been performed by considering all alternatives as feasible and adopting an exhaustive approach (Dijkstra, 1959), in which the complex explicit enumeration of existing hyperpaths is not required. To calculate user flows for each network link, assignment is performed by adopting an All or Nothing Network Loading approach.

5. SCENARIO ANALYSIS

5.1. Overview

This section provides an example of the use of the SHRT. By means of this tool, it is possible to investigate the hypothetical effects of two types of simulated scenarios on an APTNB, namely: a) disruptive events on the PTN, and b) the addition/removal of bike-sharing stations. The aim is to discuss urban resilience in four urban areas – the Brussels Capital Region, Munich, Vienna, and the MRDH – and provide some advice to stakeholders concerning four main research questions:

1) How robust is the PTN to the occurrence of disruptive events?
2) How does accessibility change after disruptive events on the PTN?
3) What is the consequent potential impact of the bike sharing service on network robustness?
4) Which PTN stops are most suitable for the implementation of new bike-sharing stations, when the goal is to improve network robustness?

For this purpose, we follow the workflow illustrated in Figure 5.1.

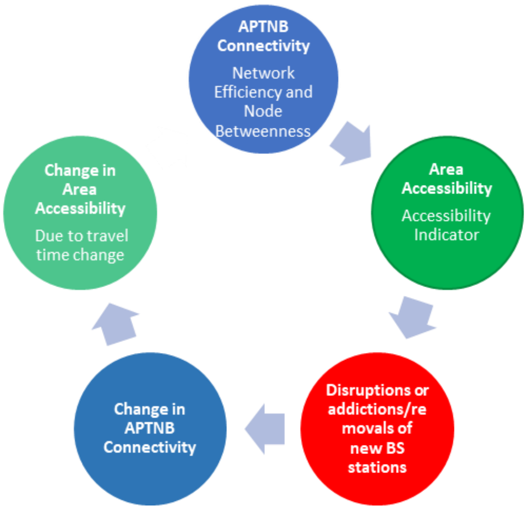

Figure 5.1. Scenario analysis: workflow

The connectivity of an APTNB is quantified through three metrics: *global efficiency* (GE),[8] w*eighted global efficiency* (WGE) and the t*op ten nodes in the betweenness rank* (TTBR). The accessibility of urban areas is evaluated using the a*ccessibility area rank* (AAR). These four metrics together shed some light on each case study's *status quo* in terms of PTN connectivity and local accessibility.

The present deliverable focuses on how the values of these metrics change in response to hypothetical disruptive scenarios on the APTNBs and/or after removal/addition of bike-sharing stations. This change provides an indication of the degree of urban resilience. The scenarios simulated here have been

[8] Global efficiency ranges from 0 to 1. A global efficiency value of 0 implies a lack of paths between nodes in the network, which could be the case in a network where all nodes are isolated, meaning there are no connections between the nodes. On the other hand, a global efficiency value of 1 indicates that each node is directly linked to every other node. This is a feature of a fully connected or complete network. Typically, PTNs exhibit low global efficiency. This could be attributed to a variety of factors, such as the network's complexity, the quantity of nodes and links, the allocation of resources, and the overall planning and administration of the PTN (Mouronte-López, M. L., 2021).

proposed by the Living Lab (LL) leaders, considering the specificities of each area. By using the NA terminology, scenarios refer to nodes and/or edges removal or addiction.[9]

In this deliverable, we assume that disruptive events do not affect bike-sharing stations, but exclusively PTN stops. Following this assumption, by measuring the variations of the selected metrics, we can assess the *potential* impact of bike-sharing supply on urban resilience.

We define such potential impact as the contribution that the bike-sharing network could provide to PTN robustness, measured as the percentage change in the global efficiency indicators. The term "potential" was introduced to address one of the shortcomings of this study: the non-consideration of capacity. A disruption on a PTN involves a variation of the path of an indefinite number of users; these will continue their journey in different ways (on foot, using nearby public transport stops, using bike-sharing if present, and so on). With the term "potential" we mean that, following a disruptive event, the bike-sharing service can handle the entire capacity of users involved in the event. Although unrealistic as a hypothesis, it provides a first measure to assess the impact of the bike-sharing option.

[9] The impact of a node's removal on a network's global efficiency is dependent on the network's specific structure and the node's role within it. For example, removing a highly connected node could increase average travel time and decrease global efficiency. Conversely, disconnecting a node might increase global efficiency as it could reduce average travel time, given that the disconnected node may have been part of longer paths in the network. Additionally, the betweenness centrality of the remaining nodes can change when a node is removed, as it may alter the network's shortest paths. If the removed node was part of many shortest paths, its removal can significantly change the betweenness centrality of other nodes. In essence, changes in global efficiency and betweenness centrality due to node removal are dependent on the network's specific topology and connectivity. This is a complex interplay of factors and cannot be generalized for all areas under analysis. Disruptive events on the PTN not only alter the network's connectivity, but also the accessibility of urban areas. As defined in Section 3.2, the variation in travel time resulting from an event can lead to a change in the accessibility of areas that are directly or indirectly impacted by it.

5.2. The Brussels Capital Region

5.2.1. City Context

In the SmartHubs project, we study the Brussels Capital Region urban PTN with the aim of providing insights into the resilience of the network. The application of the SHRT to the Brussels Capital Region is related to the SmartHubs living lab in Anderlecht.

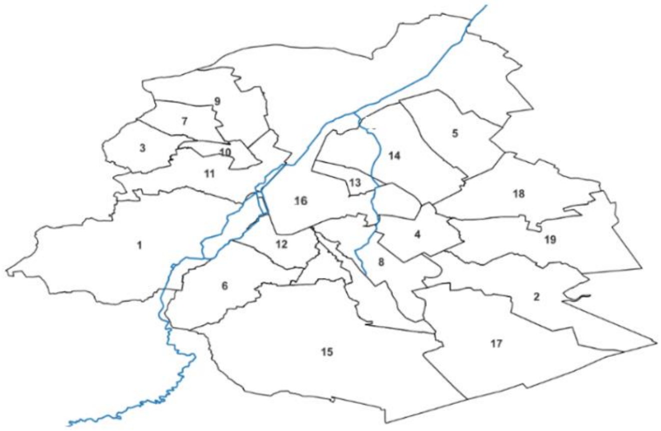

Figure 5.2. The Brussels Capital Region – Borders and districts
Source: openstreetmap.org

***Legend**: 1.Anderlecht, 2.Auderghem, 3.Berchem-Sainte-Agathe, 4.Etterbeek, 5.Evere, 6.Forest, 7.Ganshoren, 8.Ixelles, 9.Jette, 10.Koekelberg, 11.Molenbeek-Saint-Jean, 12.Saint-Gilles, 13.Saint-Josse-ten-Noode, 14.Schaerbeek, 15.Uccle, 16.Stad Brussel, 17.Watermael-Boitsfort, 18.Woluwe-Saint-Lambert, 19.Woluwe-Saint-Pierre.*

The Brussels Capital Region is a region comprising 19 municipalities and the seat of the European Parliament and NATO. The region is crossed by a canal that separates the Western area, which includes Molenbeek-Saint-Jean, Koekelberg, Jette, Ganshoren, Berchem-Sainte-Agathe, Anderlecht, and part of Stad Brussel, from the Eastern area. Figure 5.2 illustrates the city's boundaries considered in our analysis and the administrative subdivision.

The Brussels Capital Region has a population of over 1.2 million inhabitants spread over an area of 150km. Most of the wealth and the highest employment rates are concentrated in the South-Eastern part of the region. In contrast, the municipalities along the canal are significantly less rich, have higher unemployment rates, and are characterized by a higher percentage of non-European natives (Martinez et al., 2023).

The urban area has an extended PTN composed of metros, trams, and buses. The public transport network is managed by the Brussels Intermunicipal Transport Company (STIB-MIVB).[10] Bike-sharing is also popular. The primary bike-sharing service is "Villo!", which operates across all 19 municipalities.

5.2.2. Generation of the Joint Public Transport and Bike-sharing Network

In order to assess the resilience of the urban PTN, integrated with the bike-sharing service, we generate a joint public transport and bike-sharing network based on the GTFS data from STIB-MIVB web site[11] and the bike-sharing station location from the Villo! Web site.[12]
Figure 5.3A shows the PTN service between 7.00 am and 8.00 am of a random workday (2023/09/18), delimited by the city's borders. Each mode is indicated by a different colour: blue, light red, and green, represent routes of the bus, metro, and tram networks, respectively. In Figure 5.3B, the thickness of the orange lines represents the frequency of service between two stops during the selected period. Figure

[10] For the sake of completeness, there are two other PT operators active in the city, namely De Lijn, connecting the Flemish periphery with the capital, TEC, connecting some Walloon villages with the capital. These are smaller operators in the region compared to STIB-MIVB, therefore they have been not included in the analysis. Moreover, the national railway company NMBS-SNCB has an extensive S-network, serving some 35 stations within the Brussels Capital Region. However, this network is seriously underused, hence it is also excluded from our analysis (Janssens, D., et.al, 2023).
[11] https://stibmivb.opendatasoft.com/. Retrieved on September 15, 2023.
[12] https://data.mobility.brussels/nl/info/villo/. Retrieved on September 29, 2023.

5.3C shows the locations of the 343 bike stations within the considered borders. In order to measure the connectivity of the entire PTN, the SMNs have been merged, as described in Section 4.3. Figure 5.3D shows the percentage of aggregations concerning different modes: around 7% of the aggregated nodes are served by all the three modes, around 30% of them by two modes and the remaining fraction (63%) by only one mode. Figure 5.3E shows the PTN network after the aggregation process. [13] Once the joint PTN has been generated, it has been supplemented by the bike-sharing network (see Section 4.4). The result of the integration between the joint PTN and the modelled bike-sharing network is the aggregate public transport network integrated with bike sharing (APTNB) shown in Figure 5.3F. The large number of bike-sharing stations implies that they are relatively close to each other. This has resulted in the inclusion of numerous edges (shorter than 3km) within the aggregated PTN.

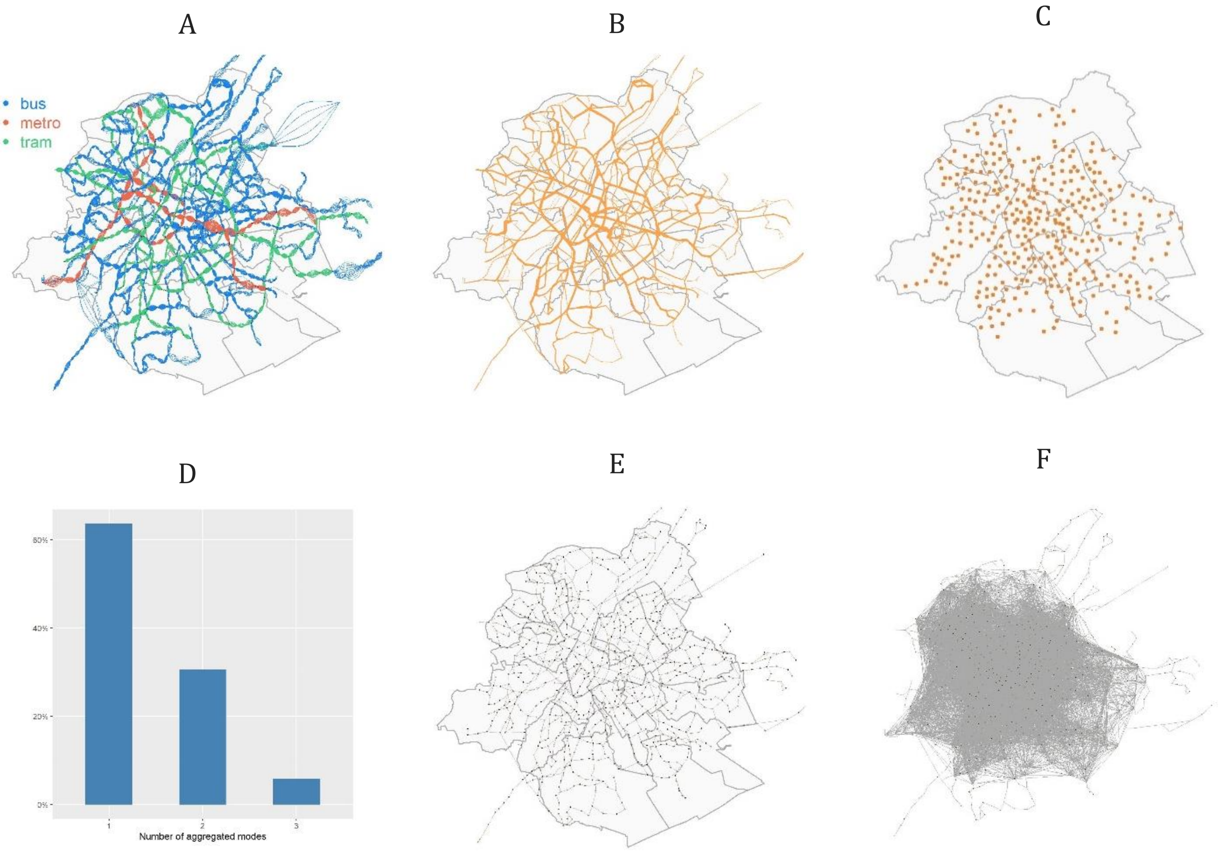

Figure 5.3. The Brussels Capital Region – APTNB generation

Note: SMNs Detailed (A), SMNs frequency (B). Time period: 7am – 8am of a random weekday. Bike-sharing stops locations (C). Percentage of aggregating stop per number of modes (D). PTN network after the aggregation procedure (E). Aggregated PTN integrated with Bike-sharing (F)

[13] All the aggregated stops fall at a distance from the geometric centroid of the stops identified by the same name below than 200 mt. Almost 70% of the aggregated stops represent the aggregation of at least four individual stops with the same name.

5.2.3. Network Connectivity and Node Centrality

To provide some insights to the urban resilience, under the perspective on PTN connectivity, we calculate the Global Efficiency (*GE*) for the ATPNB in the Brussels Capital Region. We found that *GE* = 0,0436**.**

The ten most important nodes, in terms of betweenness centrality (TTBR), results to be: Arts-Loi/Kunst-Wet, Maelbeek/Maalbeek, Schuman/Schuman, Montgomery/Montgommery, Merode/Merode, Simonis/Simonis, Rogier/Rogier, Botanique/Kruidtuin, Gare De L'Ouest/Weststation, and Beekkant/Beekkant (Figure 5.4).

Among these, several are along the canal: Arts-Loi/Kunst-Wet, Maelbeek/Maalbeek, Schuman/Schuman, Montgomery/Montgommery, Merode/Merode, Simonis/Simonis, Rogier/Rogier, Botanique/Kruidtuin, Gare De L'Ouest/Weststation, and Beekkant/Beekkant. This result is consistent with the function of betweenness centrality, which enhances the centrality of those nodes that act as "bridges" between different parts of the city. These stops turn out to be relevant in the Brussels Capital Region as their removal would result in a high probability of network disconnection, resulting in difficulty of movement between the two macro areas of the city, delimited by the canal.

In addition, many of the most central nodes are hubs that incorporate both metro and tram such as Arts-Loi/Kunst-Wet, Maelbeek/Maalbeek, Schuman/Schuman, Montgomery/Montgommery, Merode/Merode, Simonis/Simonis, Rogier/Rogier, Botanique/Kruidtuin, Gare De L'Ouest/Weststation, and Beekkant/Beekkant. Finally, the first three most important stops: Arts-Loi/Kunst-Wet, Maelbeek/Maalbeek, Schuman/Schuman, are all located in the city center. The GE and the TTBR will be used as a *baseline* to compare the effect of the senarios presented in the next subsection on PTN connectivity.

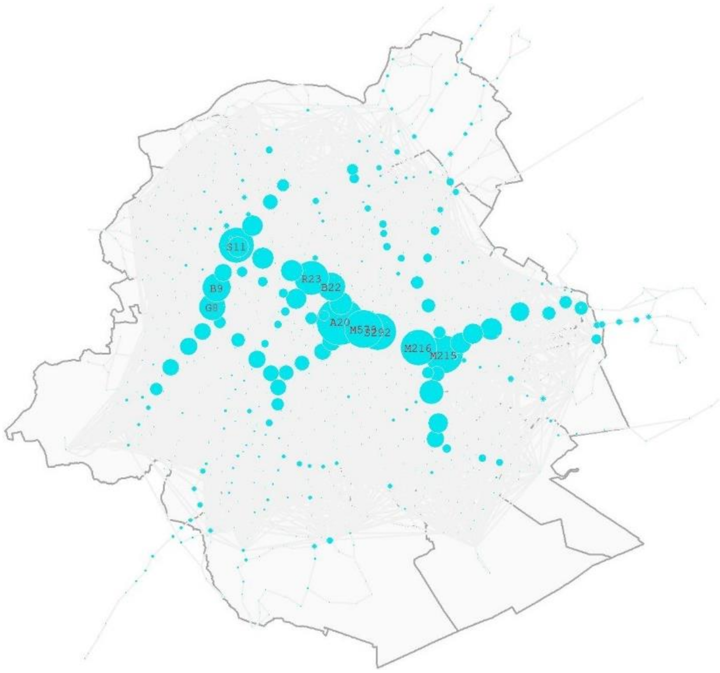

Figure 5.4. The Brussels Capital Region – Node Betweenness Centrality

Note: in red the 10 most central nodes (TTBR). Legend: A20 = Arts-Loi/Kunst-Wet, M579 = Maelbeek/Maalbeek, M215 = Montgomery/Montgommery, S292 = Schuman/Schuman, M216 = Merode/Merode, S11 = Simonis/Simonis, R23 = Rogier/Rogier, B9 = Beekkant/Beekkant, B22 = Botanique/Kruidtuin, G8 = Gare De L'Ouest/Weststation

5.2.4. Scenarios

Since our goal is to identify changes in network connectivity as a result of disruptions to the PTN (scenarios), what we are interested in is the change in the considered metrics, rather than their values. In other terms, our focus is on the percentage change in the GE, and TTBR, with regard to the *status quo.*

On the APTNB of the Brussels Capital Region, the following scenarios have been simulated:

- **Scenario 1:** The station "Gare du midi/Zuidstation" does not function due to a terrorist threat;
- **Scenario 2:** All the stops next to the canal are flooded due to an episode of extreme rainfall; [14]
- **Scenario 3:** Some stops in the EU neighbourhood are not available due to a summit; [15]
- **Scenario 4:** Selected stops (without bike stations) include a new bike-sharing station;
- **Scenario 5:** All bike-sharing stations are removed, which might happen at the end of the current concession with the current provider.

The effects of such scenarios on the network structure are depicted in Figure 5.5. In the Scenario 1, all the transport stops at "Gare du midi/Zuidstation" are removed. It is a very extensive event, involving one major and most central stops within the network. Scenarios 2 and 3 cause numerous stops to cease operations around the main canal. In each of the three scenarios, the stations subject to disruptions are entirely isolated from the remainder of the network, with the sole exception being the connections via bike-sharing. Thus, it becomes feasible to assess the potential influence of the bike-sharing network on the efficiency of the APTNB across each scenario. Scenarios 4 and 5 serve to expand upon the preceding impact analysis. In the first case adding 104 of stations, in the second case eliminating this network entirely.

The change in network connectivity is shown in Table 5.1. To give an insight into the impact of the bike-sharing network on connectivity, the change in global efficiency was divided into two columns. The first (w/ bikes) represents the change relative to the baseline, and the second (w/o bikes) represents the change relative to a hypothetical situation where there is no urban bike-sharing service.

The table shows that the removal of the city's main train station (Scenario 1) alone results in a decrease in network efficiency of 0.36% from the baseline. This loss in efficiency would be significantly greater if the bike-sharing service were not present (–3.19%). Therefore, it can be concluded that the presence of the bike-sharing service contributes to a more resilient system, with a relative loss of efficiency which is only 11.3% of the one in the case of no bike-sharing. Similar results are found in Scenarios 2 and 3.

Scenarios 4 and 5 concern the addition and removal of bike-sharing stations, respectively. For this reason, the column (w/o bikes) is not filled in for these scenarios. In Scenario 4, the inclusion of a substantial number of new stations throughout the city (104) potentially improves global efficiency by 8.91% percent compared to baseline. Finally, it is relevant to note that the exclusion of the entire bike-sharing service results in an efficiency loss of 40.92% compared to baseline.

Table 5.2 shows the impact of the scenarios on TTBR. Regarding the variations in the ranking of the most important stops in terms of betweenness centrality, we observe that, in Scenarios 1 and 4, the ranking remains almost unchanged, indicating that these scenarios do not have a significant impact. On the contrary, Scenarios 2, 3, and 5 cause a reshuffling of the importance of the stops, with new stops gaining importance following the events described by these scenarios (De Brouckère/De Brouckère, Pétillon/Pétillon, Gare du midi/Zuidstation, Tomberg/Tomberg, Porte De Hal/Hallepoort, and Osseghem/Ossegem).

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[14] Nodes removed: Delacroix/Delacrois, Yser/IJzer , Porte De Ninove/Ninoofsepoort, Porte De Flandre/ Vlaamsepoort, Sainctelette/Sainctelette, Entrepôt/Stapelhuis, Tour Et Taxis/ Thurn en Taxis, Marie-Christine/Marie-Christine, Claessens/ Claessens, Cureghem/ Kuregem, Douvres/Dover, Triangle/Driehoek, Mabru/Mabru.

[15] Nodes removed: Idalie/Idalie, Luxembourg/Luxembourg, Schuman/Schuman, Froissart/Froissartstraat, Jourdan/ Jourdanplein , Treves/Trier, Museum/ Museum, Maelbeek/Maalbeek.

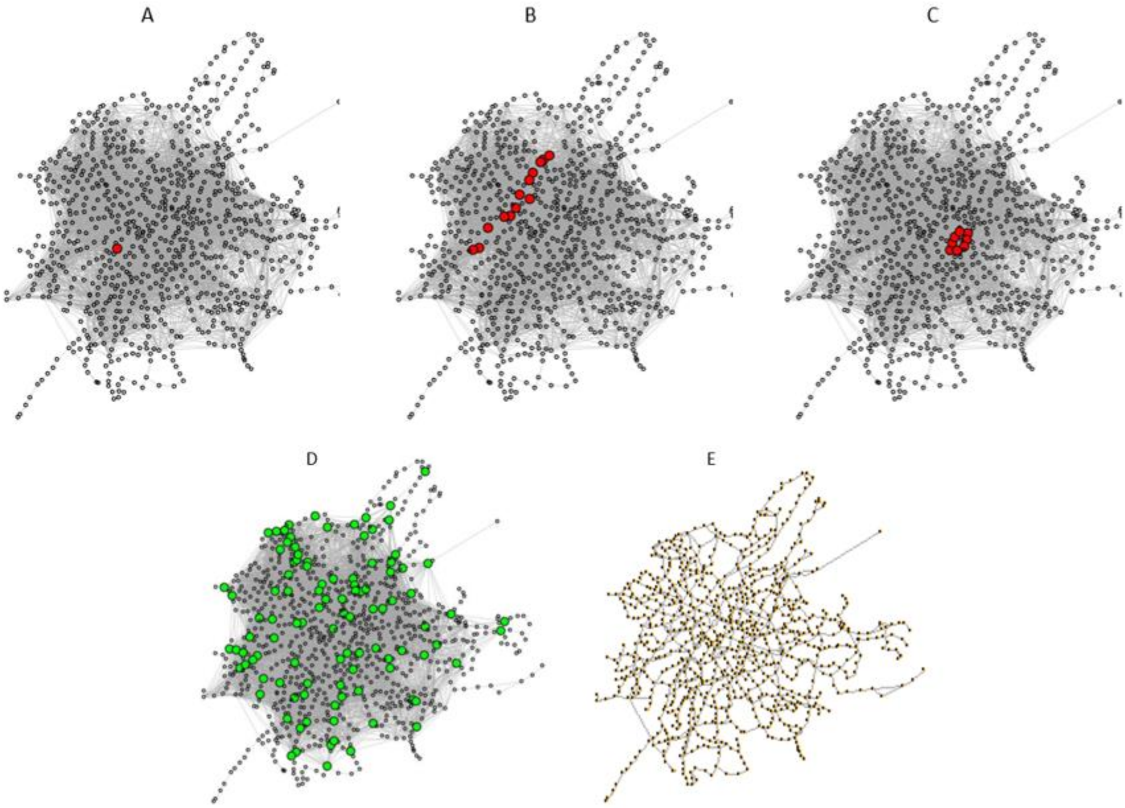

Figure 5.5. The Brussels Capital Region – Scenarios

Note. Scenario 1 (A), 2 (B), 3 (C), 4 (D), 5 (E). The red nodes are those removed from the network., the green nodes are stops equipped with a new bike station.

Table 5.1. The Brussels Capital Region – APTNB Global Efficiency Change (GEC w/ bike) and PTN Global Efficiency Change (GEC w/o bike)

SCENARIO	GEC W/ BIKES (%)	GEC W/O BIKES (%)	DIFF (%)
1. The node "Gare du midi/Zuidstation" does not function due to a terrorist threat (all the stops are removed)	–0.36	–3.19	2.83
2. All the nodes next to the canal are flooded due to an episode of extreme rainfall (all the stops are removed)	–2.15	–4.09	1.94
3. Some stops in the UE neighbourhood are not available due to a summit (all the stops are removed)	–1.64	–3.64	2
4. Selected nodes include new share bikes, which would considerably increase the number of bike-sharing stations	+8.91	-	-
5. All bike-sharing stations are removed, which might happen at the end of the current concession with the current provider	–40.92	-	-

Table 5.2. The Brussels Capital Region - Changes in the betweenness rank

	TTBR - BASELINE	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
1	Arts-Loi/Kunst-Wet	-	-	OUT	-	-
2	Maelbeek/Maalbeek	-	−1	REMOVED	−1	-
3	Montgomery/Montgommery	-	+1	+2	+1	−1
4	Schuman/Schuman	-	-	REMOVED	-	+1
5	Merode/Merode	-	-	-	-	-
6	Simonis/Simonis	−1	−4	+4	−1	OUT
7	Rogier/Rogier	+1	OUT	+4	+1	OUT
8	Beekkant/Beekkant	−1	+1	+1	−1	−2
9	Botanique/Kruidtuin	+1	OUT	+5	+1	OUT
10	Gare De L'Ouest/Weststation	-	+2	+4	-	+2
	INCLUDED (TOP 10)	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
(6)			De Brouckère/De Brouckèr			Porte De Hal/Hallepoort
(7)						De Brouckère/De Brouckèr
(8)				Gare Du Midi/ Station Brussel-Zuid		
(9)			Pétillon/Pétillon	Pétillon/Pétillon		Osseghem/Ossegem
10				Tomberg/Tomberg		

Note: OUT means that the stop goes out the top 10. In parenthesis the position in the new top 10 rank.

5.2.5. Conclusions

The analysis conducted for the Brussels Capital Region allows us to make some evaluations on:

1. The ability of the PTN to resist in response to disruptive scenarios;
2. The potential impact of the bike-sharing service during such events;
3. Which stops are most suitable for the implementation of new bike-sharing stations when the goal is to improve the robustness of the PTN;

Among the simulated scenarios, the highest loss of efficiency is observed when nodes close to the canal are disrupted. In this case, and due to the presence of the canal, which constitutes a sort of "geographical barrier", the part of the city beyond the canal results less connected to the rest of the city.

In our simulation, the presence of the bike-sharing service in the city increases global efficiency significantly with respect to a scenario (i.e. Scenario 5) where the same service does not exist (approximately +40%). Moreover, the presence of the bike-sharing service seems to be important also in case of disruptions. In fact, when some PTN stops are unavailable (Scenarios 1, 2 and 3) the presence of bike-sharing services seems to considerably increase the resilience of the network to disruptions. Finally, the addition of further bike-sharing stations may increase efficiency; with around 100 more stations, as in the case of Scenario 4, the network becomes approximately 8% more efficient.

The analysis performed here can also suggest locations where the introduction of additional bike-sharing stations could be more effective. In fact, when some nodes of the network face a disruption, the role of other nodes changes and new stops gain importance, as shown in the betweenness analysis (Table 5.2). This is the case, for example, of Scenarios 2 and 3, where the centrality, in terms of betweenness, of certain nodes (De Brouckère/De Brouckèr, Pétillon/Pétillon and others) increases. This means that, in such disruptive scenarios, users redistribute and choose paths traversing such nodes, where consequently an increase in public transport loads is experienced. In this sense, when the goal is to improve the robustness of the PTN, it should be convenient to add bike-sharing stations in these locations, i.e., in the proximity of stops acquiring a higher betweenness centrality. The addition of bike-sharing stations could be permanent or temporary; in the latter case, stakeholders may plan, for example, the displacements of bikes from other docks in the city or from an emergency reserve, immediately after the disruption.

5.3. Munich

5.3.1. City Context

In the SmartHubs project, we study the Munich urban PTN with the aim of providing insights into the resilience of the network. The application of the SHRT to the city of Munich is related to the SmartHubs living lab located near the Technical University of Munich.

Munich, the capital and most populous city of the State of Bavaria, is divided into 25 administrative and political districts, as depicted in Figure 5.6. However, for the purposes of this study, the borders are adapted to align with the Traffic Analysis Zones (TAZ),[16] from which the OD data necessary for the weighted global efficiency and accessibility indicator are available (Figure 5.7).

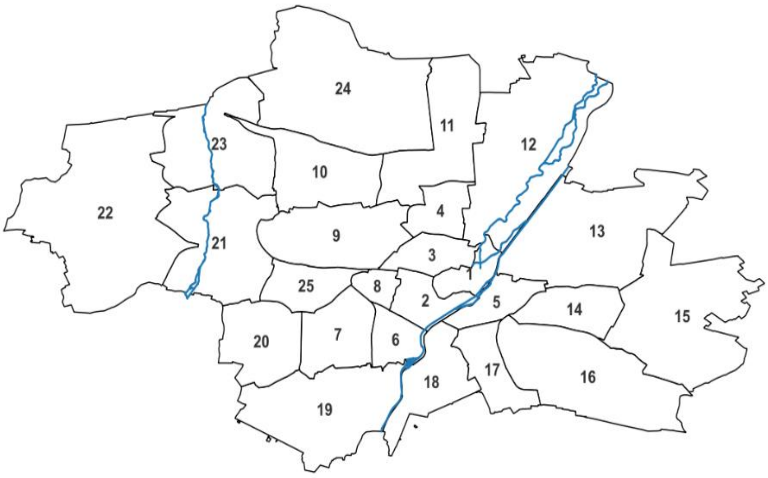

Figure 5.6. Munich - Borders and districts

Source: OpenStreetMap 2023

***Legend**: 1.Altstadt-Lehel, 2.Ludwigsvorstadt-Isarvorstadt, 3.Maxvorstadt, 4.Schwabing-West, 5.Au-Haidhausen, 6.Sendling, 7.Sendling-Westpark, 8.Schwanthalerhöhe, 9.Neuhausen-Nymphenburg, 10.Moosach, 11.Milbertshofen-Am-Hart, 12.Schwabing-Freimann, 13.Bogenhausen, 14.Berg am Laim, 15.Trudering-Riem, 16.Ramersdorf-Perlach, 17.Obergiesing-Fasangarten, 18.Untergiesing-Harlaching, 19.Thalkirchen-Obersendling-Forstenried-Fürstenried-Solln, 20.Hadern, 21.Pasing-Obermenzing, 22.Aubing-Lochhausen-Langwied, 23.Allach-Untermenzing, 24.Feldmoching-Hasenbergl, 25.Laim.*

Figure 5.7. Munich - Borders and TAZ

Source: TomTom OD analytics

The city boasts a population of 1,588,330 inhabitants. Urban public transport is mainly provided by the Münchner Verkehrsgesellschaft (MVG), through subway, tram, and bus services. Additionally, Deutsche Bahn (DB), Germany's national rail provider, operates the S-Bahn network, which connects suburban areas and small towns in the Munich region to the central city (Duran-Rodas et, al 2003).

Bike-sharing is provided by several companies. Among them, MVG Rad bikeshare system stations (mvv-muenchen.de), a hybrid type operated by Münchner Verkehrsgesellschaft mbH (MVG) has a prominent role. The MVG bikes can be returned at all MVG bike stations as well as at publicly accessible locations within the business area. Outside the business area, returns are only possible at existing MVG bike stations.

[16] A TAZ is a geographic unit used in transport planning models. The spatial extent of zones typically varies from very large zones in the peripherical areas to small zones in central business districts.

5.3.2. Generation of the Joint Public Transport and Bike-Sharing Network

In order to assess the resilience of the urban PTN, integrated with the bike-sharing service, we generate a joint public transport and bike-sharing network based on the GTFS data from *Deutschlandweite Sollfahrplandaten*[17] and the bike-sharing station locations from the MVG website.[18]

Figure 5.8A shows the PTN service between 9.00 am and 10.00 am of a random workday (2023/09/18), delimited by the city's TAZs. This time interval was selected in accordance with the available OD data. Each mode is indicated by a different colour: blue, light red, green, and dark red links represent routes of the bus, metro, train, and tram networks, respectively. In Figure 5.8B, the thickness of the orange lines represents the frequency of service between two stops during the selected period. Figure 5.8C shows the locations of the 138 bike stations within the considered borders. In order to measure the connectivity of the entire PTN, the SMNs have been merged, as described in Section 4.3. Figure 5.8D shows the percentage of aggregations concerning different modes: around 1% of aggregate nodes are served by all the four modes, around 5% of them by three modes, around 22% of them by two modes and the remaining fraction (73%) by only one mode. Figure 5.8E shows the PTN network after the aggregation process. [19] Once the joint PTN has been generated, it has been supplemented by the bike-sharing network (see Section 4.4). The result of the integration between the joint PTN and the modelled bike-sharing network is the aggregate public transport network integrated with bike sharing (APTNB) shown in Figure 5.8F. The large number of bike-sharing stations implies that they are relatively close to each other. This has resulted in the inclusion of numerous links (shorter than 3km) within the aggregated PTN.

For the case study of Munich, demand data were made available by project members.[20] Data refer to travel origins and destinations in the morning peak hour, between 9:00 am and 10:00 am. They are only for the road traffic without vehicle type categorization and does not include the non-road public transport modes. This represents a limitation for the analysis. Results from the assignment are shown in Figure 5.9, where colours are scaled depending on the passenger load on each link, with dark red referring to highest values and green ones to the lowest values. As it can be observed from the image, high loads can be observed on the train line. In the Northern part of the city, some bus lines appear to be more intensely used, likely because of the absence of a metro service connecting the Eastern and Western parts of the city.

5.3.3. Network Connectivity and Node Centrality

To provide some insights into urban resilience, under the perspective on PTN connectivity, we calculate the global efficiency (GE) and the weighted global efficiency (WGE) for the ATPNB of Munich. We found that GE = 0.0285 and WGE = 0.0379.

The ten most important nodes, in terms of betweenness centrality (TTBR), are: Hauptbahnhof (S, U, Bus, Tram), Laim, Ostbahnhof, Donnersbergerbrücke, Marienplatz, Hirschgarten, Karlsplatz (Stachus), Isartor, Rosenheimer Platz, Hackerbrücke (Figure 5.10).

Among them, two stops include a railway station: Hauptbahnhof, the main railway station in Munich, and Laim. Donnersbergerbrücke is the second largest S-Bahn station in Munich after the Hauptbahnhof. Marienplatz is an important stop on the Munich S-Bahn and U-Bahn network, located under the square by the same name in Munich's city centre. Hirschgarten is a S-Bahn railway station on the main line

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[17] Source: urchgängige Elektronische ahrgastinformationen (DELFI), 2023. Deutschlandweite Sollfahrplandaten. Retrieved on June 17, 2023. Deutschlandweite Sollfahrplandaten is a nation-wide GTFS dataset that combines local, regional, and national public transport services into a single dataset.

[18] Source: https://www.mvg.de/services/mvg-rad.html. Retrieved on October 08, 2023.

[19] All the aggregated stops fall at a distance from the geometric centroid of the stops identified by the same name below than 150 mt. Almost 70% of the aggregated stops represent the aggregation of at least four individual stops with the same name.

[20] OD are the result of a model application on data come from TomTom OD analytics.

between Laim and Donnersbergerbrücke. Karlsplatz is an underground S-Bahn and U-Bahn station below the Karlsplatz in central Munich. Hackerbrücke represents a bridge across the main railway line in Munich immediately West of the city's central station. All of these stations are part of the "Stammstrecke", or the main truck line of S-Bahn lines that runs through the center of the city.

Figure 5.8. Munich – APTNB generation

Note: Detailed SMNs (A), SMNs frequency (B). Time period: 9am – 10am of a random weekday. Bike-sharing stops locations (C). Percentage of aggregating stop per number of modes (D). PTN network after the aggregation procedure (E). APTB - Aggregated PTN integrated with Bike-sharing (F)

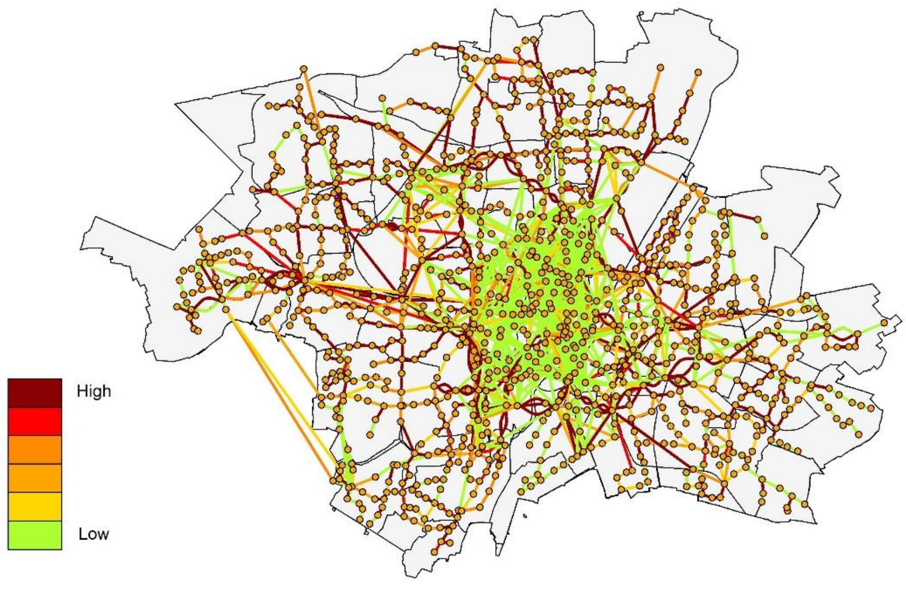

Figure 5.9. Munich – Demand assigment

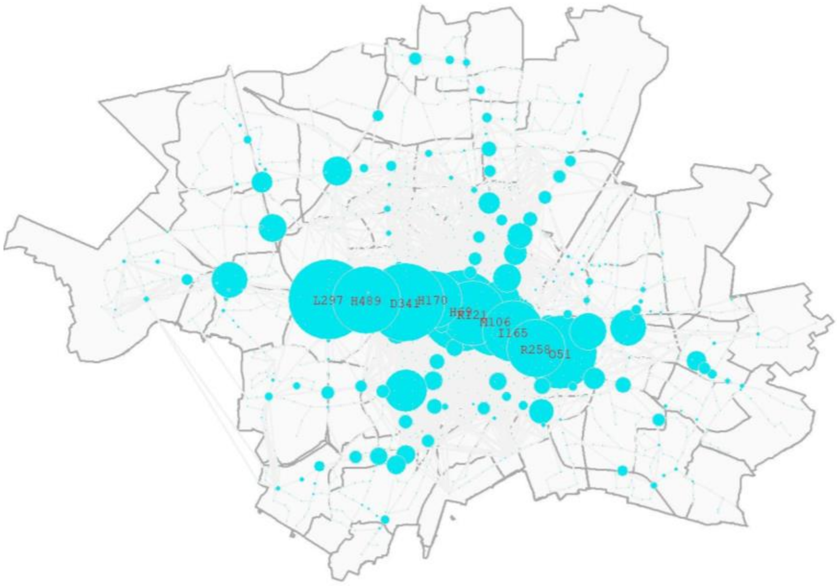

Figure 5.10. Munich – APTNB Betweenness Centrality

Note: In red the 10 most central nodes. Legend: L97 = Laim, H489= Hirschgarten, D341 = Donnersbergerbrücke, H170 = Hackerbrücke, H69 =, R121 = Hauptbahnhof (S, U, Bus, Tram), M106 = Marienplatz, I165 = Isartor, R258 = Rosenheimer Platz, O51 = Ostbahnhof

5.4.4. Area Accessibility

To shed some light on urban resilience under the perspective of local accessibility, Figure 5.11 shows the AAR in Munich, broken down by TAZs (grey borders) and districts (blue borders). The scale of values goes from dark blue (districts with high accessibility) to white (districts with low accessibility). The figure suggests that the central and South-Eastern areas are characterized by higher levels of accessibility compared to the Northern and Eastern parts of the city.

The GE, WGE, TTBR and the AAR will be used as a baseline to compare the effect of the scenarios presented in the next subsection on PTN connectivity.

5.4.5. Scenarios

Since our goal is to identify changes in network connectivity and area accessibility as a result of disruptions to the PTN (scenarios), what we are interested in is the change in the considered metrics, rather than their values. In other terms, our focus is on the percentage change in the GE, WGE, TTBR, and AAR with regard to the *status quo.*

On the APTNB of Munich, the following scenarios have been simulated:

- **Scenario 1:** Stammstrecke is closed;
- **Scenario 2:** Stammstrecke is closed and no bike-sharing system is present;
- **Scenario 3:** Sendlinger Tor and Goetheplatz stations are closed for U3 and U6 services;
- **Scenario 4:** Sendlinger Tor and Goetheplatz stations are closed for U3 and U6 services and no bike-sharing is present.

Scenario 1 happens quite often, usually due to planned construction work. If the Stammstrecke, the main rail line going through Munich, is closed, the following stations are closed: Rosenheimerplatz, Isartor, Marienplatz, Karsplatz (Stachus), Ostbahnhof, Hackerbrücke, Donnersbergerbrücke, Laim, Hirschgarten. For these stations, only the rail service is closed. Scenario 2 is the same as Scenario 1, but without the presence of the bike-sharing system.

The effects of such scenarios on the network structure are depicted in Figure 5.12.

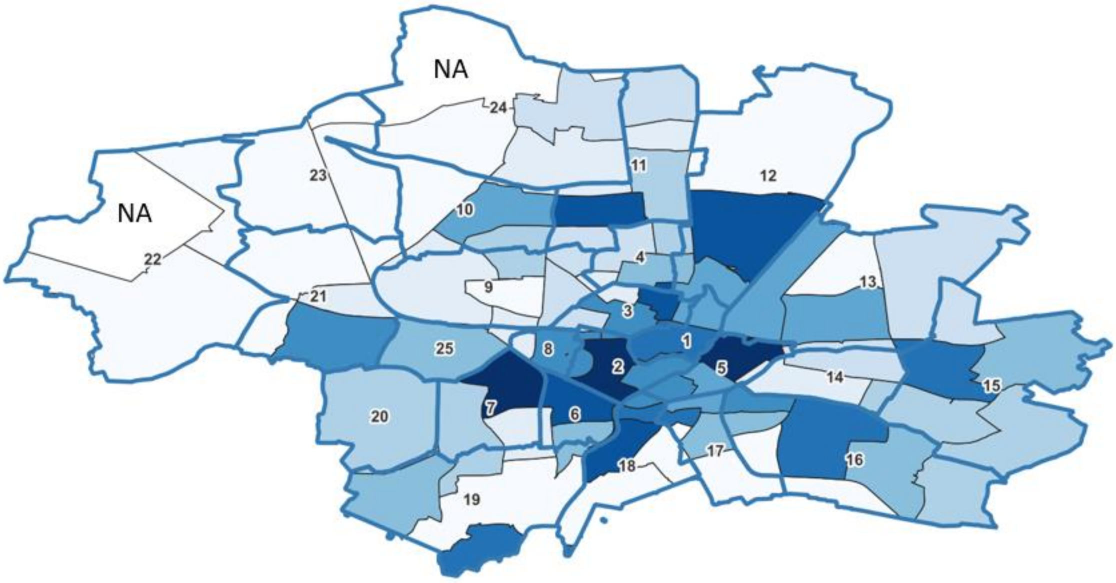

Figure 5.11. Munich – Areas Accessibility

Note: *Colour scale from dark blue (more accessible) to white (less accessible).*

Legend*: Districts (red borders) 1.Altstadt-Lehel, 2.Ludwigsvorstadt-Isarvorstadt, 3.Maxvorstadt, 4.Schwabing-West, 5.Au-Haidhausen, 6.Sendling, 7.Sendling-Westpark, 8. Schwanthalerhöhe, 9.Neuhausen-Nymphenburg, 10.Moosach, 11.Milbertshofen-Am Hart, 12.Schwabing-Freimann, 13.Bogenhausen, 14.Berg am Laim, 15.Trudering-Riem, 16.Ramersdorf-Perlach, 17.Obergiesing-Fasangarten, 18.Untergiesing-Harlaching, 19.Thalkirchen-Obersendling-Forstenried-Fürstenried-Solln, 20.Hadern, 21.Pasing-Obermenzing, 22.Aubing-Lochhausen-Langwied, 23.Allach-Untermenzing, 24.Feldmoching-Hasenbergl, 25.Laim. NA not available.*

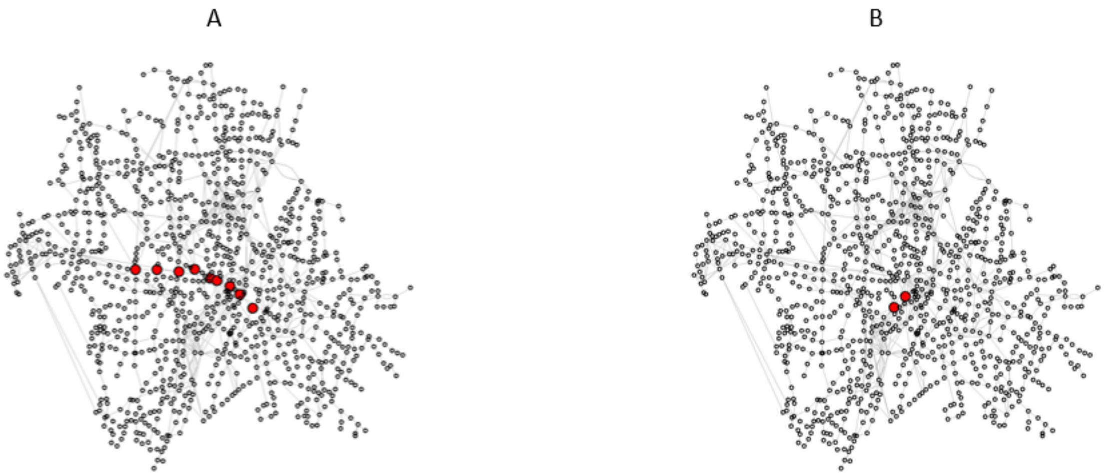

Figure 5.12. Munich – Scenarios

Note: Scenario 1 (A), Scenario 2 (B). In red stops impacted by disruptions.

The changes in network connectivity are shown in Table 5.3. To give an insight into the impact of the bike-sharing network on connectivity, the change in GE and WGE was divided into two columns. The first (without bikes) represents the change in the global efficiency of the network relative to the baseline, and the second (without bikes) represents the change in the global efficiency of the network relative to a hypothetical situation in which no urban bike-sharing service is offered.

The table shows that the removal of the city's main train service (Scenario 1) alone results in a decrease in GE of 1.76% and in WGE of 1.83% from the baseline. By focusing on the weighted efficiency WGE, it can be noted that the relative loss of efficiency is higher with respect to the unweighted case, indicating that the importance of the main train service is accentuated when flows are considered, because many users use it as part of their chosen path.

This loss would be significantly greater if the bike-sharing service was not present on site (–2.85% and –3.04%, respectively). Therefore, it can be concluded that the presence of the bike-sharing service contributes to an increase in the resilience of the transportation network, reducing the relative loss in efficiency after this kind of disruptions by about 40%. Similar results are found in Scenario 2, where Sendlinger Tor and Goetheplatz stations are closed for U3 and U6 services. In this case, the resilience effect of the bike-sharing service is even stronger, with a relative loss of efficiency which is only 26–27% of the one related to the no-bike-sharing case.

Table 5.4 shows the impact of the scenarios on the TTBR. The most interesting scenarios are 1 and 2, as eight out of the ten most important stops in terms of betweenness centrality are removed from the network. In this case, the stops that replace them in the ranking of the ten most important stops become Odeonsplatz, Heimeranplatz, Max-Weber-Platz, Lehel, Harras, Pasing, Schwanthalerhöhe, and Theresienwiese. Hauptbahnhof (S, U, Bus, Tram) remains the most central stop in all scenarios.

Figure 5.13 shows the changes in terms of accessibility rank. The areas that lose positions in the accessibility ranking following a disruptive event are identified in red, those that gain are in green, and those that remain stable are in white. In Scenario 1 (Figure 5.13A), it can be noted that the closure of the main railway line results in a greater loss of accessibility in the areas immediately to the South of it, compared to those immediately to the North. In Scenario 2, which contemplates the same disruption in the case where the bike-sharing service is not available, there is an increased negative impact in terms of accessibility also on the areas to the East and West of the line where the event occurs. This situation is almost identical to Scenario 4, where the Sendlinger Tor and Goetheplatz stops for U3 and U6 services are excluded from the PTN, in the absence of a bike-sharing service. In Scenario 3, where such a service is present, no change in the accessibility rank is observed.

Table 5.3. Munich - Global Efficiency Change (GEC) and Weighted Global Efficiency Change (WGEC) from the baseline scenario

SCENARIO	GEC W/ BIKES %	GEC W/O BIKES %	DIFF %	WGEC W/ BIKES %	DIFF W/O BIKES %	CHANGE %
Scenarios 1/2: Stammstrecke is closed[21]	–1.71	–2.85	1.14	–1.83	–3.04	1.21
Scenarios 3/4: Sendlinger Tor and Goetheplatz stations closed for U3 and U6 services[22]	–0.53	–2.04	1.51	–0.55	–2.07	1.52

[21] The train stops Rosenheimerplatz, Isartor, Marienplatz, Karsplatz (Stachus), Hauptbahnhof, Hackerbrücke, Donnersbergerbrücke, Laim, Hirschgarten are removed).

[22] The two metro stops are removed.

Table 5.4. Munich - Changes in the betweenness rank

	TTBR - BASELINE	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
1	Hauptbahnhof (S, U, Bus, Tram)	-	-	-	-
2	Laim	OUT	OUT	−2	−2
3	Donnersbergerbrücke	OUT	OUT	+1	-
4	Ostbahnhof	+2	+2	−1	−1
5	Marienplatz	OUT	OUT	−2	−2
6	Hirschgarten	OUT	OUT	-	-
7	Karlsplatz (Stachus)	OUT	OUT	+4	+5
8	Isartor	OUT	OUT	-	-
9	Rosenheimer Platz	OUT	OUT	−1	−1
10	Hackerbrücke	OUT	OUT	+1	+1
	INCLUDED (TOP 10)	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
(3)		Odeonsplatz	Odeonsplatz		
(4)		Heimeranplatz	Heimeranplatz		
(5)		Max-Weber-Platz	Max-Weber-Platz		
(6)		Lehel	Lehel		
(7)		Harras	Schwanthalerhöhe		
(8)		Pasing	Theresienwiese		
(9)		Schwanthalerhöhe	Harras		
(10)		Theresienwiese	Pasing		

Note: OUT means that the stop goes out from the top 10. In parenthesis the position in the new top 10 rank.

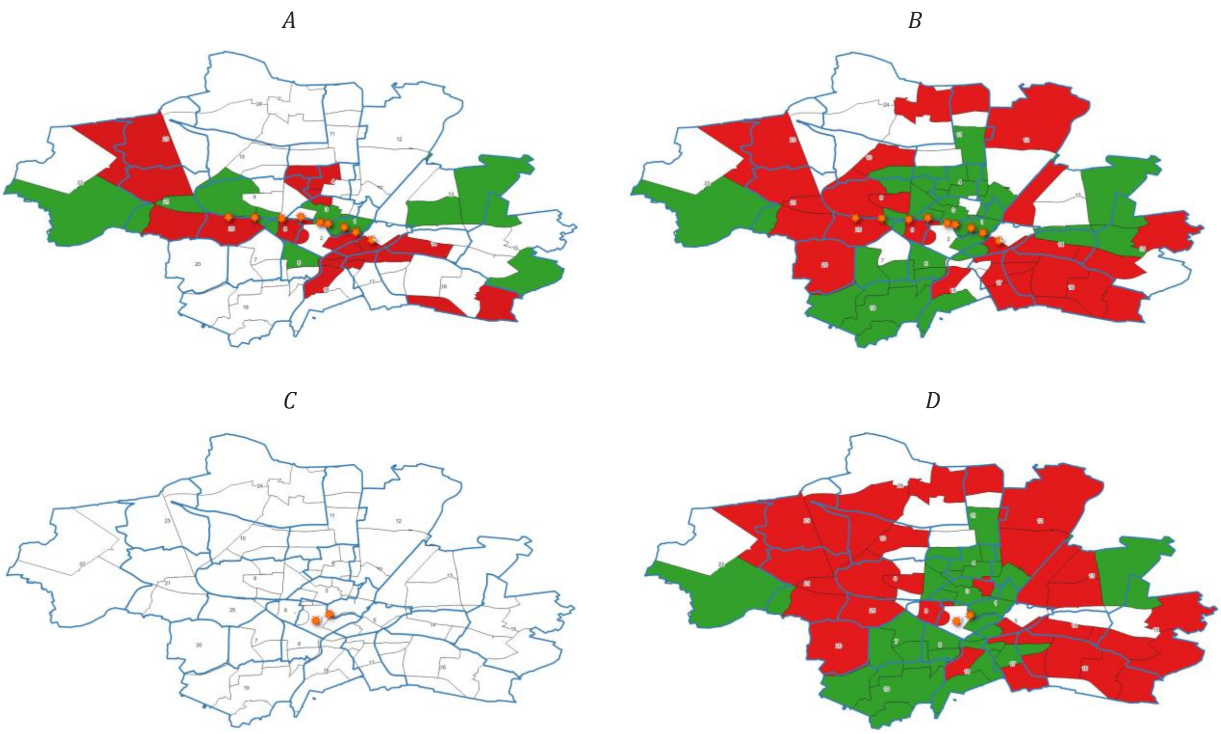

Figure 5.13. Munich – Change in accessibility rank

Note. In green (red), TAZs gaining (losing) positions. In white, TAZs remaining in the same position. (A) Scenario 1 with bikes; (B) Scenario 1 without bikes; (C) Scenario 2 with bikes; (D) Scenario 2 without bikes. In orange, the removed stops.

5.4.6. Conclusions

The analysis conducted allows us to make some evaluations on:

1. How robust is the PTN to the occurrence of disruptive events?
2. How does accessibility change after disruptive events on the PTN?
3. What is the potential impact of the bike-sharing service on network robustness?
4. Which PTN stops are most suitable for the implementation of new bike-sharing stations, when the goal is to improve network robustness?

Our simulations show how the interruption of a relevant rail station (Stammstrecke) could cause a loss of network efficiency. However, the moderate extent of this loss, can be interpreted as a sign that the PTN is robust.

It is worthy to note that the presence of bike-sharing stations could allow to better absorb the impacts of the disruptions, by providing users with additional alternatives to reach their destinations and leading to a much more contained reduction in efficiency.

To make the system more efficient, the addition of further bike-sharing stations may be considered. The analysis performed can suggest locations where the introduction of additional ones could be more effective. The addition of bike-sharing stations could be permanent or temporary; in the latter case, stakeholders may plan, for example, the displacement of bikes from other docks in the city or from an emergency reserve, immediately after the disruption.

As shown by the betweenness analysis (Table 5.4), when some nodes of the network face a disruption, the importance of other nodes changes, that is, new stops gain in importance. This is the case, for example, of Scenarios 1 and 2, where new stops gain in terms of betweenness centrality (Odeonsplatz, Heimeranplatz, Max-Weber-Platz and others). This means that, in such disruption scenarios, users redistribute and choose paths traversing new nodes, where, as a consequence, public transport loads increase. In this sense, it should be meaningful to add bike-sharing stations in these locations, that is, in the proximity of stops acquiring a higher betweenness centrality.

The impact of a disruptive event on the PTN can spill over to the accessibility of areas through the variation of travel times needed to move from one area to another. Also in this case, it is possible to provide indications on where to implement new bike-sharing stations. For instance, it might be useful to do so in those areas that, following the disruptive event, would predict a greater loss of positions in the accessibility ranking. In the case of the interruption of an important train service (Stammstrecke) as in Scenario 1, our analysis would suggest enhancing the bike-sharing service in the areas immediately South of the railway line (Figure 5.13).

5.4. The Metropolitan Region Rotterdam-The Hague (MRDH)

5.4.1. City Context

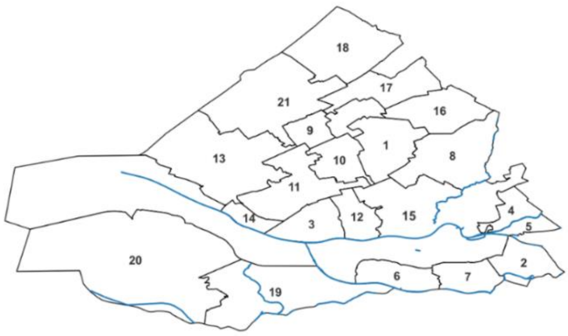

Figure 5.14. MRDH borders and districts

Source: OpenStreetMap 2023.

In the SmartHubs project, we study the MRDH PTN with the aim of providing insights into the resilience of the network. The application of the SHRT to the MRDH is related to the SmartHubs living lab located near Zuidplein, a busy metro and bus station in Rotterdam and Hobbemaplein in The Hague.

The MRDH is a partnership between 21 municipalities in the Netherlands. It is a relevant geographical aggregation of nearly 2.4 million people, with 1.3 million jobs and 13.5% of the Dutch population working there. Together, they generate 15% of the GNP[23]. Figure 5.14 shows the extremes of this region and the cities that compose it.

***Legend**: 1.Pijnacker-Nootdorp, 2.Ridderkerk, 3.Vlaardingen, 4.Capelle aan den IJssel, 5.Krimpen aan den IJssel, 6.Albrandswaard, 7.Barendrecht, 8.Lansingerland, 9.Rijswijk, 10.Delft, 11.Midden-Delfland, 12.Schiedam, 13.Westland, 14.Maassluis, 15.Rotterdam, 16.Zoetermeer, 17.Leidschendam-Voorburg, 18.Wassenaar, 19.Nissewaard, 20.Voorne aan Zee, 21.Den Haag.*

In The Hague, the public transport system is composed of bus and tram lines mainly provided by Haagsche Tramweg-Maatschappij (HTM). In Rotterdam, PTN is composed by bus, tram, and metro. It is operated by Rotterdamse Elektrische Tram (RET). The two cities are connected both by the public transport lines of the two operators and by the train service operated by Nederlandse Spoorwegen (NS)[24].

The MRDH is equipped with a bike-sharing system, facilitated by OV-fiets. This system is strategically distributed through numerous bike stations situated at various train stations.[25]Donkey Republic is another main bike-sharing operator in Rotterdam and in The Hague, where it operates by means of a hybrid model. This means that while they do have designated drop-off locations, you can also leave the bike anywhere in specific areas or in virtual drop zones. In The Hague, the service is mainly provided by Donkey Republic, for which data are not available. In the continuation of the analysis, we will exclusively consider the bike-sharing stations belonging to this operator in Rotterdam. The reason for this choice is that we do not possess the same data for The Hague, nor the data of the OV-fiets service. This represents a limitation of our analysis.

5.4.2. Generation of the Joint Public Transport and Bike-sharing Network

In order to assess the resilience of the urban PTN, integrated with the bike-sharing service, we generate a joint public transport and bike-sharing network based on the GTFS data from the *transitfeeds* web site[26] and bike-sharing station location data.[27]

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[23] https://mrdh.nl/power-partnership. Visited November 24, 2023.

[24] There are even more smaller bus providers connecting the cities and the other municipalities, which we do not take into account in this analysis.

[25] https://ovfietsbeschikbaar.nl/locaties. The MRDH had also the HTM Fiets station-based bike-sharing system provided by HTM; starting February 1st 2023, HTM Fiets is only available in Zoetermeer https://www.htm.nl/en/about-us/our-transport/htm-bike. Visited November 24, 2023.

[26] https://transitfeeds.com/. Retrieved on October 08, 2023.

[27] Provided by project partners from https://dashboarddeelmobiliteit.nl. Retrieved on September, 2023.

Figure 5.15A shows the PTN service between 7.00 am and 8.00 am of a random workday (2023/09/18), delimited by the area's borders. Each mode is indicated by a different colour: blue, light red, green, and dark red links represent routes of the bus, metro, train, and tram networks, respectively. In Figure 5.15B, the thickness of the orange lines represents the frequency of service between two stops during the selected period. Figure 5.15C shows the locations of the 577 bike stations within the considered borders. In order to measure the connectivity of the entire PTN, the SMNs have been merged, as described in Section 4.3. Figure 5.15D shows the percentage of aggregations concerning different modes: around 1% of aggregate nodes are served by all the four modes, around 3% of them by three modes, around 21% of them by two modes and the remaining fraction (75%) by only one mode. Figure 5.15E shows the PTN network after the aggregation process[28]. Once the joint PTN has been generated, it has been supplemented by the bike-sharing network (see Section 4.4). The result of the integration between the joint PTN and the modelled bike-sharing network is the aggregate public transport network integrated with bike sharing (APTNB) shown in Figure 5.15F. The large number of bike-sharing stations implies that they are relatively close to each other. This has resulted in the inclusion of numerous edges (shorter than 3km) within the aggregated PTN.

For the case study of MRDH demand data were made available from project members.[29] The OD takes into account access-egress transportation to the PT stop, using a possible combination of walking and/or bike. Results from the assignment are shown in Figure 5.16, where colors are scaled depending on the passenger load on each link, with dark red referring to highest values and green ones to the lowest values.

5.4.3. Network Connectivity and Node Centrality

To provide some insights into urban resilience, under the perspective on PTN connectivity, we calculate the Global Efficiency (GE) and the Weighted Global Efficiency (WGE) for the ATPNB in MRDH. We found that GE = 0.0285 and WGE = 0,0307.

The ten most important nodes, in terms of betweenness centrality (TTBR), are: Rotterdam Centraal, Delft Station, Den Haag-Station Moerwijk, Schiedam-Station, Schiedam Centrum, Rijswijk, Rotterdam-Station Lombardijen, Den Haag-Melis Stokelaan, Rotterdam-Station Blaak, Rotterdam - Blijdorp, Rotterdam-Melanchthonwe (Figure 5.17).

Among them, Rotterdam Centraal is the main railway station of the city of Rotterdam. Delft Centrum station is centrally located between The Hague and Rotterdam. Schiedam Centrum is a railway and metro station in Schiedam, just to the West of Rotterdam, on the railway line between The Hague and Rotterdam Centraal.

5.4.4. Area Accessibility

To shed some light on resilience under the perspective of local accessibility, Figure 5.18 shows a map of the urban accessibility of MRDH. The scale of values goes from dark blue (municipalities with high accessibility) to white (cities with low accessibility). The figure suggests that The Hague and Rotterdam are among the most accessible of the Region.

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[28] Almost all the aggregated stops fall at a distance from the geometric centroid of the stops identified by the same name below than 300 mt. Almost 80% of the aggregated stops represent the aggregation of at least four individual stops with the same name.

[29] OD data are the result of the traffic demand model of the MRDH region, called V-MRDH 2.0. We refer here to its technical description: https://mrdh.nl/sites/default/files/documents/rapport_verkeersmodel_mrdh_2.0_-_001594.20181026.r1.02.pdf.

The GE, WGE, TTBR and the AAR will be used as a baseline to compare the effect of the scenarios presented in the next subsection on PTN connectivity.

Figure 5.15. MRHD – APTNB generation

Note. SMNs Detailed (A), SMNs frequency (B). Time period: 7am – 8am of a random weekday. Bike-sharing stops locations (C). Percentage of aggregating stop per number of modes (D). PTN network after the aggregation procedure (E). APTB - Aggregated PTN integrated with Bike-sharing (F)

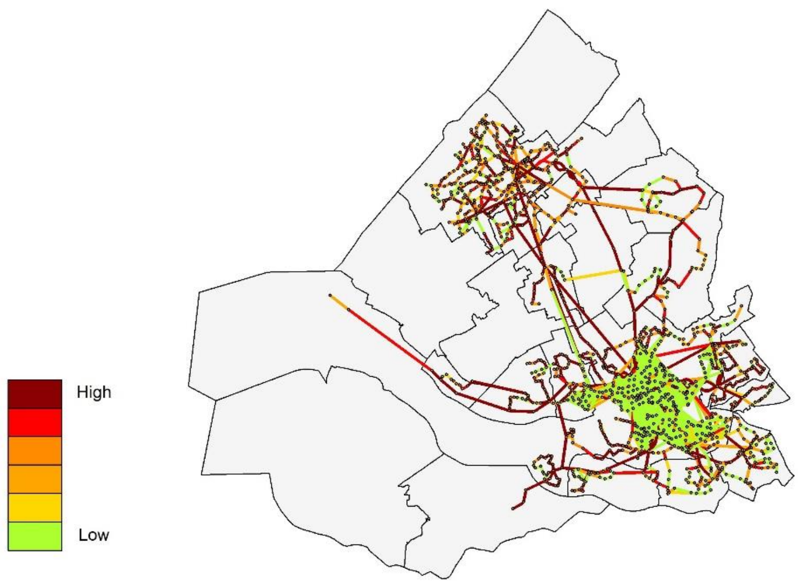

Figure 5.16. MRDH – Demand assignment

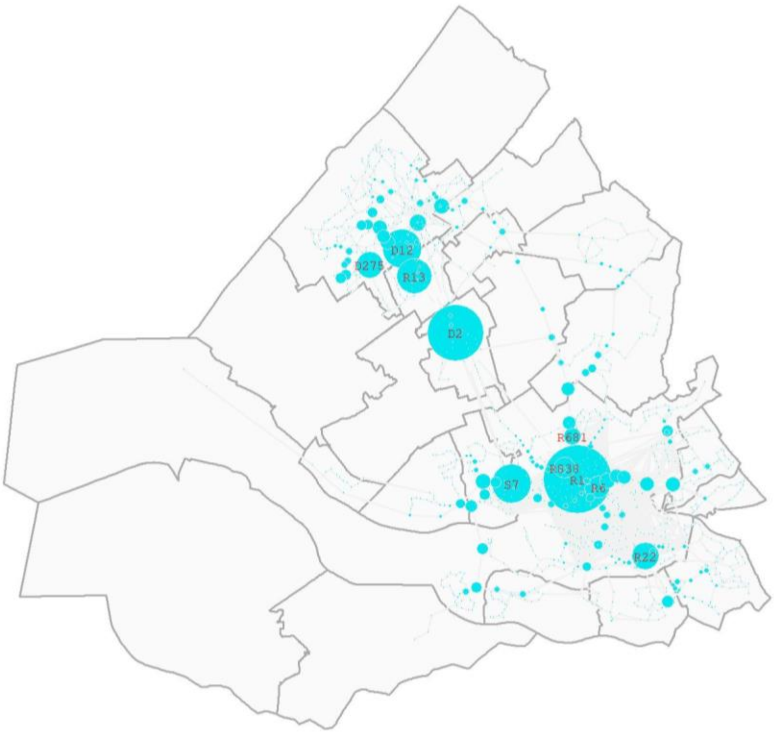

Figure 5.17. MRHD – APTNB Betweenness Centrality

Note: In red the 10 most central nodes. Legend: D275 = Den Haag, Melis Stokelaan, D12 = Den Haag, Station Moerwijk, R13 = Rijswijk, D2 = Delft Station, R681 = Rotterdam, Melanchthonweg, S7 = Station Schiedam Centrum, R838 = Rotterdam, Blijdorp, R1 = Rotterdam Centraal, R6 = Rotterdam, Station Blaak, R22 = Rotterdam, Station Lombardijen

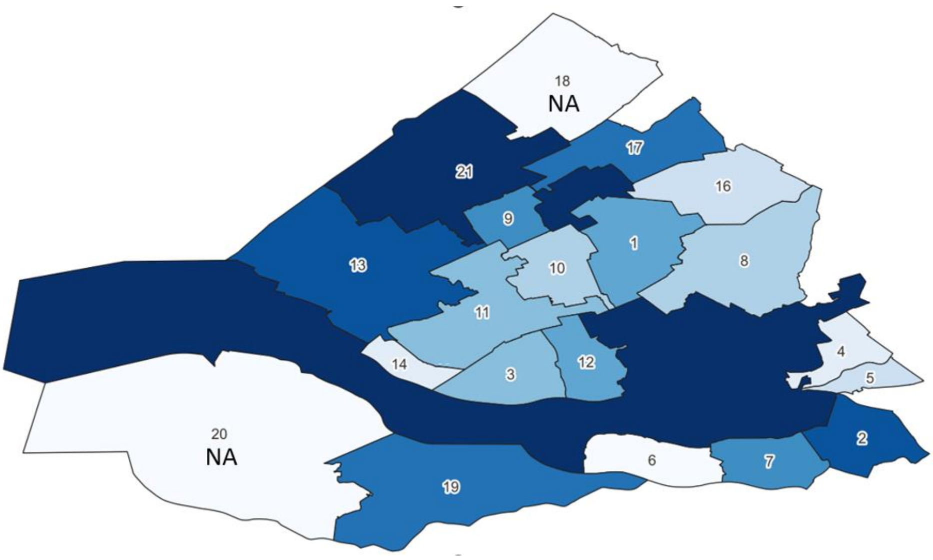

Figure 5.18. MRHD – Area Accessibility

Note: Colour scale from dark blue (more accessible) to white (less accessible).

***Legend**: 1.Pijnacker-Nootdorp, 2.Ridderkerk, 3.Vlaardingen, 4.Capelle aan den IJssel, 5.Krimpen aan den IJssel, 6.Albrandswaard, 7.Barendrecht, 8.Lansingerland, 9.Rijswijk, 10.Delft, 11.Midden-Delfland, 12.Schiedam, 13.Westland, 14.Maassluis, 15.Rotterdam, 16.Zoetermeer, 17.Leidschendam-Voorburg,*

5.4.5. Scenarios

Since our goal is to identify changes in network connectivity and area accessibility as a result of disruptions to the PTN (scenarios), what we are interested in is the change in the considered metrics, rather than their values. In other terms, our focus is on the percentage change in the GE, WGE, TTBR, and AAR with regard to the *status quo.*

On the APTNB of MRDH, the following scenarios have been simulated:

– **Scenario 1:** The Hague Central station is closed due to a bomb threat;
– **Scenario 2:** There is no metro traffic possible between Leuvehaven and Wilhelminaplein due to floodings of the metro tunnel;
– **Scenario 3:** There is no train traffic possible between Schiedam Centrum and Rijswijk due to an accident;
– **Scenario 4:** Shared bike stations are added to ten PTN stops in The Hague;[30]
– **Scenario 5:** Due to a nationwide disruption, renting bike-sharing in Rotterdam is not available.

In Scenario 1, all the transport stops at The Hague Central station are removed. It is a very extensive event, involving one major and most central stops within the network. In Scenario 2, the metro stops Rotterdam-Leuvehaven and Rotterdam–Wilhelminaplein are removed. In Scenario 3, the train nodes Rijswijk, Delft, Delft Campus, and Schiedam Centrum are removed. Scenarios 4 and 5 show the impact of the bike-sharing network on urban resilience. In the first case adding ten new bike-sharing stations. in the second case eliminating this network entirely. It should be noted that, given the lack of data for The Hague's bike-sharing service, we are hypothesizing that there are no Donkey Republic bike-sharing stations at the listed stops. In other words, the simulation is hypothetical and serves exclusively to demonstrate the variations in terms of PTN efficiency introduced by the addition of bike-sharing stations. The different scenarios are depicted in Figure 5.19.

The changes in global efficiency are shown in Tables 5.5. To provide an insight into the impact of the bike-sharing service on connectivity, the changes in GE and WGE are presented.

The table shows that the removal of the city's main PTN station in The Hague (Scenario 1) alone results in a decrease in GE of 1.25% and in WGE of 1.47% from the baseline.

When there is no metro traffic possible between Leuvehaven and Wilhelminaplein (Scenario 2), the efficiency loss is at 0.44 (unweighted) and 0.46 (weighted). When there is no train traffic possible between Schiedam Centrum and Rijswijk (Scenario 3), the efficiency loss is 5.58 (unweighted) and 3.95 (weighted), therefore significantly higher with respect to the other scenarios.

Finally, adding bike stations in selected PTN stops in The Hague (Scenario 4) increases the GE of 0.39% and WGE of 0.36%, while removing the bike-sharing service (Scenario 5) causes a loss in GE of 20.40% and WGE of 23.55%.

[30] Moerweg, Centraal Station (bus, metro, tram and train), Gravenstraat, , Brouwersgracht, Weteringplein, Laan v. NOI, Suyvesantplein, , Kunstmuseum, , Zwarte Pad, , Leidschenveen.

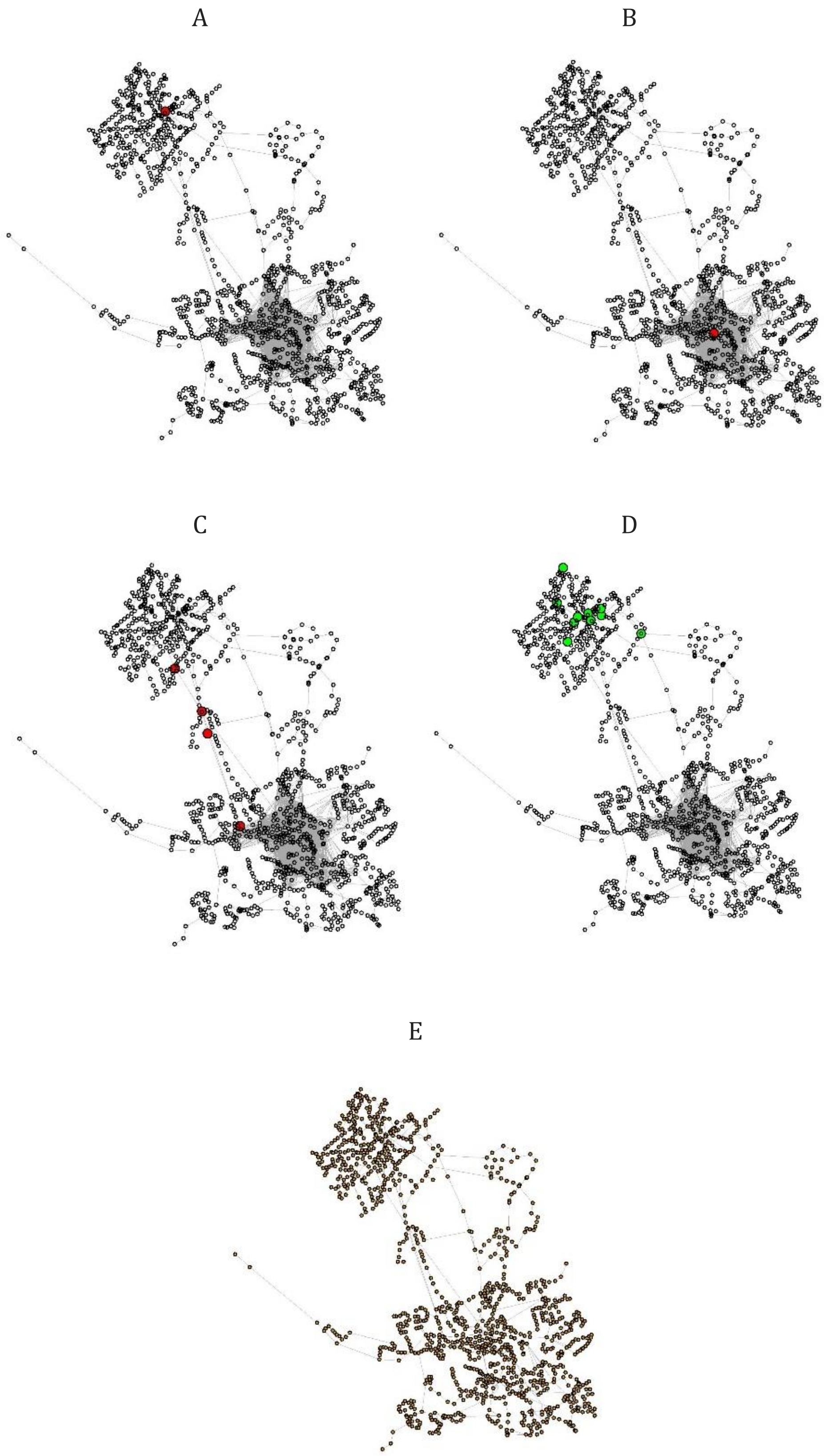

Figure 5.19. MRDH – Scenarios

Note. Scenario 1 (A), 2 (B), 3 (C), 4 (D), 5 (E). The red nodes are those removed from the network., the green nodes are stops equipped with a new bike station.

Table 5.5. MRDH - Global Efficiency Change (GEC) and Weighted Global Efficiency Change (WGEC) from the baseline scenario

SCENARIO	GEC (%)	WGEC (%)
1. The Hague Central station is closed due to a bomb threat. (all the stops are removed)	−1.25	−1.47
2.There is no metro traffic possible between Leuvehaven and Wilhelminaplein due to floodings of the metro tunnel (the metro stops are removed)	−0.44	−0.46
3. There is no train traffic possible between Schiedam Centrum and Rijswijk due to an accident (the train stops are removed)	−5.58	−3.95
4. Shared bike stations are added to the following locations in The Hague	+0.39	+0.36
5. Due to a nationwide disruption, renting bike sharing is not possible	−20.40	−23.55

Table 5.6 shows the impact of the scenarios on TTBR. The most interesting scenarios is the Scenario 3 in which there is no train traffic possible between Schiedam Centrum and Rijswijk due to an accident. In this case, the ranking of the top ten stops with the highest betweenness centrality has almost completely varied. The stops that become more important, following this scenario, turn out to be: Berkel en Rodenrijs, Rodenrijs; Rotterdam, Meijersplein / Airport; Pijnacker, Pijnacker Zuid; Den Haag, Leidschenveen; Berkel en Rodenrijs, Berkel Westpolder; Pijnacker, Pijnacker Centrum; Nootdorp, Nootdorp; and Voorburg, Voorburg 't Loo.

Figure 5.20 shows variations in terms of accessibility rank. The areas that lose positions in the accessibility ranking following the disruptive event are identified in red, those that gain are in green, and those that remain stable are in white. In Scenario 1 of Figure 5.20A, it is noted that the closure of the main PT station in The Hague results in a greater loss of accessibility in Rotterdam, since the two cities are strictly linked. In Scenario 2, the unavailability of Leuvehaven and Wilhelminaplein does not seem to affect the region accessibility as in the Scenario 4, when some bike-sharing stations are added in The Hague. On the contrary, when there is no train traffic possible between Schiedam Centrum and Rijswijk, the area around Rotterdam lose position in accessibility with respect the area around The Hague. The opposite happens in the Scenario 5, when renting bike sharing is not possible.

5.4.6. Conclusions

The analysis conducted allows us to make some evaluations on:

1. How robust is the PTN to the occurrence of disruptive events?
2. How does accessibility change after disruptive events on the PTN?
3. What is the potential impact of the bike sharing service on network robustness?
4. Which PTN stops are most suitable for the implementation of new bike-sharing stations, when the goal is to improve network robustness?

It should be noted that in the case of MRDH, the analysis conducted is limited by the fact that we were in possession of bike-sharing data exclusively for the city of Rotterdam.

Table 5.6. MRDH - Change in the betweenness rank

	TTBR - BASELINE	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
1	Rotterdam, Rotterdam Centraal	-	-	OUT	-	-
2	Delft, Delft Station	-	-	OUT	-	-
3	Schiedam, Station Schiedam Centrum	+1	-	OUT	-	+1
4	Den Haag, Station Moerwijk	−1	-	OUT	-	−1
5	Rijswijk	-	-	OUT	-	-
6	Rotterdam, Station Lombardijen	+1	-	OUT	-	-
7	Den Haag, Melis Stokelaan	−1	-	OUT	-	-
8	Rotterdam, Station Blaak	-	-	OUT	-	-
9	Rotterdam, Blijdorp	-	-	+5	-	-
10	Rotterdam, Melanchthonweg	-	-	+10	-	OUT
	INCLUDED (TOP 10)	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
(1)						
(2)				Berkel en Rodenrijs, Rodenrijs		
(3)				Rotterdam, Meijersplein / Airport		
(4)						
(5)				Pijnacker, Pijnacker Zuid		
(6)				Den Haag, Leidschenveen		
(7)				Berkel en Rodenrijs, Berkel Westpolder		
(8)				Pijnacker, Pijnacker Centrum		
(9)				Nootdorp, Nootdorp		
(10)				Voorburg, Voorburg 't Loo		Rotterdam, Oostplein

Note: OUT (IN) means that the stop goes out from (goes into) the top 10. In parenthesis the position in the new top 10 rank.

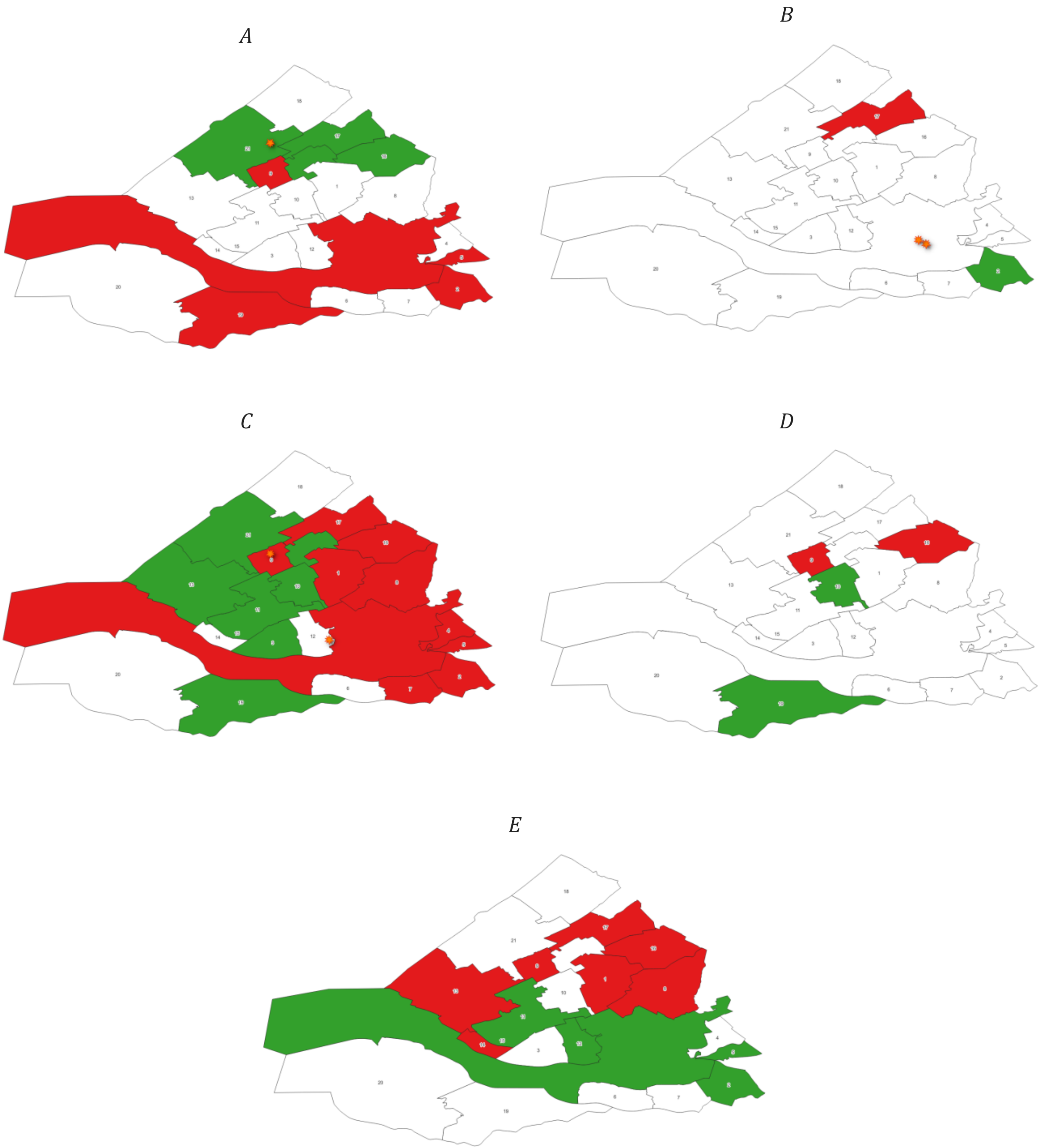

Figure 5.20. MRDH – Change in accessibility rank

Note. In green (red), cities gaining (losing) positions. In white, TAZs remaining in the same position. (A) Scenario 1; (B) Scenario 2; (C) Scenario 3; (D) Scenario 4; (E) Scenario 5. In orange, the removed stops.

***Legend**: 1.Pijnacker-Nootdorp, 2.Ridderkerk, 3.Vlaardingen, 4.Capelle aan den IJssel, 5.Krimpen aan den IJssel, 6.Albrandswaard, 7.Barendrecht, 8.Lansingerland, 9.Rijswijk, 10.Delft, 11.Midden-Delfland, 12.Schiedam, 13.Westland, 14.Maassluis, 15.Rotterdam, 16.Zoetermeer, 17.Leidschendam-Voorburg, 18.Wassenaar, 19.Nissewaard, 20.Voorne aan Zee, 21.Den Haag.*

Our simulations show how a disruption to a relevant station (Hague Central) could cause a loss of network efficiency. However, the moderate extent of this loss can be interpreted as a sign that the PTN is robust (and vast). The same conclusion applies when there is no metro traffic possible between

Leuvehaven and Wilhelminaplein. On the other hand, when there is no train traffic possible between Schiedam Centrum and Rijswijk, the loss in global efficiency seems to be more relevant.

The presence of the bike-sharing service in city seems to increase efficiency significantly with respect to a scenario when the same service does not exist (approximately +20%).

As shown in the betweenness analysis (Table 5.6), when some nodes of the network face a disruption, the importance of other nodes changes. new stops gain importance. This is the case, for example, in Scenario 3 (no metro between Schiedam Centrum and Rijswijk), where new stops gain importance in terms of betweenness centrality (Berkel en Rodenrijs, Rodenrijs, Rotterdam, Meijersplein / Airport and others). This means that, in such disruption scenarios, users redistribute and choose paths traversing new nodes, where, as a consequence, public transport loads increase. In this sense, it should be meaningful to add bike-sharing stations in these locations, i.e., in the proximity of stops acquiring a higher betweenness centrality.

The impact of a disruptive event on the PTN can spill over into the accessibility of areas through the variation of travel times needed to move from one area to another. Also in this case, it is possible to provide indications on where to implement new bike-sharing stations. For instance, it might be useful to do so in those areas that, following the disruptive event, would predict a greater loss of positions in an accessibility rank (Figure 5.20).

5.5. Vienna

5.5.1. City Context

In the SmartHubs project, we study the Vienna urban PTN with the aim of providing insights into the resilience of the network. The application of the SHRT to the city of Vienna is related to the SmartHubs living lab located near the station Bruno-Marek-Allee and Mobility station Maria-Tusch Straße.[31]

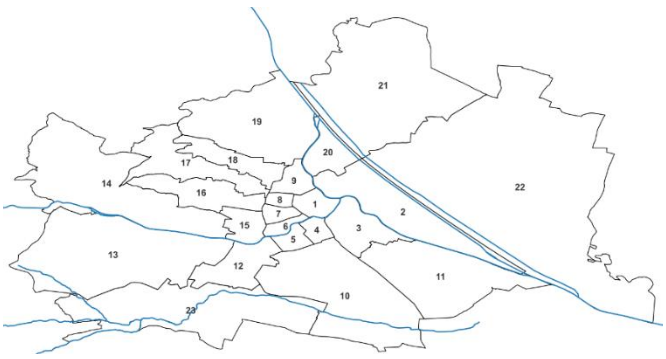

Figure 5.21. Vienna – Borders and districts

***Legend**: 1.InnereStadt, 2.Leopoldstadt, 3.Landstraße, 4.Wieden, 5.Margareten, 6.Mariahilf, 7.Neubau, 8.Josefstadt, 9.Alsergrund, 10.Favoriten, 11.Simmering, 12.Meidling, 13.Hietzing, 14.Penzing, 15.Rudolfsheim-zünfhaus, 16.Ottakring, 17.Hernals, 18.Währing, 19. Döbling, 20.Brigittenau, 21.Floridsdorf, 22.Donaustadt, 23.Liesing.*

Vienna, the capital of Austria, is divided into 23 districts. It is crossed by the Danube River, which flows from North-West to South-East (Figure 5.21).

In the broad area of Vienna (41,487.00 hectares), according to the official web site, live 1,982,097 residents at January the 1st 2023.[32] The population density between the districts is heterogeneous, ranging from districts with a high population density (districts in the city centre) to districts with a low population density (peripherical districts).

Vienna offers an extensive and widespread PTN consisting of trains (provided by OEBB Personenverkehr AG Kundenservice), metros, buses, and trams (provided by WLB and Wiener Linien).
In the city are also present over 1,600 km of bike paths and a bike-sharing stations-based service known as WienMobil Rad, available in all 23 Viennese districts.

5.5.2. Generation of the Joint Public Transport and Bike-Sharing Network

In order to assess the resilience of the urban PTN, integrated with the bike-sharing service, we generate a joint public transport and bike-sharing network based on the GTFS data from *City of Vienna*[33] and bike-sharing station location data.[34]
Figure 5.22A shows the PTN service between 7.00 am and 8.00 am of a random workday (2023/09/18), delimited by the area's borders. Each mode is indicated by a different colour: blue, light red, green, and dark red links represent routes of the bus, metro, train, and tram networks, respectively. In Figure 5.22B, the thickness of the orange lines represents the frequency of service between two stops during the selected period. Figure 5.22C shows the locations of the 239 bike stations within the considered borders. In order to measure the connectivity of the entire PTN, the SMNs have been merged, as described in Section 4.3. Figure 5.22D shows the percentage of aggregations concerning different modes: around 1% of aggregate nodes are served by all the three modes, around 7% of them by three modes, around 20% of them by two modes and the remaining

[31] https://www.smartmobilityhubs.eu/_files/ugd/c54b12_1db2eb060edd48a188761d5c64edb079.pdf.
[32] https://www.wien.gv.at.
[33] https://data.wien.gv.at. Retrieved on June, 2023.
[34] https://gladys.geog.ucl.ac.uk/bikesapi/load.php?scheme=vienna.

fraction (72%) by only one mode. Figure 5.22E shows the PTN network after the aggregation process.[35] Once the joint PTN has been generated, it has been supplemented by the bike-sharing network (see Section 4.4). The result of the integration between the joint PTN and the modelled bike-sharing network is the aggregate public transport network integrated with bike sharing (APTNB) shown in Figure 5.22F. The large number of bike-sharing stations implies that they are relatively close to each other. This has resulted in the inclusion of numerous links (shorter than 3km) within the aggregated PTN.

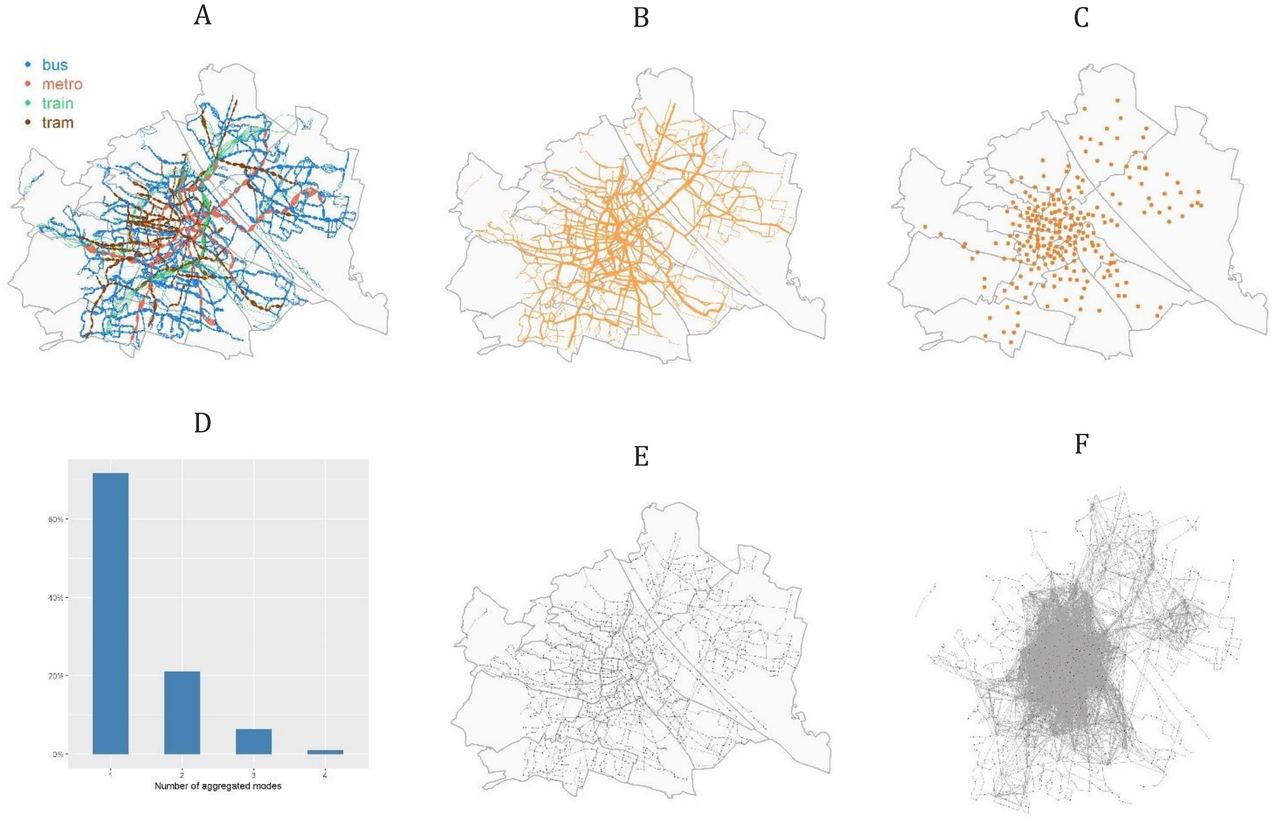

Figure 5.22. Vienna – ATPN generation

Note. SMNs Detailed (A), SMNs frequency (B). Time period: 7am – 8am of a random weekday. Bike-sharing stops locations (C). Percentage of aggregating stop per number of modes (D). PTN network after the aggregation procedure (E). APTB - Aggregated PTN integrated with Bike-sharing (F)

To compute the weighted global network efficiency and the area accessibility indicator, passenger flows are retrieved by means of the assignment procedure described in Section 4.5.

For the case study of Vienna, demand data were made available from project stakeholders. Data refer to travel origins and destinations in the morning peak hour, between 7,00 am and 8.00 am. Results from the assignment are shown in Figure 5.23, where colors are scaled depending on the passenger load on

[35] All the aggregated stops fall at a distance from the geometric centroid of the stops identified by the same name below than 200 mt. Almost 65% of the aggregated stops represent the aggregation of at least four individual stops with the same name.

each link, with dark red refer to highest values and green ones to the lowest values. As can be shown from the image, high loads can be observed on the train line. In the Northern part of the city, some bus lines appear relevantly used, mainly because of the absence of a metro service connecting the Eastern and Western parts of the city.

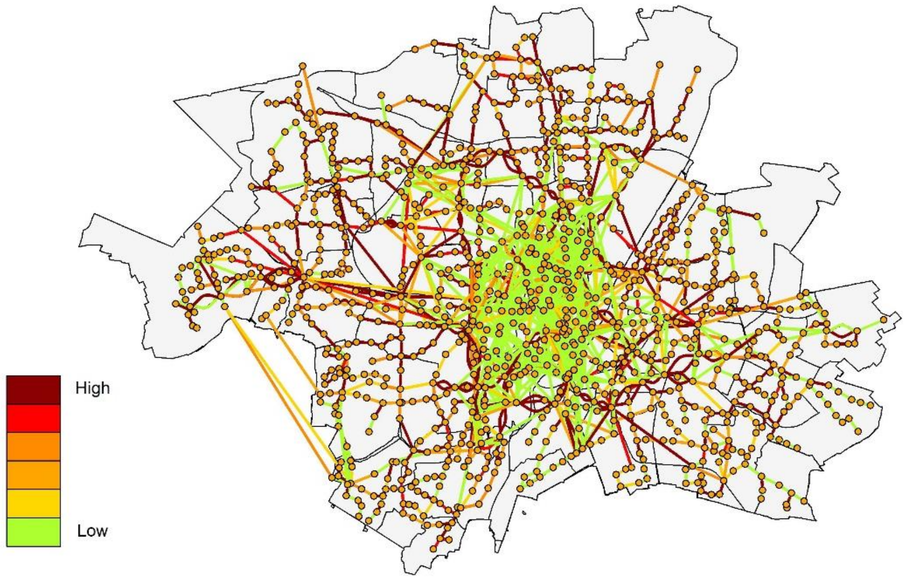

Figure 5.23. Vienna – Demand assignment

5.5.3. Network Connectivity and Node Centrality

To provide some insights to the urban resilience, under the perspective on PTN connectivity, we calculate the Global Efficiency (GE) and the Weighted Global Efficiency (WGE) for the ATPNB in Vienna. We found that GE = 0.0288 and WGE = 0.0379.

The ten most important nodes are, in terms of betweenness centrality (TTBR), are: Praterstern, Meidling, Hauptbahnhof, Matzleinsdorfer Platz, Stadlau, Simmering, Traisengasse, Handelskai, Mitte-Landstraße, Floridsdorf (Figure 5.24).

They are located in the city center and in the area bordering the Danube River (Praterstern, Traisengasse, Handelskai and Stadlau). The latter is a result consistent with the function of betweenness centrality, which is to enhance the centrality of those nodes that act as "bridges" between different parts of the city. These nodes turn out to be very important in Vienna as their removal would result in a high probability of network disconnection, resulting in difficulty of movement between the areas to the North-East and South-West with respect to the river. Note that among the top ten nodes in order of centrality, the first ones incorporate a train station (Praterstern, Meidling, Hauptbahnhof, Matzleinsdorfer Platz, Stadlau).

5.5.4. Area Accessibility

To shed some light on urban resilience under the perspective of local accessibility, Figure 5.25 shows a map of the urban accessibility of Vienna, broken down by district. The scale of values goes from dark blue (districts with high accessibility) to white (districts with low accessibility).

It’s not surprising that the most accessible districts are the central ones with Innere Stadt leading, along with Neubau and Alsergrund. The least accessible ones turn out to be the peripheral Donaustadt and Liesing along with Hernals.

The GE, WGE, TTBR and the AAR will be used as a baseline to compare the effect of the scenarios presented in the next subsection on PTN connectivity.

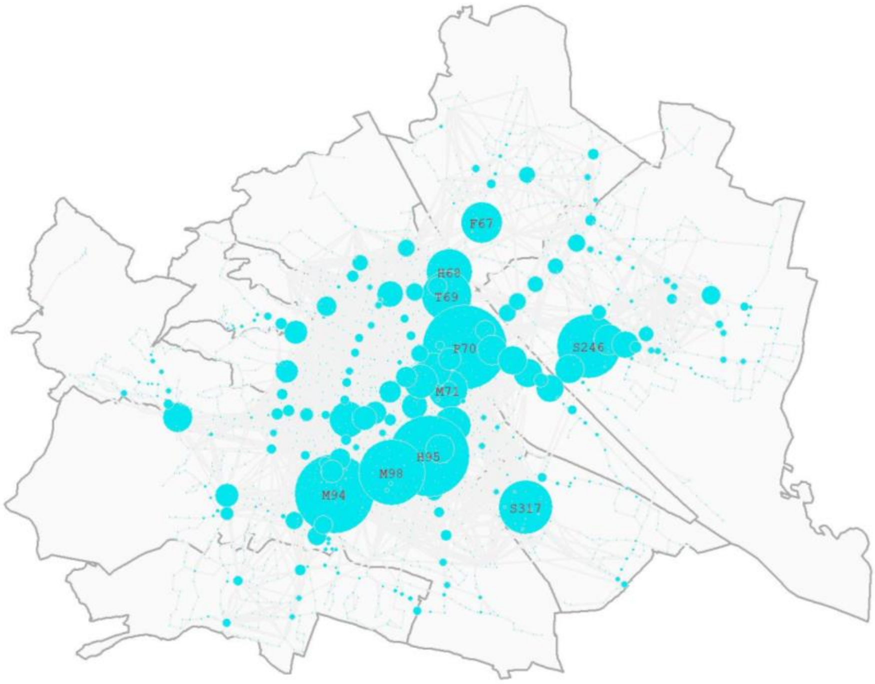

Figure 5.24. Vienna – APTNB Betweenness Centrality

Note: In red the 10 most central nodes

Legend: F67 = Floridsdorf , H68 = Handelskai , T69 = Traisengasse , P70 = Praterstern, S246 = Stadlau , M71 = Mitte-Landstraße , H95 = Hauptbahnhof , M98 = Matzleinsdorfer Platz , M94 = Meidling, S317 = Simmering

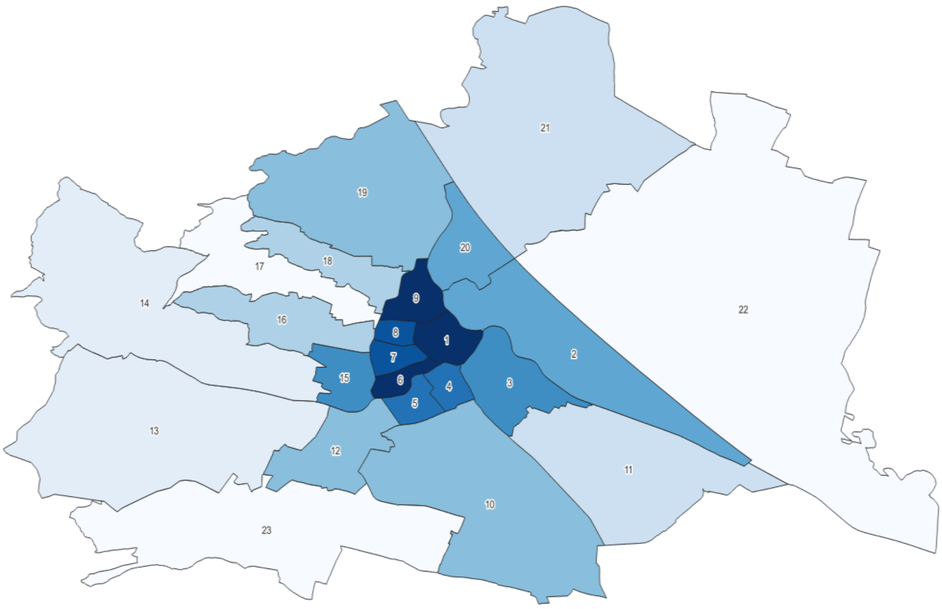

Figure 5.25. Vienna – Area Accessibility

Note: Colour scale from dark blue (more accessible) to white (less accessible).

Legend: 1.InnereStadt, 2.Leopoldstadt, 3.Landstraße, 4.Wieden, 5.Margareten, 6.Mariahilf, 7.Neubau, 8.Josefstadt, 9.Alsergrund, 10.Favoriten, 11.Simmering, 12.Meidling, 13.Hietzing, 14.Penzing, 15.Rudolfsheim-zünfhaus, 16.Ottakring, 17.Hernals, 18.Währing,19. Döbling, 20.Brigittenau, 21.Floridsdorf, 22.Donaustadt, 23.Liesing.

The results of GE, WGE, TTBRand ACC, shown in the present subsection, will be used as a *baseline* to compare the effect of the *senarios* presented in the next subsection.

Since we are interested in how network connectivity and accessibility changes in the different with resepect the *status quo,* rather than in their absolute value, the next paragraph will show the impact of different *scenarios* in terms of indicator changes and change in ranks of node centrality and area accessibility.

5.5.5. Scenarios and Results

Since our goal is to identify changes in network connectivity and area accessibility as a result of disruptions to the PTN (scenarios), what we are interested in is the change in the considered metrics, rather than their values. In other terms, our focus is on the percentage change in the GE, WGE, TTBR, and AAR with regard to the *status quo.*

On the APTNB of Vienna, the following scenarios have been simulated:

– **Scenario 1:** All bike-sharing stations are removed from the network.
The bike-sharing stations are removed from the network:
  - **Scenario 2:** at bus stops (where there is only bus service at a hub)
  - **Scenario 3:** at tram stops (where there is only bus and tram service at a hub)
  - **Scenario 4:** at metro stops (where there are any other public network services)

– **Scenario 5:** Add bike-sharing stations at APTNB in the sub-districts: Flugfeld Aspern, Aspern, and Eßling - Im Neuriß

In Scenarios 1 and 2, the bike-sharing network is disconnected from the APTNB. In the first case, this removal is total. Unlike Scenario 1, which allows the impact of bike-sharing to be studied in a global manner, Scenario 2 allows the impact of removing bike-sharing stations to be studied in a localized manner. In Scenario 2, stations are removed at stops where only the bus mode is present (A), at those where only bus and tram stops are present (B), and at those where all modes of public transportation except train are present (C). Finally, Scenario 3 shows a hypothetical addition of bike-sharing stations at public transport stations in the areas of Flugfeld Aspern, Aspern, and Eßling - Im Neuriß. This allocation was made randomly, considering 20 percent of the total stops in the considered area (Figure 5.26).

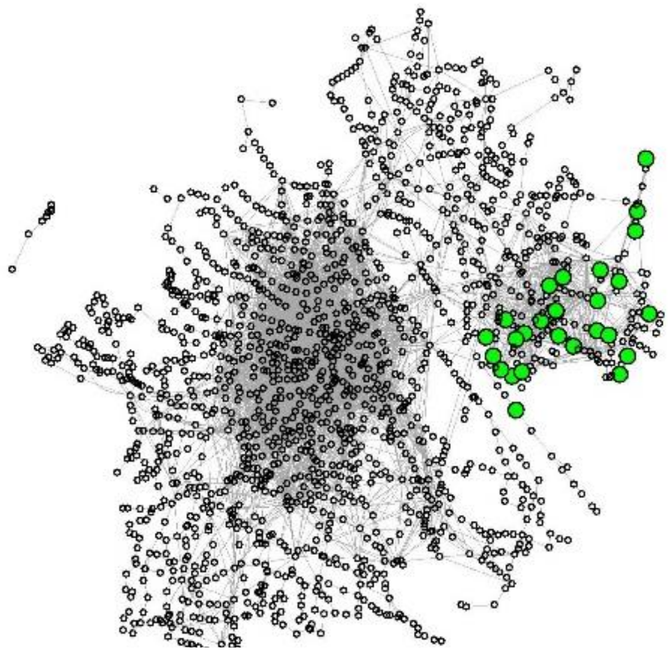

Figure 5.26. Vienna – Scenario 4

Note. The green nodes are stops equipped with a new bike station.

The variation in network efficiency is shown in Table 5.7. To give an insight into the impact of the bike-sharing network on connectivity, the change in GE and WGE.

The table shows that the removal of the city's bike-sharing (Scenario 1) results in a relevant decrease in GE of 25.26% and in WGE of 30.06% from the baseline. Similar results are obtained after Scenarios 2–4. As could be expected, the greater impact on network efficiency appears to be caused by the removal of bike-sharing stations located close to stops where there is only bus service, because of the lack of viable alternatives.

Finally, the impact of an addition of bike-sharing stations at 20 percent of the total stops the areas of Flugfeld Aspern, Aspern, and Eßling - Im Neuriß. Improves the network efficiency by 0.83% (weighted) and 0.63% (unweighted).

Table 5.7. Vienna - Global Efficiency Change (GEC) and Weighted Global Efficiency Change (WGEC)

SCENARIO	GEC (%)	WGEC (%)
1.All bike-sharing stations are removed from the network	−25,26%	−30,05%
2.A. The bike-sharing stations are removed from the network at bus stops (where there is only bus service at a hub)	−23,44%	−27,40%
2.B. The bike-sharing stations are removed from the network at tram stops (where there is only bus and tram service at a hub)	−22,78%	−25,84%
2.C. The bike-sharing stations are removed from the network at metro stops (where there are any other public network services)	−22,40%	−23,56%
3. Add bike-sharing stations at APTNB in the sub-districts: Flugfeld Aspern, Aspern, and Eßling - Im Neuriß	+0,83%	+0,63%

Table 5.8 shows the impact of the scenarios on TTBR. It is observed that the various scenarios do not cause significant variations in the ranking of the top ten stops in order of betweenness centrality. The only observation worthy of note is the entry into the ranking of the Westbahnhof and Stephansplatz stops.

Table 5.8. Vienna – Change in the betweenness rank

	TTBR - BASELINE	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
1	Praterstern	-	-	-	-	-
2	Hauptbahnhof	-	-	-	-	-
3	Meidling	-	-	-	-	-
4	Matzleinsdorfer Platz	-	-	-	-	-
5	Stadlau	-	-	-	-	-
6	Simmering	−1	−1	−1	−1	-
7	Traisengasse	+1	+1	+1	+1	-
8	Handelskai	−1	−1	−1	−1	-
9	Floridsdorf	OUT	OUT	OUT	OUT	-
10	Mitte-Landstraße	OUT	OUT	OUT	OUT	-
	INCLUDED (TOP 10)	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
(8)		Westbahnhof	Westbahnhof	Westbahnhof	Westbahnhof	
(10)		Stephansplatz	Stephansplatz	Stephansplatz	Stephansplatz	

Note: OUT means that the stop goes out from the top 10. In parenthesis the position in the new top 10 rank.

Figure 5.27 shows variations in terms of accessibility rank. In Scenarios 1–3, the districts that lose positions in the connectivity ranking, following the removal of the bike-sharing stations, are those above the South and East of the city. In Scenario 3, when the removal of bike-sharing stations is where there is any other public network service, the districts that lose positions are those in the North-East. No evidence on change in accessibility ranks are obtained adding bike-sharing stations at APTNB in the sub-districts: Flugfeld Aspern, Aspern, and Eßling - Im Neuriß (Scenario 3).

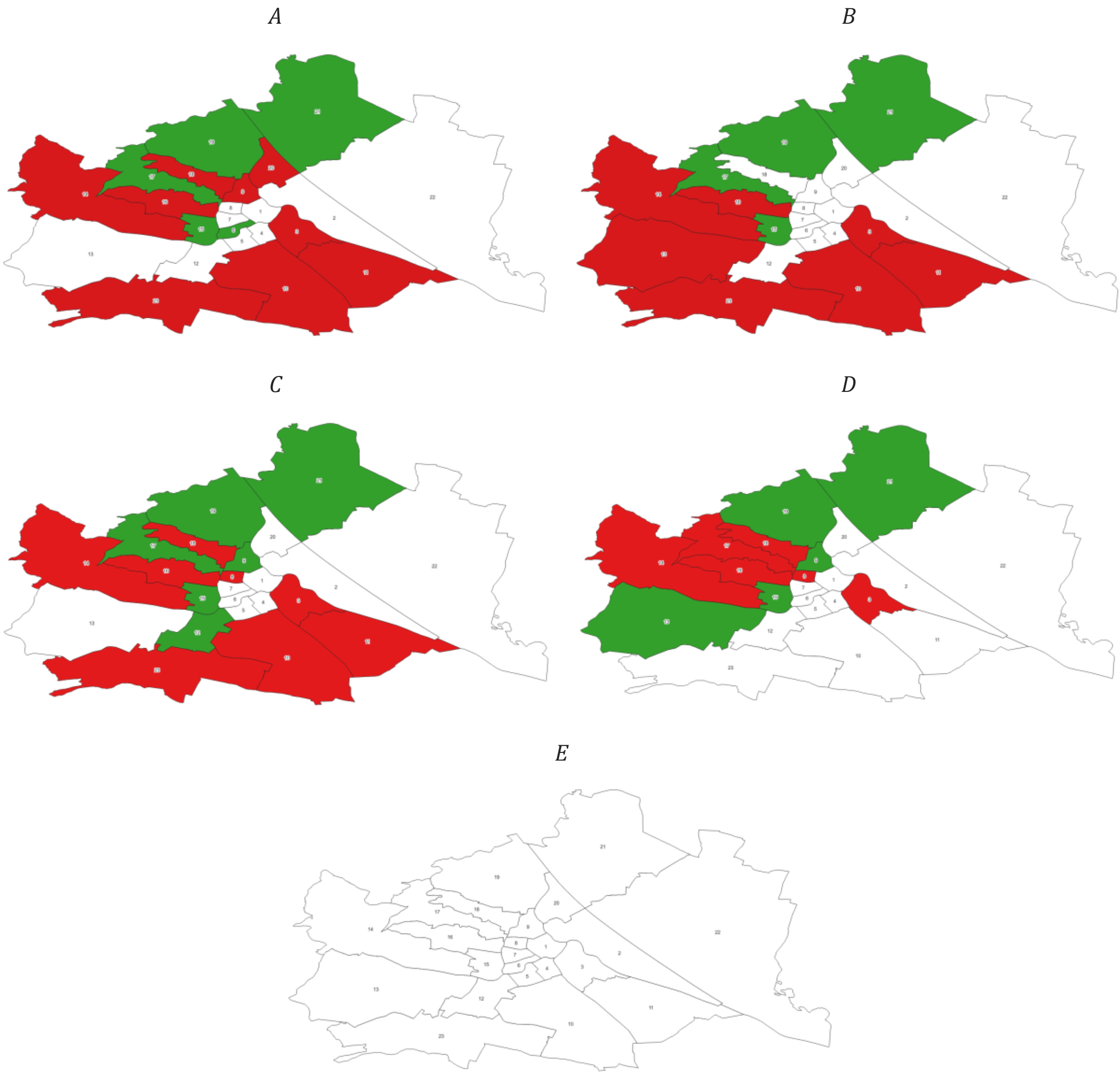

Figure 5.27. Vienna – Accessibility Change

Note. In green (red), cities gaining (losing) positions. In white, TAZs remaining in the same position. (A) Scenario 1; (B) Scenario 2; (C) Scenario 3; (D) Scenario 4; (E) Scenario 5. .

***Legend**: 1.InnereStadt, 2.Leopoldstadt, 3.Landstraße, 4.Wieden, 5.Margareten, 6.Mariahilf, 7.Neubau, 8.Josefstadt, 9.Alsergrund, 10.Favoriten, 11.Simmering, 12.Meidling, 13.Hietzing, 14.Penzing, 15.Rudolfsheim-zünfhaus, 16.Ottakring, 17.Hernals, 18.Währing,19. Döbling, 20.Brigittenau, 21.Floridsdorf, 22.Donaustadt, 23.Liesing.*

5.5.6. Conclusions

The analysis conducted allows us to make some evaluations on:

1. How robust is the PTN to the occurrence of disruptive events?
2. How does accessibility change after disruptive events on the PTN?
3. What is the potential impact of the bike sharing service on network robustness?
4. Which PTN stops are most suitable for the implementation of new bike-sharing stations, when the goal is to improve network robustness?

In our simulation the presence of the bike-sharing service in the city increases global efficiency significantly with respect to a scenario when the same service does not exist (approximately +20%).

As shown in the betweenness analysis (Table 5.8), The mere removal of bike-sharing stations does not seem to have significant effects on the importance of the individual (main) stops, therefore it is not possible to provide indications on where to implement new bike-sharing stations. For this purpose, one should think of scenarios that involve the removal of public transport stops, or carry out a bike-station addition exercise based on different initial prerequisites.

The impact of a disruptive event on the bike-sharing service can spill over into the accessibility of areas through the variation of travel times needed to move from one area to another. In this case it is possible to provide indications on where to implement new bike-sharing stations. For instance, it might be useful to do so in those areas that, following the disruptive event, would predict a greater loss of positions in an accessibility rank. In most cases (Scenarios 1, 2, and 3), the most impacted areas are those in the South-East of the city (Table 5.27).

6. CONCLUDING REMARKS

The objective of Task 5.4, reported in this document, was to analyse the relevance of network connectivity and accessibility in the dynamic analysis of public transport networks and mobility hubs, in particular in the presence of possible shocks/disruptions which might change the former's configuration and efficiency.

From a theoretical viewpoint, a novel approach was adopted, combining spatial interaction, accessibility and network analysis, in the light of network resilience. Methodologically, this approach highlights the importance of considering connectivity and accessibility metrics in the dynamic analysis of a transport network, by analysing their impact on the network efficiency/resilience. In particular, the accessibility analysis adopted here is rather unique, since the related cost parameter is determined by the calibration of real flows, while this cost parameter often takes fixed values that may bias the accessibility ranking.

This multi-disciplinary approach linking transport models and network analysis has been empirically applied to case studies related to the SmartHubs Living Labs, in particular to the areas of the Brussels Capital Region, the Rotterdam-the Hague metropolitan region, Munich, and Vienna.

The emerging results confirm the power of this approach in analysing the relevance of changes to the network, such as the introduction of bike-sharing stations, and in particular to the mobility hubs, where new transport modes can be adopted.

In addition, the application of this methodology to different geographical areas and cities, where transport data are available, shows the wide potential of this approach for further case studies. We provide then a useful tool for decisionmakers willing to exploit mobility hubs to improve transport resilience and sustainability. In future extensions, this tool could be fruitfully integrated within a multicriteria analysis decision-making support system, allowing to answer specific research questions (e.g. choosing between alternative locations of new mobility-hubs), also beyond the mobility hubs interest, and employing further data about socio-economic variables and amenities.

ACKNOWLEDGEMENTS

The Unibo team would like to thank all the partners from the SmartHubs Consortium for the fruitful and pleasant collaboration during the project, and for continued feedback at the different development stages of Task 5.4. In particular, we are grateful to colleagues from Mpact, the Technical University of Munich (TUM), The University of Natural Resources and Life Sciences (BOKU) and the University of Twente, who have provided detailed comments on a previous draft of this report. We would also like to thank Olivier Torrent and Ezgi Karakoç for great research assistance.

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