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SUSTAINABLE AND INTEGRATED URBAN TRANSPORT NETWORKS: THE
ROLE OF MOBILITY HUBS

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Abstract

The thesis on “Sustainable and Integrated Urban Transport Networks: the Role of Mobility Hubs” finds its foundation on the need for an effective green urban transition towards sustainable and shared mobility. Indeed, this research focuses on contemporary transport and urban development, in order to shape urban mobility that is resilient, accessible and sustainable. Mobility hubs (MHs) are proposed at the core of such goal, because they are able to efficiently integrate different transport modes and can reflect the broader ambition to achieve resilient and sustainable cities.

Within this thesis, MHs are described as dedicated stations offering citizens a range of shared and sustainable mobility options, supported by digital tools and services. The aim of introducing MHs is also to investigate how transport networks increase their resilience and, consequently, reduce their vulnerability to shocks affecting their functionality. By doing so, MHs can finally influence the attractiveness of sustainable modes, in contrast to the use of private vehicles, and generate tangible benefits for cities and users.

These complex issues are assessed into this thesis divided into four parts, each of which groups associated content. The first part is an overview of the MH topic, outlining the context in which they are inserted, the challenges of defining sustainable urban mobility, as well as the research objectives and corresponding questions. It also comprehends the significance and the structure of the thesis.

The second part gets into the core of the thesis with a systematic review of transport network resilience, particularly within the context of multimodal urban mobility. The chapter frames the concepts of resilience, transport resilience, and MHs in transport networks. It categorizes various resilience approaches—topological measures, recovery approaches, optimization approaches, data-driven methods, and simulation approaches. The application of these frameworks in urban mobility is then discussed, with a focus on multimodal and multilayered contexts.

Chapter three is developed from the previous one, because it represents a practical application of resilience indicators, feasible for the multimodal context in which we focus. This chapter establishes the basis to guide the location of MHs, employing metrics such as betweenness centrality and network efficiency. This approach gives relevance to stop criticality within transport networks and proposes the integration between bike-sharing systems and public transport as a way to enhance network resilience. Methods and metrics, including network analysis, are employed to analyse a case study of Munich. It offers practical insights into MH implementation, further developed in the followed chapter.

Part three combines the previous approach with the stakeholder involvement in locating and defining MHs. It corresponds to the core of the thesis, with the most methodological and consistent findings. Hence, Chapter four apply a multi-criteria analysis (MCA) for MH best location, incorporating network robustness as a key factor. This approach aims to suggest the optimal location to efficiently integrate transport modes and shape resilient urban mobility. The methodology encompasses survey design, alternative generation, criteria selection, as well as the Analytical Hierarchy Process (AHP) results. A case study of Munich illustrates the practical application of these methods, providing a robust framework for the decision-making process.

Chapter five employs a mixed-methods approach to understand the needs and expectations of stakeholders regarding MHs. A co-design approach is used to engage stakeholders in the research process, incorporating survey and interview data to capture diverse perspectives. The chapter reveals critical insights into stakeholder priorities and preferences for MH features and performance.

Lastly, Part four provides a policy perspective for integrated mobility, extending the analysis to various urban contexts. It evaluates the key outcomes of the research and discusses strategies to foster MHs and sustainable mobility. Within this part, Chapter six refers to research collaborations in which the author is involved, significant in terms of stakeholder engagement in mobility planning. Concurrently, the chapter

partially discloses the discussion derived from the collaboration with Patrimonio per la Mobilità di Rimini, and focuses on quantitative to qualitative research over ongoing projects, such as the Bus Rapid Transit system in Rimini. Furthermore, the chapter explores the influence of urban form on mobility supply and highlights the strengths and limits of sustainable mobility in such a context. Finally, policy evaluation is incorporated in this chapter to give final conclusions and develop actionable recommendations for urban planners and policymakers.

Ultimately, the interdisciplinary perspective of this thesis is emphasised in the concluding remarks, which relate the overall results and limitations encountered in the research, as well as guide further research. By advancing the understanding of MHs as catalysts for a sustainable urban transition, the thesis offers a model for moving forward with innovative mobility solutions in urban contexts.

Sommario

La tesi “Reti di trasporto urbano sostenibili e integrate: il ruolo degli hub di mobilità” si fonda sulla necessità di un’efficace transizione urbana green verso una mobilità sostenibile e condivisa. Questa ricerca si concentra infatti sui trasporti contemporanei e sullo sviluppo urbano, al fine di plasmare una mobilità urbana che sia resiliente, accessibile e sostenibile. Gli hub della mobilità (MH) sono proposti al centro di tale obiettivo, perché sono in grado di integrare in modo efficiente diverse modalità di trasporto e possono riflettere l’ambizione più ampia di città resilienti e sostenibili.

In questa tesi, i MH sono descritti come stazioni dedicate che offrono ai cittadini una serie di opzioni di mobilità condivisa e sostenibile, supportati da strumenti e servizi digitali. L’obiettivo dell’introduzione dei MH è anche quello di studiare come le reti di trasporto aumentino la loro resilienza e, di conseguenza, riducano la loro vulnerabilità agli shock che ne compromettono la funzionalità. In questo modo, i MH possono finalmente influenzare l’attrattiva dei trasporti sostenibili, in contrasto con l’uso di veicoli privati, e generare benefici tangibili per le città e gli utenti.

Queste complesse questioni sono valutate in questa tesi divisa in quattro parti, ognuna delle quali raggruppa contenuti tra loro connessi. La prima parte è una panoramica dell’argomento MH, che delinea il contesto in cui si inserisce, le sfide della definizione di mobilità urbana sostenibile, nonché gli obiettivi della ricerca e le domande corrispondenti. Comprende anche il valore scientifico e la struttura della tesi.

La seconda parte entra nel vivo della tesi, con una revisione sistematica della resilienza delle reti di trasporto, in particolare nel contesto della mobilità urbana multimodale. Il capitolo inquadra i concetti di resilienza, resilienza dei trasporti e MH nelle reti di trasporto. Vengono classificati diversi approcci alla resilienza: misure topologiche, approcci di recupero, approcci di ottimizzazione, metodi basati sui dati e approcci di simulazione. Viene poi discussa l’applicazione di questi approcci alla mobilità urbana, con particolare attenzione ai contesti multimodali.

Il terzo capitolo si sviluppa a partire dal precedente, perché rappresenta un’applicazione pratica degli indicatori di resilienza, fattibile per il contesto multimodale in cui ci concentriamo. Questo capitolo stabilisce le basi per guidare la localizzazione dei MH, utilizzando metriche come la betweenness centrality e l’efficienza della rete. Questo approccio dà rilevanza alla criticità delle fermate all’interno delle reti di trasporto e propone l’integrazione tra i sistemi di bike-sharing e il trasporto pubblico come un modo per migliorare la resilienza della rete. Metodi e metriche, tra cui l’analisi di rete, sono utilizzati per analizzare il caso di studio di Monaco di Baviera. La ricerca offre spunti pratici per l’implementazione dei MH, ulteriormente sviluppati nel capitolo successivo.

La terza parte della tesi combina l’approccio precedente con il coinvolgimento degli stakeholder nella localizzazione e nella definizione dei MH. Corrisponde al nucleo della tesi, con i risultati più metodologici. Pertanto, il capitolo quattro applica un’analisi multicriteriale per individuare il miglior posizionamento dei MH, incorporando la robustezza della rete come criterio chiave. Questo approccio mira a suggerire la posizione ottimale per integrare in modo efficiente le modalità di trasporto e dare forma a una mobilità urbana resiliente. La metodologia comprende la progettazione di un questionario, la generazione di alternative, la selezione dei criteri e i risultati del Analytical Hierarchy Process, un metodo per creare un rank di opzioni migliori rispetto a una serie di alternative. Il caso di studio su Monaco di Baviera illustra l’applicazione pratica di questi metodi, fornendo un quadro solido per il processo decisionale.

Il quinto capitolo impiega il mixed-methods approach per comprendere le esigenze e le aspettative degli stakeholder in merito ai MH. Viene utilizzato un approccio di co-progettazione per coinvolgere gli stakeholder nel processo di ricerca, incorporando dati di indagine e interviste per catturare prospettive diverse. Il

capitolo rivela le priorità e le preferenze degli stakeholder per quanto riguarda le caratteristiche e le prestazioni dei MH.

Infine, la quarta parte fornisce una prospettiva politica per la mobilità integrata, estendendo l'analisi a vari contesti urbani. Valuta i risultati chiave della ricerca e discute le strategie per promuovere i MH e la mobilità sostenibile. Il sesto capitolo si riferisce alle collaborazioni di ricerca in cui l'autrice è coinvolta, significative in termini di "stakeholder engagement" nella pianificazione della mobilità. Contemporaneamente, il capitolo illustra in parte la discussione derivata dalla collaborazione con Patrimonio per la Mobilità di Rimini e si concentra sulla ricerca quantitativa e qualitativa sui progetti in corso, come il sistema Bus Rapid Transit di Rimini. Inoltre, il capitolo affronta anche l'influenza della forma urbana sull'offerta di mobilità e mette in evidenza i punti di forza e i limiti della mobilità sostenibile in questo contesto.

Infine, la valutazione delle politiche è incorporata in questo capitolo per fornire le conclusioni finali e sviluppare raccomandazioni attuabili per i pianificatori urbani e i decisori politici. Da ultimo, la prospettiva interdisciplinare di questa tesi è enfatizzata nelle osservazioni conclusive, che mettono in relazione i risultati complessivi e i limiti incontrati nella ricerca, oltre a rappresentare una guida per delineare ricerche future. Attraverso la proposta dei MH come catalizzatori di una transizione urbana sostenibile, la tesi offre un modello per procedere con soluzioni di mobilità innovative nei contesti urbani.

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Part I

INTRODUCTION OF MOBILITY HUBS

Chapter 1

Introduction to the Thesis

1.1 Motivation of the study

The transport sector plays an increasingly pivotal role in the acceleration of global warming, standing as one of the primary contributors to the climate crisis. Greenhouse gas (GHG) emissions, derived from anthropogenic global warming, have exhibited a persistent and alarming upward trajectory. These emissions have escalated from approximately 30 billion tonnes in 1990 to nearly 50 billion tonnes in the present era (Ritchie and Roser, 2020). This substantial increase in GHG emissions is intricately associated with the persistent growth in global mobility demand, coupled with overarching and misaligned developments within the transportation sector over recent decades. Presently, passenger transportation accounts for approximately 15% of the total global GHG emissions (Ritchie and Roser, 2020).

Urban mobility is part of the problem, but essential to make a difference in this path. The provision of sustainable mobility, based on the reduction of pollutant emissions and the mitigation of the environmental impact, influences the choices made by people. High connectivity is required to facilitate people in their daily mobility, but it has economic, social, and environmental costs. People are wondering if and which private or public transport mode to use, based on the impacts of the target means of transport, as well as based on personal needs or reasons.

Nowadays, cities are still intensively car-dependent because of the comfort and flexibility that cars offer. A solution could be the supply of a diverse range of transport choices to reduce reliance on personal vehicles. According to a 2023 survey conducted by IPSOS¹, approximately 32% of European car owners indicated they could potentially forgo owning a private car in the future, with the trend being more pronounced among younger individuals (40% of those aged 18 to 34). However, this shift is contingent upon the availability of appealing and convenient alternatives. The recent innovations in micro-mobility and electromobility allows shifting from the intense use of private cars to a more sustainable way of movement, which is more aligned with the challenges of climate change. To advance future mobility levels while concurrently mitigating GHG emissions within the transport sector, a shift away from predominantly privately-owned combustion vehicles towards low-emission public modes of transport, especially electric vehicles, is imperative (Machado et al., 2018; Murphy, 2016). Mobility hubs (MHs), purposefully designed and coordinated transport solutions, offer a promising answer. They are easily recognisable, accessible, and user-friendly. The essential characteristics of MHs—providing multiple visible options in well-connected locations—highlight their potential as a key strategy for reducing urban car dependency. A MH enables people to choose the most sustainable and efficient way to move, which must also satisfy their needs.

In this perspective, it is necessary to refer to and include shared transport modes, such as micromobility options (bike sharing and e-scooter sharing), and ride and car sharing. Shared mobility services, along with the expansion of electric charging infrastructure (Shahraki et al., 2015), have experienced notable growth over the last decade. These services serve as standalone modes of transport and in conjunction with existing public transport services, as first- and last-mile options (Younes et al., 2020).

In this context, MHs perform a focal task in facilitating and promoting sustainable mobility modes through a multi- or intermodal approach (Schemel et al., 2020). MHs have increasingly emerged in major cities globally, garnering heightened attention from contemporary mobility planners (Aono, 2018; Miramontes Villarreal, 2018). MHs are expected to be key drivers in the sustainable transport transition of the future. Their principal feature lies in providing multi-modal journeys with seamless connections between diverse modes of transport, tailored to the specific spatial requirements of the analysed area.

¹<https://www.ipsos.com/en/mobility-one-three-european-car-owner-could-consider-not-having-personal-car-future>

Given these aspects, the motivation behind this thesis is to explore the capabilities of introducing MHs into urban areas and to identify the factors that can enhance the integration of sustainable transport networks. The expected outcome will be the assessment of key drivers for an ever-evolving user-centric mobility that meets the needs of a large part of the citizens and visitors. This topic is constantly developing, as well as the literature dealing with it. Most contributions come from Northern Europe, where some proof-of-concepts have already been implemented. Mobility Hubs guidance (CoMoUK, 2020²) and the Mobility Hubs guide³ represent the guidelines for this subject.

The research presented in this thesis draws significantly from direct involvement in international projects. Specifically, it is closely linked to the ERA-NET Cofund Urban Accessibility and Connectivity, JPI-Urban Europe project SmartHubs, within which we had the opportunity to contribute actively to the development and implementation phases. The insights gained through SmartHubs have enriched the research with real-world applications and empirical data, bridging theoretical models and practical approaches. Similarly, engagement with project MOVE21 (HORIZON2020 Innovation Action) has provided exposure to innovative methodologies and stakeholder engagement strategies, which have been instrumental in shaping the approach to MHs discussed in this work.

These projects emphasise integrating multimodal mobility solutions within urban ecosystems, focusing on stakeholder involvement, co-design processes, and the prioritisation of user-centric needs—all of which align closely with the objectives of this thesis. By leveraging these experiences, this thesis goes beyond addressing practical challenges, such as the optimal positioning of MHs for enhancing network resilience and the critical role of stakeholder participation in ensuring the success and sustainability of mobility solutions.

The definition of MH is still under-discussed, but the common pillar is the spatial connection of multiple mobility options that allow users to switch modes in a defined location. This research also aims to contribute to the MH definition by including innovative factors that are scarcely assessed in earlier literature on MHs: the transport networks' resilience, the accessibility and the co-creation approach. By considering these aspects, urban life is then facilitated and the intermodality is effectively boosted, which is intrinsic to the role of the hubs (Amoroso et al., 2012).

MHs represent a strategic field of work in which more research and innovation should be done. It can provide profitable opportunities to both private and public transport markets and to all parallel markets. The research's goal is to support development policies and transport organisations in order to contribute to the implementation of research models, to respond to the digital and technological challenges that determine green research and innovation.

1.2 Background and Context

The transport industry, contributing to 25% of global GHG emissions, is increasingly becoming a key factor in climate change (Kords, 2021). Notably, passenger cars contribute approximately 60% of total CO₂

²<https://www.como.org.uk/documents/comouk-mobility-hubs-guidance>

³<https://ladot.lacity.gov/sites/default/files/documents/mobility-hubs-readers-guide.pdf>

emissions from road traffic in Europe alone (European Parliament, 2019⁴). Urban areas are anticipated to witness a surge in motorised individual transport unless there are substantial changes to current structures (International Transport Forum, 2018). According to the International Transport Forum (2018), the demand for urban mobility is projected to rise by 94% by 2050, driven by increasing individualisation and urbanisation trends.

The scientific understanding of the consequences of these developments implies a necessity to alter our mobility behaviours to align with carbon reduction targets, such as those outlined in the Paris Agreement (Banister, 2011). In response to these challenges, there is a growing need for urban mobility to reconfigure public spaces, ensure connectivity, and prioritise social, environmental, and economic considerations. The focal point for urban and transport planning is thus to encourage a transition from cars to more environmentally friendly alternatives. This transition is crucial for addressing the pressing demands imposed by climate change and aligning with Sustainable Development Goals.

Given this context, this thesis covers the topic of the Digital Agenda, Smart Communities, and Smart Mobility Systems discussed, within the Italian context, in the last SNSI (Strategia Nazionale di Specializzazione Intelligente) and in the National Recovery and Resilient Plan (NRRP⁵), to foster an open approach to innovation and greater interchange between the world of research and the world of production. With a focus on sustainable mobility, this thesis intends to offer a more adequate level of competitiveness in the field of innovation and research, which allows the community, stakeholders, and enterprises to reach the objective listed in the PON R&I 2014-2021 quickly.

Institutions, local, national and European ones, as well as enterprises and financial actors, give increasing emphasis to the subjects of mobility and transport services, as they are essential for the Italian and European leaderships in order to meet sustainability goals. Mobility and transport can create a strong link between research and its real-life application, thanks to the many opportunities that new technologies offer to the productive system. A key element is the development of MHs, which enable the creation of a sustainable and accessible transport network. These aspects respond to the issues raised in the Sustainable Development Goals (SDGs) 9.1 and 11.2, two of the 17 global goals established by the United Nations in their 2030 Agenda for Sustainable Development.

Specifically, SDG 9 focuses on "Building resilient infrastructure, promoting inclusive and sustainable industrialisation, and fostering innovation", which refers to the need to develop infrastructure that can withstand and recover from natural disasters, climate change impacts, and other shocks. Resilient infrastructure is crucial for ensuring the continuity of economic activities and the well-being of communities, within which transport infrastructure and services are also included. Likewise, SDG 9 merges with inclusivity and sustainable industrialisation because the benefits of economic growth and industrial development need to be shared by all segments of society, including marginalised and vulnerable populations. To do so, industrial development has to consider minimising negative environmental impacts, optimising resource use, and promoting ethical and responsible business practices. Key elements of this kind of development are new technologies, processes, and business models that contribute to economic growth while addressing social and environmental challenges, such as sustainable mobility innovations that are promoted by the introduction of MHs.

An extension of the previous goal is SDG 11 "Sustainable Cities and Communities" and its target 11.2,

⁴<https://www.europarl.europa.eu/topics/en/article/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics>

⁵NRRP defines a broad package of investments and reforms to unleash Italian growth potential that the European Union negotiated in response to the pandemic crisis, and it is developed around three strategic axes shared at a European level: digitisation and innovation, ecological transition, and social inclusion. (<https://www.mef.gov.it/en/focus/The-National-Recovery-and-Resilience-Plan-NRRP/>)

which aims to "provide access to safe, affordable, accessible and sustainable transport systems for all". Overall, this thesis has the ambition to propose practical solutions toward this objective, considering several aspects (i.e. efficiency, resilience, accessibility and equity) in the analysis of urban mobility, in order to outline feasible policy suggestions in this field.

The study presented in this thesis is also consistent with the research field "Climate, energy, sustainable mobility" proposed in the NRRP, which highlights the potential benefit of environmental policies based on the transition to urban development that must go through more sustainable mobility. In this sense, sustainable mobility assumes a core role in this thesis because it represents a mandatory step to transit to an overall sustainable society. Indeed, the increased phenomenon of urbanisation leads society to face some challenges related to air pollution, energy production and consumption, and unconditional exploitation of the soil, which inevitably contribute to the increase of pollution. Because more than half of the world's population already lives in urban areas (World Bank Data, 2024⁶), the urban population is expected to reach 68% of the world's population by 2050 (UN, 2019). However, this growth entails some problems for the environment and human health. Because of the increasing rate of urbanisation, demand for local transit is also on the rise, calling for a new urban mobility plan to comply with the need for decarbonisation. In this context, MHs, which will be better described in the next chapters, are part of the strategy towards clean air, addressing congestion by reducing private car ownership and creating liveable neighbourhoods.

1.2.1 Challenges of Sustainable Urban Mobility

Urban mobility transcends traditional views of transportation, which typically focus solely on public transport services or private car use. It goes beyond the simple transportation system, but includes other surrounding systems, i.e., environmental, social, and economic. Thus, it requires a comprehensive approach to deal with it and to drive urban transitions towards sustainability. This approach is efficiently exemplified by what is called SUMP (Sustainable Urban Mobility Plans), which propose a broader perspective by integrating environmental, social, and economic systems to promote a holistic approach to urban transport. In this sense, conventional urban transport necessitates a revaluation of how we design, implement, and manage sustainable urban mobility (Banister, 2008). Unlike traditional models, which prioritise demand and travel cost minimisation of users, sustainable urban mobility is more flexible, and it emphasises the integration of various systems to achieve environmental protection, social equity, and economic viability.

Cities are every day more polycentric, which calls for the proximity of facilities and high levels of accessibility. In such a city, walking and cycling are maximised, so that car use would be minimised (Banister, 2008). Concurrently, innovations in public transport services and shared services can also increase the quality and suitability of these newly shaped cities, where people would not need to have and use a private car. Their reliability, in terms of degree of certainty, is one of the essential factors that emerged for them to replace private cars (Noland and Polak, 2002).

SUMPs can be considered as a strategic framework in line with what was stated before to foster sustainable urban mobility. They aim to improve accessibility, reduce environmental impacts, and enhance quality of life by considering a wide range of factors, including land use, social inclusion and economic development. According to the European Commission, SUMP are essential tools for cities to address current and future mobility challenges in a structured and inclusive manner (European Commission, 2013⁷).

One of the primary environmental challenges of sustainable urban mobility is reducing GHG emissions.

⁶<https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS>

⁷https://transport.ec.europa.eu/index_en

Urban areas are significant contributors to global emissions, primarily due to high levels of vehicle traffic, but on the other hand, they can lead to the mitigation of climate change impacts (Belaïd and Arora, 2024). Implementing SUMP's can help alleviate these impacts through the promotion of cleaner transport options, such as electric or shared vehicles, as well as cycling and walking. However, transitioning to these modes requires substantial investment in infrastructure and changes in public behaviour (Geels, 2012).

Achieving social equity in urban mobility is another significant challenge. Sustainable urban mobility must ensure that all demographic groups, including the elderly, disabled, and economically disadvantaged, have access to reliable and affordable transport. This goal necessitates inclusive planning processes that consider the diverse needs of urban populations (Lucas and Jones, 2012).

However, there are barriers to achieving social equity, such as the unequal distribution of transport services and infrastructure. Marginalised communities are often located in areas with poor transport connectivity, limiting their access to essential services and opportunities. Overcoming these disparities requires targeted interventions and community engagement to ensure that mobility solutions are equitable and inclusive (Pereira et al., 2017).

From an economic perspective, the implementation of sustainable urban mobility systems presents both opportunities and challenges. On the one hand, investing in sustainable transport can stimulate economic growth by creating jobs and improving productivity. On the other hand, the initial costs associated with infrastructure development and technological innovation can be prohibitively high for many cities (Gössling and Choi, 2015). Moreover, there is often a gap between long-term economic benefits and short-term financial constraints. Policymakers must navigate this tension by securing funding, fostering public-private partnerships, and prioritising investments that offer the greatest returns in terms of sustainability and quality of life (Gwilliam, 2003).

The transition to sustainable urban mobility is also hindered by institutional and policy challenges. Effective governance requires coordination across various levels of government and sectors, which can be difficult to achieve. Additionally, existing policies and regulations may not align with sustainability goals, necessitating reforms that can be politically and administratively challenging (Marsden and Reardon, 2018).

Furthermore, public acceptance and participation are crucial for the success of sustainable mobility initiatives. Engaging stakeholders and fostering a culture of sustainability requires transparent communication, education, and involvement in the planning process (Bickerstaff and Walker, 2005). In this regard, one additional challenge of sustainable urban mobility is the transferability of knowledge from producer to consumer, which means that innovative mobility systems require the active involvement of citizens and stakeholders in order to discuss and suggest useful changes.

In summary, Banister (2008) defines sustainable mobility as less necessity for travel, a shift to more sustainable transport modes, shorter trip distances, and a greater overall efficiency of the transport system. The consequent definition of SUMP's, given by the European Commission in Annex I "A Concept For Sustainable Urban Mobility Plans" 17.12.2013, is: "a Sustainable Urban Mobility Plan that has as its central goal improving accessibility of urban areas and providing high-quality and sustainable mobility and transport, through and within the urban area. It regards the needs of the 'functioning city' and its hinterland rather than a municipal administrative region (p.2)".

From this definition, it is interesting to highlight the differences between traditional transport planning and SUMP's, which are listed in Table 1.1, derived from the Guidelines for Developing and Implementing a Sustainable Urban Mobility Plan, Second Edition, 2019.

Traditional Transport Planning	Sustainable Urban Mobility Planning
Focus on traffic	Focus on people
Primary objectives: traffic flow capacity and speed	Primary objectives: accessibility and quality of life , including social equity, health and environmental quality, economic viability
Mode-focussed	Integrated development of all transport modes and shift towards sustainable mobility
Infrastructure as the main topic	Combination of infrastructures, market, regulation, information
Sectoral planning document	Interdisciplinary planning document consistent with different policy areas
Short and medium-term delivery plan	Long-term vision and strategy
Covering an administrative area	Covering a functional urban area based on travel-to-work flows
Domain of traffic engineers	Interdisciplinary planning teams
Planning by experts	Planning with the involvement of stakeholders and citizens using a transparent and participatory approach
Limited impact assessment	Systematic evaluation of impacts to facilitate learning and improvement

Table 1.1: SUMP transformation compared to traditional transport planning. Source: own depiction from Guidelines for Developing and Implementing a Sustainable Urban Mobility Plan, Second Edition, 2019.

Mobility is intended to be sustainable if it respects the eight principles described in the Guidelines for SUMP, which are:

1. Meeting the basic mobility needs of all users;
2. Balancing and responding to diverse demands from citizens, businesses and industry;
3. Ensuring social, economic and environmental sustainability
4. Optimising efficiency and cost-effectiveness;
5. Enhancing the utilisation of urban space and existing transport infrastructure and services;
6. Boosting the appeal of the urban environment, enhances quality of life, and promotes public health;
7. Increasing road safety and security;
8. Reducing air and noise pollution, greenhouse gas emissions, and energy consumption;
9. Improving the European and trans-European transport network's efficiency.

In this thesis, we will concentrate on some specific topics regarding the efficiency of public transport networks and shared transport modes, as well as the needs of users and stakeholders, taking a broader view of urban mobility planning based on proximity and accessibility. To do so, this thesis tries to connect all these issues under the umbrella of the MH development as a fundamental element for sustainable urban mobility.

1.2.2 Overview of Mobility Hubs

MHs are based on the broader concept of sustainable urban mobility, which involves innovations in mobility supply, but also a wide range of improvements in the overall urban system in terms of connectivity, accessibility and sustainability.

Clearly, these latter concepts are strongly linked to the introduction of shared mobility as one of the main elements of MHs. Indeed, this new concept of urban mobility revolves around shared mobility for various reasons, recognising it as a distinct mode of transport.⁸ The opportunities that shared mobility adds to the traditional transport system are several. Among them, are the reduction in car use, with consequent less space consumption by cars and less traffic, and a more efficient use of public transport.

The proliferation of MHs creates multimodal transport networks that, despite critical challenges as disruptions and interruptions, are generating a rapid change in urban mobility. A multimodal planning process is required to bring these modes into the planning process in a comprehensive approach, which is able to expand the performance of the transport system. The implementation of MHs represents a strategy to tackle these aspects.

According to Co.Mo.Uk, MHs are safe and convenient locations to switch between modes of transport, but also to increase the supply of further services in order to implement the full travel experience, adding socio-economic benefits to this facilitated intermodality. This configuration links MHs to the larger concept of Mobility as a Service (MaaS), which aims at replacing private car rides with a more efficient modal split and shared rides, satisfying passengers' needs. The latter are usually resistant to mode change, and MHs may be useful in making the process smoother, with a minimised loss of time. In such a view, co-creation based on customer-oriented approaches may assure that passengers' needs will be addressed, and that MHs' acceptance levels are higher.

More details on MH definitions and characteristics are available in the next section, where specific research objectives are defined.

1.3 Research Objectives

In the context previously described, we introduced the “Mobility Hub” as the core of this doctoral thesis. The concept is approached through a deep study of the existing literature defining MHs (Aono, 2018; Ambroz et al., 2016; Geurs et al., 2024; Schemel et al., 2020), and mainly referring to the SmartHubs project, in which the author of this thesis and her research team are involved.

From an academic point of view, we are interested in defining the role of MHs in increasing the resilience of transport networks, thus, in other words, in efficiently integrating and complementing the public transport system by offering shared mobility options. To better understand this role, it is fundamental to define MHs and their main characteristics, which will be discussed in the next chapters of this thesis. Furthermore, we need to define the concepts of resilience, connectivity and efficiency of a transport network in order to find assessment methods to measure potential impacts of MHs.

⁸https://share-north.eu/wp-content/uploads/2022/05/Shared-Mobility-Guide_ENGLISH.pdf

We have to note that there is no single definition for MHs or consensus on the specific functions they need to provide, nor a single term. The terminology varies from “Smart Hubs”, “Smart Mobility Hubs”, “Mobility Stations”, “Multimodal Hubs” or “Public Transportation Hubs”.

In this thesis, we will refer to MHs only, focusing not on the “smart” component, but rather on the role of connectivity and integration. The term “smart” is embedded in the smart city concept, which implies the collection, analysis and provision of data that increases the information and services provided to users (Papa et al., 2017). The smart dimension undoubtedly improves the user mobility experience, as the knowledge of mobility options usage is enhanced as well (Benevolo et al., 2016). However, our primary focus is on the potential of MHs for the structural improvement of transport networks, in terms of linking different transport modes, enhancing accessibility, and fostering a shift toward sustainable mobility.

Other aspects of this term are more related to the digital services offered to users, such as mobile apps for planning and booking, as well as wi-fi connection and charging stations (for mobile phones and e-vehicles) (Frank et al., 2021; Schemel et al., 2020). In addition, real-time information contributes to the “smart” aspect of MHs and then to the flexibility and comfort of the journey (Conticelli et al., 2021). Whenever these elements are available, also for visually- or hearing-impaired people, they contribute to raising the social accessibility of MHs. We will partially discuss these elements in Chapter 5, where we highlight the requirements for MH implementation according to stakeholders.

The literature offers different perspectives to categorise MHs, operationalised as multimodal interchanges of traditional transport modes (Monzon-de Caceres and Di Ciommo, 2016), or with a focus on shared options (Liao and Correia, 2020). Others prefer a more general definition of MH as “an interface between the transport network and spatial structure of an area” (Co.Mo.Uk, 2019). According to the same author, MHs also supply mobility with additional services, in terms of facilities and information features for users, which represent one of their most attractive elements.

Geurs et al. (2024) also note that proximity to a public transport stop is often included in the MH definition as an essential component, which means that those public transport stops close to shared mobility services can be intended as MHs themselves. We will discuss this aspect in Chapter 4, where we use existing public transport stops as potential locations for new bike-sharing stations in order to develop MHs.

The common elements of almost all definitions, reviewed by Geurs et al. (2024), are the spatial connection between different transport modes and the physical location where users can switch between them. However, MHs can differ in size, function and location, as classified by Bell (2019) and SmartHubs (Deliverable 3.1), even if in different ways. Here, we present a merged version of both classifications:

- Urban central hub: the connection is between local and supra-regional transport modes, such as bus, train, tram and pedestrian accessibility, cycling and e-mobility options.
- Suburban hub: the role is to connect peripheral regions and city centres, focusing on commuting trips between these areas. This typology is also described as neighbourhood/district hubs.
- Regional central hub: the principal function is to enhance the connections of rural areas due to public transport. Thus the main focus is to reduce car usage.
- Gateway hub: active modes and public transport are at the core, both in urban and rural areas.

In this thesis, we will be focusing more on urban central hubs and suburban hubs, because of the urban context on which we focus. Furthermore, as already mentioned, we are interested in highlighting the integration between shared modes and public transport that is facilitated by MHs, but some factors (spatial,

demographic and socioeconomic) need to be taken into account to better distribute this service and make it effective. Indeed, several studies have determined that the relationship between users' characteristics and other spatial factors influences people's decision to use one transport mode instead of another, shaping the potential impact of different transport modes at a MH (Horjus et al., 2022).

Another key aspect to describe and differentiate MHs is the multidimensional typology to which they belong. The multidimensional typology of MHs was recently described in a study by Geurs et al. (2024), through three dimensions: physical, digital, and democratic.

For physical integration, we refer to the transition between multiple transport modes (Metrolinx, 2011) and to other points of interest (POIs). Spatial factors are included in this dimension in terms of land use, POIs, demographics, population density and transport network, some of which will be deployed in Chapter 4, as factors driving the choice of MH location. Indeed, the proximity to specific POIs and public transport stops can increase the usage of MHs and encourage users to reduce car dependency (Urban-Design-Studio, 2016; Nielsen et al., 2005; Anderson et al., 2017). Physical integration, on which we will put more emphasis in the next chapter, also refers to physical impediments, conflicts to access and barriers. Moreover, it implies a prioritisation of public transport over private modes, but also dedicated space for active modes and separate routes from motorised vehicles (Chidambara, 2019). These features deal with the inclusive design of MHs, which is a way to maximise acceptance and usage.

Digital integration concerns the integration of information on a single digital platform, easily accessible for users to plan, book and pay for their trip, but also for receiving information about delays, traffic, and failures. Digital accessibility can be limited for people with no digital skills, thus MHs should always offer a low-tech alternative (Geurs et al., 2024).

Lastly, democratic integration covers the public planning process, which involves citizens, NGOs and researchers, defining a decentralised form of participation such as Collaborative Governance (Ansell and Gash, 2008; Emerson et al., 2012), Democratic Innovation (Smith, 2009) or Co-creation (Ansell and Torfing, 2021). This thesis will deal with co-creation and co-design in Chapters 5 and 6, emphasising the importance of involving multiple actors in developing MHs. These approaches aim to achieve public support, compliance and acceptance among stakeholders (Fischer, 2018; Meadowcroft, 2004; Newig and Fritsch, 2009).

This introduction to the topics that will be discussed in the thesis is fundamental towards creating a common basis for understanding the research methodology and outputs of the next chapters. Indeed, the first part of the thesis is concentrated on the role of connectivity that MHs play in influencing the resilience of transport networks. The approach chosen here is to define transport network resilience and its assessment methods that can be applied in practice in specific case studies. Network metrics are approached and discussed at this stage, and then used in solving MH location problem.

Additionally, one chapter is dedicated to the features that a MH should offer in order to satisfy the needs and expectations of users and stakeholders. This part of the thesis is extended through a set of final policy directions, defined to extend the research of this thesis to a broader sustainable urban perspective. Indeed, our findings can define policy suggestions helpful in re-designing sustainable urban mobility, including other related concepts, such as mobility justice and environmental and behavioural economics.

In summary, based on the above discussion, the main roles of MHs are:

- a) Enhancing the connectivity of public transport services and efficiently creating links between different transport modes for the first-last mile mobility (Aono, 2018; Urban-Design-Studio, 2016; Shaheen and Christensen, 2014).

- b) Promoting sustainable mobility in environmental, social and economic terms, reducing emissions derived from car dependence and including socially excluded groups and economically disadvantaged individuals (Aono, 2018; Metrolinx, 2011).
- c) Complementing public transport networks with shared modes, improving mobility supply in contrast to private transport.

1.4 Research Questions

Each part of this thesis is structured to address specific research questions that aim to define the role of MHs in creating resilient and integrated urban mobility systems. The questions focus on different aspects of MHs, from their contribution to transport network resilience to their integration of public and shared transport modes, as well as the expectations of stakeholders. These research questions serve as a guide for the thesis and are addressed through a combination of literature review, empirical analyses and policy reflections.

We formulate our research questions as follows:

- How do MHs contribute to making transport networks more resilient?

This question is primarily addressed in the literature review and network analysis chapters. We explore the concept of resilience in transport networks, particularly how MHs can help cities respond to disruptions, maintain continuity of service, and adapt to future challenges, such as climate change or unexpected crises and disruptions. The analysis will review existing frameworks and case studies to identify key factors that contribute to the resilience of multimodal transport networks.

- How do MHs favour the integration between public transport (PT) and shared transport (ST), and what are the benefits of this integration?

The previous analyses are followed by the application of a resilience indicator in a study defining the best location to implement MHs. At this stage, the optimisation of the MH location is assessed with a focus on enhanced connectivity. We examine how MHs can improve the synergy between public and shared modes of transport, reducing fragmentation in urban mobility. The benefits of this integration are considered in terms of operational efficiency and network robustness. In doing so, stakeholders are involved in the analysis through a multi-criteria approach, which facilitates the decision-making process aimed at exploring how well-integrated MHs can reduce reliance on private cars, thereby promoting more sustainable travel patterns.

- What are the needs and expectations of stakeholders regarding MHs?

This research question investigates the participatory process of designing and implementing MHs. Understanding the expectations of key stakeholders—including local authorities, transport operators, private sector players and the community—is crucial to the success of MHs. We address how incorporating stakeholder input can lead to more user-friendly, functional and socially accepted MHs. In particular, we analyse data from surveys and interviews to understand what stakeholders prioritise when it comes to MH features and performance.

- How can MHs shape more sustainable urban mobility based on network resilience and stakeholder engagement?

The last part of this thesis offers a set of policy reflections discussing the broader implications of MHs for sustainable urban development. By improving proximity (locating hubs near key activity centres) and enhancing accessibility (making transport services easier to use and reach), MHs can shift urban mobility towards more sustainable modes. This discussion also reflects on how policies that support MH development can further enhance their role in creating more resilient, accessible and sustainable urban mobility systems. In this framework, we will extend our analysis to different contexts by incorporating knowledge and experiences from other projects in which the authors were involved.

These research questions form the backbone of the thesis, helping to dissect the multifaceted role of MHs in promoting resilience, integration and sustainability in urban mobility. The answers derived from this thesis will provide valuable insights into how cities can design transport systems that are not only more efficient and connected, but also better equipped to withstand future challenges while fostering a shift toward greener, more livable urban environments.

1.5 Significance of the Study

The research questions outlined in the previous section are relevant not only in terms of transport policy but also from a research perspective. Indeed, while considerable research has been conducted on the efficiency and connectivity of transport networks, there is still a significant gap in the assessment of transport resilience in the presence of multimodal networks and strategically located MHs, particularly in the face of increasing challenges posed by urbanisation, climate change and fluctuating mobility demand.

Despite the valuable contributions of past research, a critical gap exists in understanding how MHs can enhance the resilience of transport networks as a whole. While existing studies have demonstrated the environmental and operational benefits of sustainable mobility ([Santos et al., 2010](#); [Banister, 2008](#)), they have not sufficiently addressed how these networks can be made more resilient to a variety of challenges, including climatic events, infrastructure failures and disruptions.

Indeed, part of the existing literature on mobility and transportation has focused on improving the sustainability and efficiency of urban transport networks. Researchers have explored strategies to promote the use of public transport, reduce congestion, and integrate new technologies, such as electric vehicles and smart infrastructure ([Murphy, 2016](#); [Figueroa and Ribeiro, 2013](#)). Some studies have also examined the potential of MHs in enhancing connectivity between different transport modes and encouraging a shift away from private car use ([Chatterjee et al., 2020](#)). However, these studies tend to focus more on short-term improvements in operational efficiency and user convenience.

While some research has explored resilience in transport networks, such as the ability to withstand disruptions from natural disasters or technical failures, these efforts have often been fragmented or limited to specific case studies ([Aljoufie et al., 2013](#); [Vuchic, 2007](#)). Most analyses address the resilience of individual transport modes (e.g., buses or trains) rather than viewing the system as a multimodal, interconnected

network (Zhao and Zhang, 2020). Additionally, the potential of MHs to contribute to overall network resilience—by creating flexible and adaptable transit options—remains vastly underexplored.

Another aspect addressed by this thesis that contributes to the increasing literature coming from a range of disciplines in social sciences, like economics and environmental studies, regards the involvement of stakeholders. Our aim is to contribute to the development of bottom-up approaches in mobility planning, which reduces the distance between researchers, policymakers and citizens. Indeed, one of the thesis’s purposes is also to meet the needs of a broad range of stakeholders towards MHs and, more generally, urban mobility.

In line with these objectives, this thesis aims to develop a framework for assessing the resilience of multimodal transport systems, focusing on how MHs can enhance the adaptability and robustness of urban transport networks. By integrating resilience into the design and operation of these hubs, the thesis will contribute to a more sustainable, connected, and attractive mobility system, one that can better cope with future uncertainties and challenges (Barthélemy, 2011; Benevolo et al., 2016).

Furthermore, by providing practical examples of integrated transport systems, this thesis attempts to orient the development of a more sustainable urban context through the proposal of policy suggestions, which might be useful for visionary policy-makers and urban planners.

1.6 Structure of the Thesis

The thesis structure can be described through the following flowchart (Figure 1.1), which provides a structured framework for understanding the integration of MHs in fostering sustainable and resilient urban mobility systems. It graphically represents the process behind the choice of the research topics as well as the expected outcomes to be implemented at different levels.

The scheme is developed around the problem statement, which highlights three main critical challenges: the contribution of transport to global warming, increasing urban mobility demand driven by urbanisation, and the vulnerability of mobility systems to disruptions that undermine connectivity and efficiency. These challenges set the stage for exploring interdisciplinary solutions in academic and practical terms. A common ground on which to propose and develop a feasible solution is the urban mobility context, where we have detected MHs as a potential solution.

Consequently, the central focus of this thesis is the MH as a tool for integrated and sustainable mobility. The topic is included in a broad scope of sustainable urban transition, to which cities, metropolitan areas and regions are called to answer and take actions. This path should lead to the abandonment of cars in favour of public transport and shared mobility options. This striving change is only possible if we offer efficient, resilient and accessible mobility that can attract users and facilitate their movements.

Furthermore, from a research question perspective, MHs are underpinned by a dual set of objectives: investigating their role in enhancing resilience, and engaging stakeholders to locate and define the essential components of MHs through collaborative processes. The sum of these research directions is extended to a macro view of the issue in order to suggest policy reflections and influence the transitions to sustainable mobility.

The remainder of the thesis reflects the composition of the flowchart. PART II is composed of two chapters:

Chapter 2, which provides a literature review of transport network resilience indicators, and Chapter 3, which presents an analytical framework of resilience metrics for the case of the Munich PT network.

Based on this framework, the thesis moves to the most innovative part, which assesses the location of MHs by employing different methods. Indeed, PART III is a combination of multi-criteria and mixed methods approaches, both aiming to involve stakeholders in mobility planning, in particular when defining MH locations and components. It deals with Chapters 4 and 5, respectively, applying a multi-criteria analysis for driving the choice of the best location of new MHs, and a mixed-methods approach to include needs and expectations of stakeholders towards MHs. These chapters can be intended as complementary because they refer to the same case study.

Lastly, PART IV is a conjunction between the more technical parts of the thesis, which are translated into a policy framework. 6 is built around the findings of this thesis and presents the additional contributions derived from collaborations with other research groups and policymakers. This part aims to be a bridge between the topic of the research and the broader mobility field, which embraces disciplines as political science, economics, and environmental engineering sciences. The integrated framework underscores the practical utility of MHs in creating more resilient, accessible and sustainable urban transport systems, while emphasising the significance of stakeholder collaboration and co-design. This chapter also includes the final remarks and conclusions, as well as limitations and further research directions.

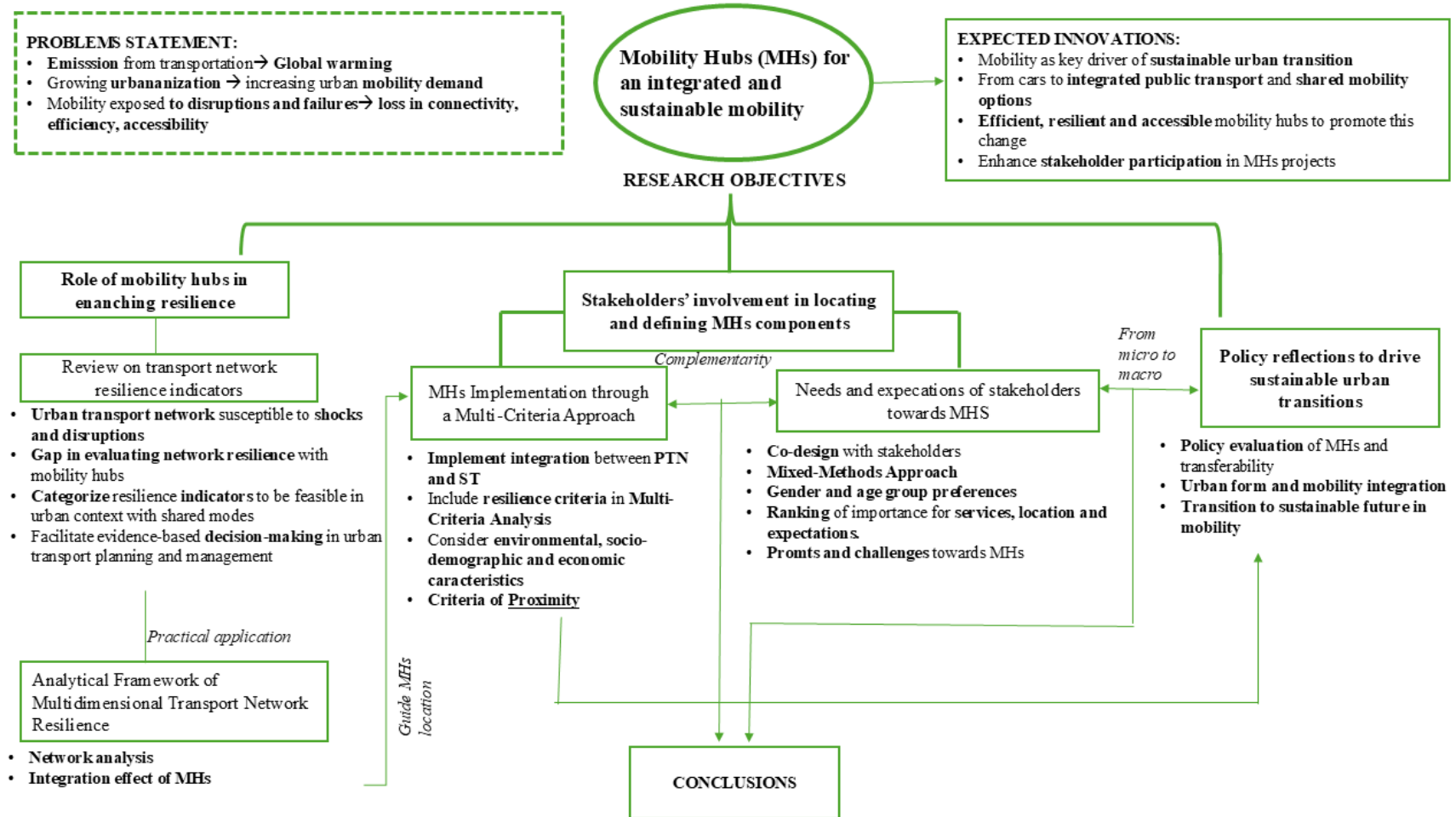


Figure 1.1: Thesis flowchart

Part II

A TRANSPORT NETWORK RESILIENCE PERSPECTIVE FOR MOBILITY HUBS

Chapter 2

Transport Network Resilience: A Systematic Review and a Focus on Multimodal Urban Mobility

2.1 Motivation of the study

In this thesis, the concept of MHs is approached primarily through the lens of transport resilience. The objective is twofold: to discern their role in evaluating the resilience of transport networks, and to ascertain whether their presence enhances the overall resilience of urban transport systems. This perspective is crucial as it distinguishes between a conventional single-layer transport network, where individual modes are considered in isolation, and a multilayered and multimodal transport network that characterises urban mobility.

Although there is extensive literature on the resilience of single-transport networks, which encompasses events that disrupt network functionality, leading to delays, congestion, or interruptions, resilience concerns remain relatively underexplored in the multimodal context.

Therefore, there is a pressing need to develop or identify feasible metrics to assess the resilience of multimodal transport networks, specifically focusing on the role of shared modes in supplementing or substituting public transport (PT) options during disruptions.

The concept of multimodal urban mobility is intricately linked to MHs, which facilitate seamless transitions between different transport modes, including PT and shared modes, even in the event of disruptions at specific nodes or links.

This chapter aims to categorise and consolidate a set of network metrics essential for measuring transport network resilience in the presence of MHs. The literature review undertaken in this regard holds particular significance, as it transcends traditional narrative reviews to offer a systematic perspective on previous research. In doing so, it aims to extract insights for potential future studies and applications. Moreover, this chapter seeks to clarify key terms that will be used throughout the thesis, such as connectivity, efficiency and resilience. Historically, a lack of standardised definitions has led to confusion and hindered practical applicability. Therefore, providing a clear overview of these concepts and the MH concept is essential for establishing a common understanding and facilitating meaningful discourse in the field.

This systematic literature review on transport network resilience is characterised by transparency and reproducibility. It serves as a valuable tool for identifying the most appropriate resilience indicators tailored to the specific context of the study. By adopting this methodological approach, this research aims to contribute to the advancement of knowledge in the field of transport resilience and facilitate evidence-based decision-making in urban transport planning and management.

2.2 Introduction

Increasing urbanisation poses environmental problems that are inevitably linked to the transport sector. The United Nations Environment Programme provides an idea of how impactful this sector is, from the standpoint of environmental sustainability, showing that it contributes a quarter of all energy-greenhouse gas emissions.⁹ It is evident that transport is one of the key sectors in which we primarily intervene in order to achieve sustainability objectives.

Therefore, the promotion of sustainable urban transport is key to reducing the environmental impact of cities and urban agglomerations, but also to influencing individuals' daily lives and decision-making processes. To achieve this goal, it is necessary for urban transport not only to be accessible, affordable and safe, but also to preserve its functionality when exposed to shocks, which can be unusual or day-to-day events. A critical

⁹<https://www.unep.org/explore-topics/energy/what-we-do/transport>

facet of any transport network is its susceptibility to various shocks from system failures and climate change (Mattsson and Jenelius, 2015). Some of these shocks are natural, such as floods, cyclones, hurricanes and earthquakes, and others are man-made, such as terrorist attacks, infrastructure failures, service disruptions and strikes (Reggiani et al., 2015). These events underscore the necessity to quantify the repercussions of disruptions and track the system’s evolution (Bešinović, 2020). Transport infrastructures are particularly vulnerable to such shocks, which directly impede network functionality and accessibility, in particular in a context of growing demand for mobility (Pan et al., 2021). To maintain the functionality of the transport network during and after these events, the latter must be adequately prepared, ex-ante, to respond and adapt (ex-post) to shocks. In other words, it must be resilient.

While a universally accepted definition of transport network resilience remains controversial, it can be interpreted as the system’s capacity to withstand disruptions, mitigate their effects, and restore functionality (Sun et al., 2022). Addressing this formidable challenge necessitates a concerted interdisciplinary effort embracing physics, engineering, ecology, social sciences and economics (Reggiani et al., 2015). These disparate fields collectively inform an exhaustive appraisal of the current state-of-the-art of transport sector and seek to enhance its efficacy.

The purpose of our contribution is to offer a comprehensive review of existing methodologies for assessing transport network resilience in the face of disruptions, with an emphasis on urban transport, which encompasses a mosaic of interconnected transport modes, mostly through MHs. These modes typically operate across various layers (e.g., streets, rails, bicycle paths/lanes), allowing resilience benefits by facilitating mode-switching during network disruptions. Consequently, our review outlines a broad framework for exploration in this domain.

Indeed, the analysis conducted for this review aims at recognizing and filling the literature gap on distinguishing the general approaches to transport network resilience and the more specific ones that refer to the multimodal urban context. A comparison between the two aspects is indispensable because of the common features in the settings and the possible replication of some methods in both. Our interest is to investigate whether common approaches exist and how they are implemented in the case of urban mobility, because of the higher complexity it presents. We expect to see further development in this field, because it could be useful for the implementation of resilient programs aimed at facing the effects of climate change and other risks for urban connectivity and accessibility.

The structure of the review is as follows: in Section 2.3, we introduce the context of our study, including a definition of the main concepts, such as resilience, transport resilience and connectivity; in Sections 2.4 and 2.5 we illustrate the methodology followed, including the choice of previous reviews on transport network resilience, which are the basis for improving the study on the topic and for proposing new approaches, the selection of articles, and the categories in which we divide them; additionally, in Section 2.6, we differentiate the contributions which allow for an urban application of resilience measures. Finally, in Section 2.7, we present the results and considerations emerging from our analysis, emphasizing the limited contribution of the research on the resilience of multimodal and multilayered urban transport networks. Section 2.8 presents a final discussion and concludes with some final remarks and future research proposals.

2.3 Setting the Context

This section aims to offer a theoretical foundation to understand the main concepts we use in this thesis. It is useful at this stage to establish a clear conceptual framework by clarifying and contextualising resilience in a structured manner, progressively from a broad perspective to its specific application to transport networks. So, while the first subsection explores the origins and general definitions of resilience, we subsequently move to examine how resilience is interpreted in the context of transport networks. The last subsection regards the connection between resilience and the main topic of the thesis, which is MHs in the urban environment as a key driver for resilient transport networks.

2.3.1 Conceptual Framing of Resilience

Before providing a review of resilience measurement methods, it is necessary to thoroughly clarify the general concept of resilience. This is not an easy task, as it is shaped by the field of adoption and the concept manifests in various facets depending on its uses and objectives (Modica and Reggiani, 2015). A large contribution of studies on resilience comes from a wide range of disciplines, such as physics, engineering, ecological, social, and economic studies, which corresponds also to multifaceted terms of transport resilience (Modica and Reggiani, 2015). The first appearance of the term was in the field of ecological science, as a “measure of perseverance of systems and their capability to absorb changes and disturbances and still sustain the same relationships between populations or state variables” (Holling et al., 1973, p. 14).

In the following years, other definitions were given by various authors. In Park et al. (2013), it is considered a dynamic property of the system that is always changing. The phases of system resilience can be identified as pre-event, during-event, and recovery (Peeta et al., 2010). The National Academy of Sciences associates these phases with a system’s ability to prepare for, absorb, recover from, and adapt to disturbances.

A differentiation based on system stability can be done between engineering definitions of resilience and ecological ones: the former recognises a return to a previous state of perturbation, and the latter assumes multiple stable states (Leobons et al., 2019).

Another perspective can be found in Carpenter et al. (2001), where resilience is the amount of change that a system can undergo while keeping the same controls on structure and function, and it is the system’s ability to self-organise. Under this perspective, McGlade et al. (2006) argues that resilience is concerned with the role of instabilities in pushing a system beyond a threshold or bifurcation point to a new stability domain.

A different strand of research focuses on the economic implications of shocks in the transportation system. As pointed out in the literature, the transport system is closely related to the social economy and a large number of participants and variables encountered in the system (Pan et al., 2021). A stable functionality of transport networks is necessary both from economic and welfare perspectives (Zhou et al., 2019).

It is well known that major disruptions, such as natural disasters, economic recession, and terrorist attacks, affect the entire economic landscape (Modica and Reggiani, 2015) and occur frequently, altering the economic structure locally or globally.

The definition of economic resilience is proposed by Rose (2009), who defines economic resilience as the inherent adaptive responses during and after disasters, that enable individuals and communities to avoid some potential losses, in opposition to the pre-event character of mitigation. In addition to this contribution, Reggiani (2022) largely addresses the issue by differentiating three approaches to studying economic resilience: the single equilibrium of the socio-economic status, which rebounds upon recovery; the multiple equilibria, when the system rebounds to a different socioeconomic status; the complex adaptive systems, where the shock

is a constant state of change and resilience is the ability to adjust to changes in the economic environment. The last approach is more appropriate in the context of a complex system, including the transport system and its interconnected subsystems.

In [Shutters et al. \(2021\)](#), resilience is the return of some attribute of the economic system to its previous level and not the return of the system's overall structure, which is supposed to be dynamic and co-evolving. In his study, economic resilience is strongly associated with resilience in transport systems because both are requirements for sustainable urban futures ([Shutters et al., 2021](#)). Therefore, it is noticeable that different fields are interrelated around the topic of resilience, and it is key to analyse the efficiency and functionality of any complex system.

Although the contributions to this topic are increasing, economic resilience is not yet fully understood ([Shutters et al., 2021](#)) and it requires more emphasis.

As a synthesis of all these definitions, we finally propose the one accepted by most and given by the United Nations¹⁰: “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (p. 24)”.

2.3.2 Conceptual Framing of Transport Resilience

Even considering only the transport system, the definition of resilience is not unique. [Leobons et al. \(2019\)](#) amplify the definition within the transport studies as the “ability to maintain the mobility at acceptable levels and to recover the normality of the operation (p. 323)” because it is often associated with the continuity of service provision or the restoration of the normal functions, after a disruption or failure ([Leobons et al., 2019](#)).

A transport system can be conceptualised as a network comprising interconnected links and nodes. Typically, in the modelling of transport networks, links represent the physical connections such as roads and streets, while nodes denote the intersections where these links converge, serving as origin, destination, or intermediate points along a route. A formalisation of resilience within transport networks can be traced to [Berdica \(2002\)](#), who evaluates resilience vis-à-vis vulnerability, defining it as the “time to restore serviceability (p. 120)”. Other notable contributions come from [Reggiani \(2013, 2022\)](#), who characterise network resilience analysis as “the speed at which a network reverts to its equilibrium following a shock, and the perturbations/shocks it can absorb” ([Reggiani, 2022](#), p. 415). Moreover, the same author extends this definition to encompass the system's elasticity or capacity to recover post-shock, signifying its flexibility, persistence of key functions, or adaptive capability.

Building on this conceptualisation of resilience, it is essential to consider the different types of stress or disturbances which directly affect the network's operability. They are classified based on their typology by [Snelder et al. \(2012\)](#):

- Recurrent (such as weekday peak hour congestion- predictable) and non-recurrent (such as floods and other events of nature) disturbances.
- Predictable and non-predictable conditions or between regular and non-regular conditions.

They can be subdivided by nature, based on the cause behind the shock ([Husdal et al., 2004](#)):

¹⁰<https://www.undrr.org/publication/2009-unisdr-terminology-disaster-risk-reduction>

- Structure-related or structure-generated vulnerability, which relates to the way the road is built and its attributes, in terms of topology, connectivity, geometry, width, curvature, gradient, tunnels, bridges, weight restrictions for certain vehicle types, etc.
- Nature-related or nature-generated vulnerability stems from the characteristics of the natural environment and terrain that the road network traverses. It includes natural hazards such as flash floods, avalanches, rockfalls, snow and ice, fog, earthquakes and tsunamis, to mention just a few of them.
- Traffic-related or traffic-generated vulnerability, linked to the dynamics of traffic flow and its potential interruptions. This includes predictable fluctuations, such as rush hours and weekend peaks, as well as disruptions caused by maintenance operations, snow clearing, accident clean-up, or ongoing construction projects. These factors reduce network efficiency and can lead to significant delays or congestion (Husdal et al., 2004).

Further classifications are based on the impacts provoked by the disturbances that can be temporary or permanent, and on the effects (network-wide effect or local effect).

In the transport context, as already introduced in the aforementioned classifications, resilience is a concept closely related to vulnerability, which can be intended as the degree to which a system is susceptible to harm (Modica and Reggiani, 2015). The resilience framework emphasises the concept of vulnerability assessment because it helps to capture the influence of disruptive events (El Rashidy and Grant-Muller, 2019).

The relationship between vulnerability and resilience in transport networks has been investigated by Modica and Reggiani (2015), which underlines that the first one refers to the pre-event characteristic of the network and the latter to the post-disaster response. The same authors highlight that as network resilience is enhanced, the vulnerability of the system decreases.

As a matter of fact, compared to resilience, vulnerability has a negative connotation because it refers to the quality reduction of the network. This is stated by Reggiani (2022), which describes network resilience as the “response to vulnerability and chaos, calling for robustness and stability of the network in the presence of shocks and disruptions (p. 415)”.

Overall transport network resilience can be intended as the ability to resist-operate-recover. Given these assumptions, it is also crucial to mention the concept of adaptation concerning resilience ability, which is stressed by Zhang et al. (2018). The author claims that preparation and adaptation to changing conditions and rapid recovery from disruption are the two pillars of a system’s resilience. Indeed, based on the review of Modica and Reggiani (2015), Zhou et al. (2019) differentiates two groups of definitions of transport resilience in two common perspectives: (1) the ability to maintain functionality under disruptions; and (2) the time and resources required to restore performance level after disruptions.

According to this, resilience is quantified as a loss area in grey represented by the difference between a normal performance evolution curve and a disrupted performance curve (Figure 2.1) (Zhang et al., 2018).

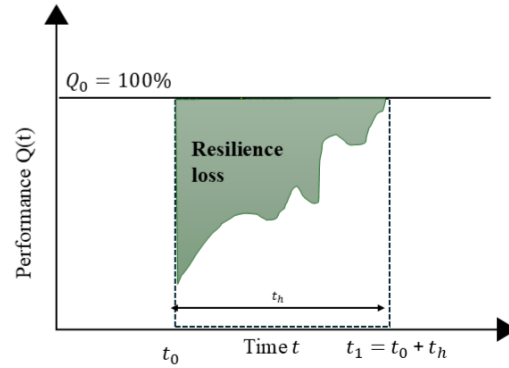


Figure 2.1: Resilience loss graphical representation. Source: own depiction from [Zhang et al. \(2018\)](#)

Despite the importance of theoretically defining transport resilience, throughout the review phase, we note that most of the existing approaches are more concentrated on theory instead of practical application. Proof of this is the two reviews on transport network resilience proposed by [Goncalves and Ribeiro \(2020\)](#) and [Bešinović \(2020\)](#), which include 'conceptual frameworks' as a qualitative group of measures for resilience in a transport network. In this group, they determine best practices, without quantitative evaluations or give a theoretical overview of the topic with no practical advances.

The present review excludes this category because an organised conceptualisation of the main terms is already offered above, and the purpose is to set several practical methods that can be functionally applicable in the real transport network and urban mobility. An example of a review that focuses on transport resilience metrics is [Zhou et al. \(2019\)](#), which distinguishes between topological metrics, attribute-based metrics, and performance-based metrics. The authors also recognise that most of the studies selected concentrate only on road, freight, or railway networks, instead of providing an analysis of the whole transport network, which includes different transport modes, among which there are shared options.

One possible reason for the focus of earlier research could be that the methods used for urban networks and multilayer networks, which combine different network categories, are varied, usually mixed, and also more complex. While, if we consider the transport infrastructure for every single mode, the analysis required is simplified, with no reason to deal with modal substitution or failures that affect different transport modes. Furthermore, many studies focus on the recovery time of the transport network but do not consider alternative transport options that could still permit the connectivity of the network even during disruptions, i.e., shared services. Moreover, neither of those indicators of transport network resilience based solely on traffic congestion is appropriate for urban networks for the same reasons: they fail to account for the interplay between modes or the availability of alternative solutions that preserve network functionality.

Given the pragmatic purpose of this review, the accent is on the urban context, which is characterised by mobility and multimodal transport interactions, developing and changing over time. Especially in large cities, urban mobility, naturally described as a dynamic system of interdependent networks, seems to be expanding and increasing the modes of transport offered, contributing to the creation of a 'smart city', more fluid and user-friendly ([Heddebaut and Di Ciommo, 2018](#)). Increasing relevance is given to the prominent role of 'smart transportation' as a tool for increasing the quality of city life and integrating land use and transport planning ([Elshater and Ibraheem, 2014](#)). The big challenge is to reverse the hierarchical pyramid of transport modes, giving less importance to private cars and putting the most sustainable modes, such as

walking, bicycling, car-sharing and bike-sharing, on top, which is intended as 'smart mobility'.

Within this conceptual framing, increased emphasis must be given to the resilience of transport networks in the context of urban mobility. As we have already pointed out, urban mobility becomes more fragile due to unexpected changes in transport networks, which implies raising attention on the individuation and resolution of such disturbances, disasters, or disruptions (Bešinović, 2020).

Urban mobility is usually modelled through multilayer networks where multimodal transport coexist. The realisation of more efficient transport modes is a key element for city growth, which results in more liveable, accessible, and resilient cities under environmental, social, and economic aspects (Heddebaut and Di Ciommo, 2018). Transport multimodality and interactions among transport facilities cause increased complexity. The management of such complexity represents one of the focuses of this review.

2.3.3 Conceptual Framing of Mobility Hubs in Transport Networks

Within the general framework of transport complexity, in this section, we discuss the role of MHs. Indeed, as urban mobility evolves, it is increasingly developing around them, which serve as critical nodes within the transport network. We refer to them as physical places that assume importance because of the confluence of multiple transport modes and services in a specific location (Anderson et al., 2017), which is, in other words, their ability to efficiently integrate multiple transport modes and services within a single location.

Given their characteristics, MHs emerge as key elements in structuring resilient transport networks, as we will discuss in this thesis. The presence of a MH, unlike traditional nodes, which typically represent simple intersections or points of connectivity in a single-mode network, allows for improved utilisation of transport capacities (Rupp and Funke, 2021). These benefits are also achieved by considering factors such as the shortest path across multiple modes of transport, as well as the strength of connections between these modes (Sun et al., 2018). Furthermore, in road networks, MHs have the role of directing users to the most important intersections, also in the case of evacuation, by avoiding the risk of being congested (Sun et al., 2018) and they permit redirecting trips away from overstressed infrastructure and toward available services with higher capacity (Anderson et al., 2017).

In this regard, it is also appropriate to attach the concept of connectivity to the resilience one. Connectivity is a key element for detecting network resilience in the presence of hubs and hierarchies of hubs. It is the ability to make and maintain a connection between sections of the spatial network, and, when hubs are created in a network, is also a way to enhance resilience and reduce vulnerability (Reggiani, 2022). Thanks to network connectivity, hubs resist slight changes and other shocks, which increases the resilience of the whole network (Reggiani, 2022).

According to these statements, Reggiani et al. (2015) affirm that the connectivity structure, better if evaluated by economic indicators, influences the resilience of the network because it plays a critical role when shocks or disruptions happen. Especially when a hub is damaged or incapacitated, it can lead to the removal of critical shortest paths that connect other key nodes in the network. This loss disrupts the efficiency of the network and reduces its resilience, as highlighted by Sun et al. (2018).

Despite the few studies referenced, there is a gap in research addressing the impact of MHs on transport network resilience, even if they constitute one of the network's main elements and fundamental components of current urban mobility. In order to effectively evaluate the capacity of multimodal transport networks to withstand, respond to, and recover from external disruptions that lead to substantial changes, it is needed to extend the research to the entire system instead of only one part or mode affected by shocks. This is possible through the introduction of a holistic approach, which includes different modes of transport and key elements,

such as MHs.

The resilience of the whole network, including its MHs, is essential to mitigate the adverse impacts of extreme events derived from climate change (El Rashidy and Grant-Muller, 2019) and human failures. Supply and demand sides of transport networks are influenced by weather conditions that deteriorate road surface and functionality of some links, nodes, or availability of certain modes and, from the demand side, affect traffic flow patterns, mode choice and average speed (El Rashidy and Grant-Muller, 2019).

To better understand these aspects, resilience indicators are useful for observing behavioural patterns under disruption scenarios and controlling them (Reggiani et al., 2015). This is partially possible because it is still challenging to address and identify suitable implementation measures to diminish the negative consequences of such shocks (Bešinović, 2020). The impacts of disruptions and failure can be consistent when vital hubs are affected, increasing their vulnerability. These removals influence adjacent areas and can produce severe degradation for the entire network, causing a loss of resilience (O’Kelly, 2015), which can be limited in case of large-sized networks.

The impacts of incidents and other events on traffic mobility at local and global levels can be assessed from the time and spatial dimensions, also through intersections, such as hubs (Sun et al., 2018). Analysing the range of impacts on network subsets, derived by their disruption or variation, can help define the reliability level of each part, which hubs are more susceptible, and eventually identify a rank of significance. The location and the number of hubs are crucial for describing different scenarios and understanding the framework to propose optimal resilient strategies (Anderson et al., 2017), which will be a key aspect assessed in Chapter 4.

The selection of the hub location directly affects the fixed costs of the system and transport costs, besides being influenced by the demand for transport between different origins and destinations (Khaleghi and Eydi, 2021). Indeed, because MHs are agglomerations of transport modes that concentrate on emerging shared mobility services in well-defined locations, they deliver several benefits to users and increase network accessibility. The implemented accessibility regards also more vulnerable groups, such as the elderly, lower-income individuals, and people with disabilities, because MHs enhance the connectivity of the transport system and reduce the lack of inadequate services (Anderson et al., 2017).

The same author argues that the hub is “a source of value for travellers who benefit from the multimodal connectivity and resulting travel time or cost savings (p. 65)”, because of the reduction in overall transport costs by using the most cost-effective mode for each portion of a trip (Henry and Marsh, 2008).

Given this context, MHs have assumed a significant role in assessing transport network resilience, in terms of connectivity, efficiency, and the overall functionality of the transport network. The recent development of the transport sector has reinforced the potential of mobility as a strong link between academic research and practical application. As the transport sector evolves, driven by technological innovation, sustainability goals, and policy shifts, the potential of MHs to bridge academic research and practical application is further amplified. In this context, developing a systematic approach to resilience indicators is essential for capturing the complex dynamics of transport networks and supporting more informed planning and decision-making.

2.4 Literature Search Methodology

The methodology we follow for our review is composed of 9 phases. Our research starts with the problem definition that is already enounced in Section 2.2, which regards the multiple definitions of transport network resilience and the analysis of previous reviews on the topic (see Table 6.3 in Annex 1: Overview of Resilience Studies in Transport Systems). We use these studies to establish our search methodology and guide the categorisation of each selected paper. The third and main phase of our research consists of selecting articles centred on the resilience of transport networks and the resilience of urban mobility as their primary themes. For this purpose, we used the Scopus database in March 2023, filtering the results with the following keywords:

- “Resilience” AND “Transport” AND “Network”;
- “Resilience” AND “Mobility” AND “Network” ;
- “Resilience” AND “Multilayer” AND “Network”;
- “Resilience” AND “Multimodal” AND “Network”;
- “Resilience” AND “Urban” AND “Mobility”.

The selected keywords do not cover other aforementioned correlated concepts (i.e. vulnerability, robustness), which would lead us to a different literature, not primarily focusing on resilience. We note that there exists a broad literature on such concepts and we acknowledge their significance, in particular with regard to "vulnerability". We do incorporate it in the theoretical framework in Section 2.3.1, but we recognise that resilience and vulnerability, although interconnected, are not interchangeable. The core objective of this chapter is to highlight "resilience" in transport networks instead of shifting the focus toward a distinct research domain.

In order to ensure adequate scientific value and to comply with the need to use a shared language, the first list of papers resulting from these searches is subsequently refined by including only those that have reached the final publication stage and are written in English. Then, we also reduce this list to the papers containing at least one keyword we want to be present in the title, abstract, or keywords. These keywords are, for example, resilience, transport, network, and mobility (see Table 2.1 for the complete list). This restriction is justified by the need to focus on the transport area, where resilience is expressly analysed and is the core of the article.

Subsequently, we obtain 753 documents that meet the given criteria. From this list, we exclude 76 duplicates. After that, we restrict the list through some inclusion and exclusion criteria to align with the purpose of this review. Thus, only works focusing on the resilience of transport networks were considered, despite the considerable number of studies originating from other fields, such as engineering, biology and communication, which primarily address other kinds of networks. Among the selected studies, we retained only those that propose a quantitative assessment method for the resilience of transport networks. This reflects the scope of this review: to suggest studies that offer indicators able to quantify transport resilience and quantitatively influence urban mobility policy. This computational aspect is a key assignment of the Smarthubs project to our team, and it will be integrated with more qualitative approaches in the following chapters (Chapters 4 and 5).

Finally, our attention is directed to recent and unrestricted access papers, validated in journal articles, book chapters or books. At the end of this process, the list of papers covered by our review includes 109

items. Table 2.1 shows the results of the Scopus query, while Table 2.2 lists the inclusion and exclusion criteria adopted to refine the Scopus results. Finally, Figure 2.2 shows the distribution of the final list of 109 papers, by year of publication, while Figure 2.3 illustrates the process we follow to select the papers and the further steps.

Table 2.1: Search results and document refinement.

Note: K=Keywords, P=Publication stage: final, L=Language: English.

Search TITLE-ABS-KEY	Documents	Limit to	Document after K, P, L refinement
resilience AND transport AND network	1216	K= resilience, transport, network	310
resilience AND mobility AND network	675	K= resilience, mobility	133
resilience AND multi-layer AND network	195	K= resilience, multi-layer network, multilayers, network layers, multilayer networks, complex network	97
resilience AND multi-modal AND network	73	K= resilience, multi-modal, multimodal transportation, multimodal transport, multimodal, multimodal transportation networks, multimodal network, complex networks	35
resilience AND urban AND mobility	430	K= resilience, mobility, urban mobility, urban transport, urban transportation	178
Total	2589		753

Table 2.2: Inclusion and exclusion criteria after results from Scopus

INCLUSION CRITERIA	EXCLUSION CRITERIA
- Journal articles, book chapters, books - Published between 2012 and 2023 - Transportation area approached by social, economic, and environmental fields - Quantitative assessment method of network resilience	- Duplicates - Conference papers, technical reports - Engineering area, biological area, communication area - Only qualitative analysis of network resilience - No open access

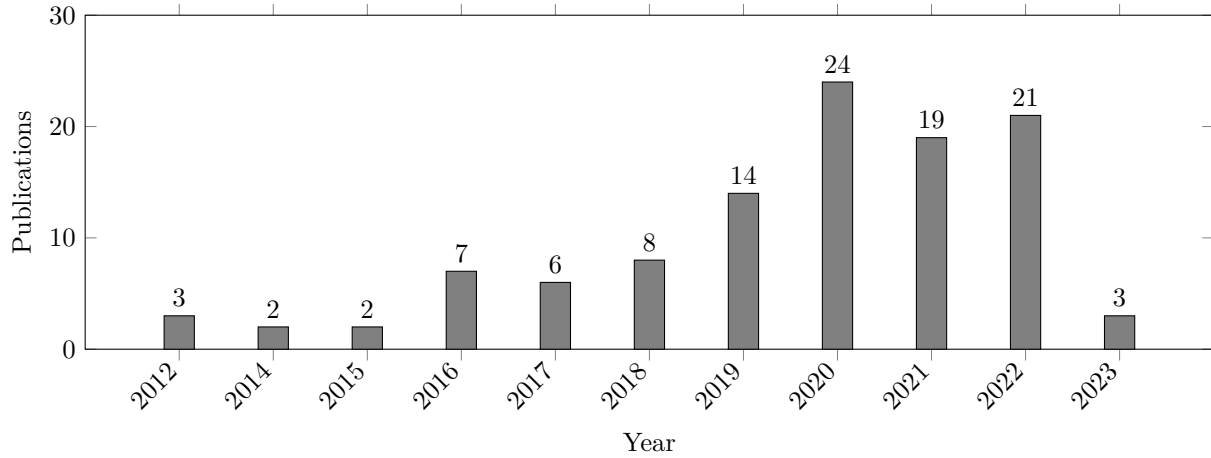


Figure 2.2: Publication per year

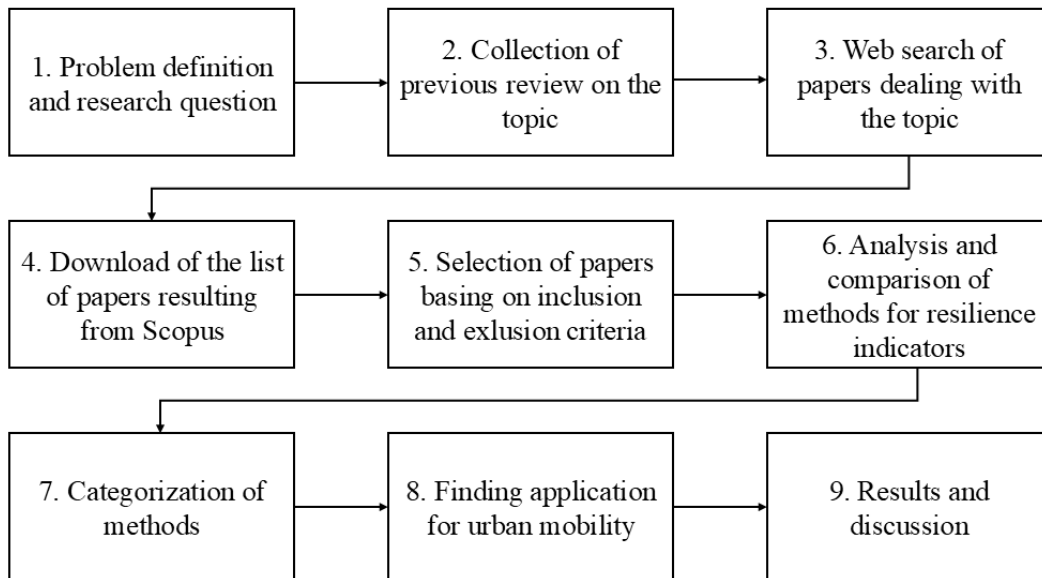


Figure 2.3: Phases of the review process

2.5 Categorisation

This section presents the results of the categorisation exercise, used by the authors to differentiate transport network resilience approaches, presented in the selected papers. The purpose is to guide the reader in choosing the most suitable methodology for studying the resilience of transport networks, based on the specific characteristics of the study to be conducted. These categorisations differentiate between resilience indicators applicable to broader transport frameworks and those designed for specific urban contexts.

Although a clear separation between methods is not always possible, because in most cases the authors use different methods or approaches simultaneously, this categorisation is considered useful to distinguish when and how different models are applied. By standing on the side of the researcher, this review aims to provide an overview of the most appropriate measures of the resilience of transport networks depending on the research objective, available tools, data and geographic extensions.

The taxonomy of the methods we propose is as follows. First, we separate approaches into two typologies: those studying static resilience and those studying dynamic resilience.

Static resilience indicators are concerned with the properties of the network, such as its robustness and redundancy (Snelder et al., 2012), more related to transport infrastructures (Goncalves and Ribeiro, 2020). They regard the system's ability to self-organise and function (Carpenter et al., 2001), after a certain amount of change. As already mentioned, this is the perspective proposed by (McGlade et al., 2006), in which static resilience is concerned with instabilities pushing a system beyond a threshold and reaching a new static domain.

Dynamic resilience, instead, can be considered as a dynamic property of the system that is always changing (Park et al., 2013), thus it is more related to adaptation (Goncalves and Ribeiro, 2020). The articles dealing with this perspective can be synthesised with the definition given by Berdica (2002), where resilience is considered as the time to restore serviceability.

Moreover, this definition is expanded by including the elasticity or capacity of the system to rebound after a shock, which indicates its flexibility and persistence of key functions or ability to transform (Reggiani et al., 2015). All these meanings imply the inclusion of time as a fundamental variable of the resilience indicator and are based on the dynamic variation of traffic conditions or road capacity.

The result of this differentiation amounts to 39% of papers with static indicators and 61% of papers with dynamic indicators. For each of these two typologies, we identify 6 categories (see Annex 1, Table 6.4), which are described in the following subsections.

2.5.1 Topological Measure

Topological measures are classical tools to investigate transport resilience through network analysis (Zhou et al., 2019). This category deals with the structure of the transport network, and it usually refers to properties such as redundancy and robustness, including betweenness centrality, shortest path length, size of the giant component, efficiency, and average degree as metrics for transport resilience.

Usually, efficiency describes transport network resilience as the inverse harmonic mean of the shortest path distances between origin-destination (OD) pairs. It can also be calculated after the removal of one or more nodes. This concept is close to the connectivity of a network, which is the ability to make and maintain a connection between sections of the spatial network (Reggiani, 2022). Similarly to them, redundancy also describes a topological characteristic related to efficiency and connectivity, and it is specifically the possibility of finding an alternative path when one is not available because of failure or disruption. Generalisation of the

formulas for network resilience, from a topological perspective, is then usually associated with the efficiency of the network. [Latora and Marchiori \(2001\)](#) proposed the formulation for network efficiency, then replicated by several authors like [Chan et al. \(2021\)](#); [Ilbeigi \(2019\)](#); [Osei-Asamoah and Lownes \(2014\)](#). This is:

$$\Psi(G) = \frac{1}{N(N-1)} \sum_{\substack{i \neq j \\ i, j \in G}} \frac{1}{d_{ij}}.$$

N stands for the number of nodes in the network, and d_{ij} is the shortest path distance between OD pairs in the entire network G . The assessment of network topological resilience involves calculating the ratio of links within the maximally connected subgraph post-disruption to the total number of links in the undisturbed network. Often, this method is complemented by simulations involving the removal of nodes, resulting in diverse scenarios and resilience metrics, facilitating comparative analysis ([Chan et al., 2021](#)). Through this approach, it becomes feasible to assess the impact of disruptions and identify critical nodes, thus enabling the investigation of their temporal evolution. Such analysis is instrumental in guiding cost-effective resource allocation strategies aimed at bolstering network resilience ([Chan et al., 2021](#)).

Furthermore, we include in this category those measures that consider weighted networks, which means attaching to some topological element a specific weight representing, for example, passenger flows.

This is the case of [Pagani et al. \(2019\)](#), which improves the pure topological analysis with the real passenger travel flows, in particular in the context of demand stress conditions. The authors attempt to match the theoretical analysis with reality through the consideration of the cascade effects of perturbations, which is the propagation of the shock through the network, and it significantly degrades network performance. Furthermore, the cascade effect has more real implications on the network performance than isolated failures, so it is significantly important to be considered. The resulting network, after a propagated perturbation, is a directed and weighted network in which resilience is measured with trophic coherence, a property that describes how much a directed graph hierarchically structures its nodes. In other words, the functionality of the network depends respectively on the direction of the flows as well as the capacity of the links (in this case, calculated as the volume of passenger flow).

Because resilience is evaluated by the graph's structure and its alignment with a hierarchy, where some nodes primarily supply others, it is essential to understand the meaning of basal nodes that influence the high or low trophic levels. They are nodes that receive passengers or provide passengers, so they are nodes, with their corresponding edges (the connection between one node and the following one), to which the flow is still allowed even in case of shocks ([Pagani et al., 2019](#)).

In this study, the resilience indicators are the incoherence coefficient q and the basal ensemble expectation $\sim q$, as a null model to compare the incoherence parameter of the network. The ratio between the two ($q/\sim q$) is used to analyse the coherence of the network. The formulas of the two parameters are:

$$q = \sqrt{\frac{1}{L} \sum_{ij} a_{ij} x_{ij}^2 - 1} \quad (2.1)$$

where L is the number of edges between nodes, a_{ij} is the adjacency matrix, and x_{ij} is the trophic difference (the difference between the trophic level of node i and node j);

$$\tilde{q} = \sqrt{\frac{L}{L_b} - 1} \quad (2.2)$$

where L_b is the number of edges connected to basal nodes. The ratio of the parameters above gives the

coherence of the network, which is the resilience according to the aforementioned authors. A value lower than 1 means a coherence network, while values greater than 1 reveal incoherent networks (Pagani et al., 2019).

Another case of weighted networks is presented by Martín et al. (2021), where the authors use accessibility measures to evaluate the impacts of the elimination of network sections. The resilience of the network is inferred from this process by assessing how the loss of sections affects overall accessibility. According to them, the formulas above give a sense of resilience interpretation. In particular, they firstly measures potential accessibility PA_i of each origin as:

$$PA_i = \sum_j \frac{P_j}{T_{ij}}, \quad (2.3)$$

where P_j is the population of each destination j and T_{ij} is the generalised time that the traveller takes to reach destination j . From this formula, regional accessibility A_s is calculated for scenario s as:

$$A_s = \frac{\sum_i PA_i \cdot P_i}{\sum_i P_i} \quad (2.4)$$

This formula reflects the average accessibility experienced by the population within the region, considering the potential to reach destinations and the population distribution.

The resilience of the network is assessed by comparing regional accessibility between two scenarios: the undisturbed network and the disrupted one. The difference between scenarios 0 and s stands for the percentage of decline in regional accessibility, derived by the loss of network sections. This causes a reduction in network resilience, while a lower decline in accessibility indicates greater resilience (Martín et al., 2021). To simplify, the approach links accessibility to resilience, pointing out how capable the network is of sustaining its functionality (allowing people to reach their destinations) under adverse conditions.

2.5.2 Recovery Approaches

Recovery approaches focus on measuring resilience by evaluating the performance of the transport network during a defined recovery period following a disruption. It includes metrics such as recovery speed, travel time, operational cost, and adaptive capacity (Zhou et al., 2019). Mostly, it refers to the ability to repair physical disruption in the shortest time with the minimum cost (Gilbert et al., 2016).

Among the studies that integrate recovery cost and time, there is Argyroudis et al. (2021b), which introduces a comprehensive perspective on network recovery by not only evaluating the restoration of functionality but also accounting for the associated costs of this process. Similarly, Nogal and Honfi (2019) argues about the extra cost generated by the perturbation over time. The cost can be restoration (direct cost) or vehicle time loss (indirect cost) caused by the damage. The former represents expenses directly related to the repair of damaged infrastructure or the restoration of operations, such as the reconstruction of roads, bridges, or transit systems, while indirect costs are associated with the reduced efficiency of the network, such as delays and increased travel times.

Other studies focus on the challenges and expenditures necessary to restore the transport network to a normal or acceptable functionality level. Chen and Miller-Hooks (2012) affirms that the measurement of network resilience should consider the effort in terms of cost, time, and resources to return to a normal or acceptable level of network functionality. The functionality ranges from 100%, when the network is fully performing and undisturbed, to 0%, when the network functions are totally disrupted. However, the most important variable in the resilience assessment, from a recovery approach perspective, is time, which

determines the short-term or long-term functionality disturbance (Titko et al., 2020). Fast recovery suggests high resilience and effective mitigation strategies, while prolonged recovery periods indicate lower resilience and higher vulnerability, necessitating further investments or systemic improvements. This kind of model can be generalised in a single formula as follows:

$$R = \int_{t_0}^{t_1} [100 - Q(t)] dt \quad (2.5)$$

Q_t is the quality of a system at time t expressed as a percentage of operational capacity under normal conditions. Resilience loss, interpreted as loss in functionality over time (Titko et al., 2020), serves as a measure of failure. It is calculated for the period between the initial disruption at t_0 and t_1 , when the system is fully recovered (Mattsson and Jenelius, 2015).

In this regard, resilience can be estimated as the ratio between the reduction in output (services, maximum demand satisfied for OD pairs) and the maximum output of the system (Cox et al., 2011; Chen and Miller-Hooks, 2012). In these cases, the general formula appears as:

$$R = \frac{\text{output} - \Delta\text{output}}{\text{output}_{\max}} \quad (2.6)$$

The results of the previous two measurements depend also on the characteristics of the disruption event itself (Chen and Miller-Hooks, 2012), including its duration and its consequences that directly affect the recovery ability. While formula 2.5 strictly associates resilience with the rapidity in the recovery of the physical network's infrastructure, formula 2.6 can be more extensively applied for the social dimension of disruptions, as it accommodates a wider range of variable factors.

The importance of disruption events extends beyond the physical impacts of disruption events, including social dimensions as well, as highlighted in Yabe et al. (2021). This dual perspective will be further explored in the context of a data-driven approach, where the socio-physical interdependencies in urban systems and their effects on disaster recovery and resilience are analysed.

2.5.3 Optimisation Approaches

Optimisation approaches concern processes to find the best solutions or alternatives according to a specific objective function (Goncalves and Ribeiro, 2020), when failure or disruption occurs. The alternatives involve decisions related to resource allocation and reconstruction scheduling, often employing a scenario-specific optimisation approach (Bešinović, 2020). In such scenarios, the scope is to define a network performance function that maximises flow or throughput (Faturechi and Miller-Hooks, 2014; Georgiadis et al., 2006).

These methods aim to measure the disruption's impact on the transport network performance, which enables the assessment of transport network resilience. This kind of approach is instrumental in identifying the most critical nodes or links (Faturechi and Miller-Hooks, 2014; Wang et al., 2016). However, due to the computational complexity, resilience is typically evaluated for specific disruption scenarios rather than for all potential or multiple disruptions (Bešinović, 2020).

The study by Wang et al. (2016) is noteworthy to cite among those that applied optimisation approaches, as it focuses on the identification of the critical elements of the transport network, in particular, the most vulnerable links, due to a mixed-integer non-linear programming (MILP). Indeed, to carry out this investigation, the authors present a MILP with equilibrium constraints to determine the combination of links that, if deteriorated, would lead to the greatest increase in total travel cost.

To solve the model, a global optimisation approach is proposed, referred to as a Network Design Problem (NDP). The latter is developed in two steps: the upper-level problem, pursuing a link or a combination of links maximising the total travel cost; the lower-level problem, which satisfies the Wardrop equilibrium conditions (based on the travellers' routing decisions).

To enhance computational efficiency, the model is reformulated as a single-level mixed-integer linear programming problem, which is integrated with the NDP. The results can provide assistance tools for decision makers, in order to allocate limited budgets for the construction and maintenance of transport infrastructure, aiming to maximise the resilience of the network (Wang et al., 2016). The study highlights the frequency of multiple-link failures in real-world scenarios and acknowledges the limited research dedicated to evaluating such issues. Addressing this gap, it provides a comprehensive framework for assessing and mitigating the impact of link failures, ultimately supporting the resilience of transport networks.

To give a methodological example, studies of this nature typically start by listing all the relevant variables and parameters at the beginning, categorising them as either continuous or discrete. By doing this, all elements influencing the analysis are explicitly identified and allow for a clear framework for the optimisation process.

A common feature of these studies is the formulation of local or network-level optimisation problems using general mathematical models, which are often adapted to fit specific case studies. One typical example is the system-optimal traffic assignment problem, which aims to minimise the total travel time across the network:

$$\min Z = \sum_{a \in A} x_a \cdot t_a(x_a) \quad (2.7)$$

where A is the set of links in the network, x_a is the flow on link a (a decision variable), $t_a(x_a)$ is the travel time on link a , often modeled as a function of x_a , to reflect congestion effects. This formulation aims to improve the efficiency and resilience of transport systems by optimising overall travel time, particularly under conditions of limited capacity or disrupted operations.

An alternative and more specific version, the total system travel cost function, is often linearised as:

$$\max F = \sum_{w \in W} d^w \cdot \pi^w \quad (2.8)$$

where W is the set of OD pairs, d_w is the OD travel demand of the OD pair $w \in W$, π^w is the minimum path travel cost between the OD pair $w \in W$.

Further insight is provided by Chen and Miller-Hooks (2012), who explicitly offers a formula for network resilience α as the post-disaster expectation of the maximum demand fulfilment d_w over the total demand satisfied at pre-disaster D_w :

$$\alpha = E \frac{(\sum_{w \in W} d_w)}{\sum_{w \in W} D_w} \quad (2.9)$$

This optimisation problem minimises the expected portion of demand that cannot be accommodated, or, in other words, maximises the expected satisfied demand, under some constraints. This application frames network resilience as a set of actions that can be taken post-disaster, when the impacts are known (Chen and Miller-Hooks, 2012).

Finally, Pan et al. (2021) integrates optimisation models with the dynamic travel demand and changes in passenger flow, but he recognises the hard application to large-scale networks due to the intensive

computational effort required for simulations. Despite these limitations, optimisation models obtain growing relevance in addressing complex problems, demonstrated by the studies analysed below. From their results, it is possible to derive qualitative considerations that can be elaborated for future research and that can increase the application.

2.5.4 Data-driven Methods

Data-driven methods are closely related to topological models because they often involve constructing weighted networks from travel data (Pan et al., 2021; Henry and Marsh, 2008). Unlike traditional approaches, data-driven methods do not focus on the inherent mechanism of the system, but instead capture changes in the system performance in different scenarios to evaluate its properties (Zhou et al., 2019). This approach can reflect the real operational status and characteristics of the network, providing detailed insights into its resilience (Pan et al., 2021; Bešinović, 2020). A significant advantage of data-driven methods is that they do not require extensive pre-modelling efforts, but instead rely on a sufficient amount of historical data (Bešinović, 2020). It is widely used for ex post analysis, both for real and simulated scenarios. As well as the optimisation models, data-driven approaches are grounded in the spatial-temporal characteristics of traffic congestion, often using GPS data to identify interrupting events in transport networks (Pan et al., 2021).

In some cases (Henry and Marsh, 2008; Voltes-Dorta et al., 2017; Argyroudis et al., 2021b), data-driven approaches contribute to understanding the dynamic resilience of the transport network. For example, Argyroudis et al. (2021b) explores the transport infrastructure exposed to multiple hazards, using multiscale monitoring data to quantify quantitative risk and resilience of the network. This is intended to enhance asset management and support adaptive and preventive measures for hazard preparedness. This study is an explanation of which kinds of data are collected and their utility in understanding transport network failures caused by hazards.

Because the core of these approaches is real data, they can be categorised into two main types. Data can be terrestrial, which are generated by cameras and mobile activity, instrumented monitoring of bridges and geotechnical assets, or they can be airborne (for example, InSAR, hyperspectral imaging, aerial photography, UAV/Drone sensors) (Argyroudis et al., 2021b). While data from Google and Waze are open access, the author criticises the underutilization of available transport data. In contrast with this lack, Argyroudis et al. (2021b) underscores that advances in monitoring systems and new technologies can enable accurate and low-cost evaluation, also in case of risk of disruption, reducing uncertainties, as in the case of long-term monitoring data, which are invaluable for tracking structural changes over time.

Moreover, data and maps can also describe the severity and characteristics of the hazard, which is called the intensity measure. They can quantify the risk with functions that predict the probability of damage occurrence and its typology. In particular, traffic data provides valuable evidence for the recovery process and can be a stimulus to improve or develop new restoration models Argyroudis et al. (2021b). Indeed, dynamic adaptations of the OD matrices based on pre- and post-hazard traffic analysis allow for tracking the gradual repair and recovery process (Bucar and Hayeri, 2020).

In Voltes-Dorta et al. (2017), the integration of data-driven and topological methods is explored through the construction of two OD matrixes: the Text and Data Mining (TDM), which search for alternative routing options for passenger recovery, considering the status of the origin and destination nodes; Rescheduling Matrix (RES), which provides the optimal alternative routing for the disrupted passengers. Here, the mix between a data-driven approach and topological methods identifies the critical components of the network based on the cost and downtime caused by their disruption.

Historical data can be leveraged with machine learning algorithms and other predictive models to forecast changes in travel time and performance (Pan et al., 2021). However, data collection, documentation of disruption-related data and their analysis are not simple and always available, but a broader methodology will regard the combination with other methods. By integrating diverse techniques, it will be possible to address the complexities of dynamic disruptions and advance the understanding of resilience in transport networks.

2.5.5 Simulation Approaches

Simulation approaches are crucial in transport network resilience as they are always associated with one of the previous methods. Thanks to the support, validation and extension of theoretical models or optimisation strategies, they are useful for studying the effectiveness of proposed methods under varied conditions (Pan et al., 2021). These approaches accurately simulate different interrupted scenarios and can give the occurrence probability or hypothesise the consequences of a certain disruption event. Simulation tools are versatile, enabling analyses of evacuation performance, the impacts of disruptions, recovery capabilities and changes in travel time or distance, all of which contribute to a comprehensive assessment of transport network resilience.

While complex and detailed simulations of the entire network are impractical and time-consuming, it is suitable to focus the study on a single or a limited number of disruptions (Bešinović, 2020). As already discussed before, the simulation method can be added to identify vulnerable network points and the percolation process, which is what is exposed in Voltes-Dorta et al. (2017). The latter explores the closure of a hub and its impacts on affected passengers by relocating them to delay-minimising alternative itineraries of the same network. The relocation process is simulated using the Dijkstra algorithm, submitted to capacity constraints. A similar approach is also featured in Yoo and Yeo (2016), where simulation measures the adaptive capacity of the network under a single attack and a sustained attack. Their simulation approach analyses cascading node failures, resulting in a sub-network resilience evaluation that captures the dynamic response to disruptions.

Martín et al. (2021), already mentioned in the topological session, suggests different scenarios to compare the decline in territorial accessibility changing through the elimination of sections of the network. The determinants of section failure correspond to a variety of eliminations, and they can be simulated randomly or deterministically (Martín et al., 2021). This framework aims to study the behaviour of the network in a different scenario and to assess resilience through the accessibility measure. It indicates the most fragile sections, providing the decision-makers with actionable information to formulate defensive policies or implement preventive measures (Martín et al., 2021).

An alternative and widely used simulation technique is the Monte Carlo method, which generates a large sample of random scenarios by iteratively simulating disruptions with assigned probabilities (Faturechi and Miller-Hooks, 2014). By sampling random variables repeatedly, the Monte Carlo simulation is used to predict the random behaviour of the system under uncertainty and provide probabilistic insights into resilience and disruption impacts (Chen and Miller-Hooks, 2012).

To synthesise, the simulation analysis is useful to estimate the network resilience because it describes and predicts system behaviour under disruption (Goncalves and Ribeiro, 2020). Although simulations do not directly assess resilience, they offer valuable input settings for other analytical methods and contribute to broader resilience assessments (Zhou et al., 2019). Moreover, simulation are a cornerstone for planning and construction of a more resilient network because of the results they offer in adapting to dynamic challenges (Pan et al., 2021). By testing scenarios, comparing results and evaluating investment options, they help prioritise strategies to strengthen network performance (Faturechi and Miller-Hooks, 2014).

2.5.6 Other Approaches and Summary

We refer to "Other Approaches" for those studies that propose different approaches but are numerically insufficient to constitute a category in their own right. We find considerable studies that apply the Bayesian Network Model, Fuzzy Logit, or economic analysis to assess transport network resilience, and we decide to include them in our review because of the relevant content they propose.

The selected articles are shown in Annex 1 (Table 6.4), where a systematic categorisation of assessment methods and approaches for transport network resilience is also presented. This categorisation provides a structured way to distinguish between different methods and synthesise the several available indicators into a more general formulation.

The categorization is particularly useful, as it allows the indicators to be adapted to different contexts, general or urban, based on several factors, such as: data availability, which also refer to the type of disrupted event occurred and the amount of data accessible for analysis; variables observed, which are the parameters and metrics monitored in the study; the aim of the study, so the primary goal of the research. For this reason, before moving to the categorisation based on specific frameworks, it is helpful to provide a synthetic scheme of the pros and cons of the categories selected, in which we divided the different resilience indicators (Table 2.3).

The aforementioned categories are the starting point for the more innovative part of the review, which intends to give relevance to those methods feasible in multimodal and multilayered networks, in other words, in the urban mobility context.

The next sections will focus on these topics by presenting multilayered and multimodal approaches concerning MHs in the urban context. This means exploring resilience across interconnected systems as well as integrating different modes of transport into resilience assessments. In doing so, the role of MHs as critical nodes in urban networks is highlighted and influences the design and planning of resilient urban mobility.

Table 2.3: Pros and cons of assessment methods for transport network resilience

	PROS	CONS
TOPOLOGICAL MEASURES	Based on graph theory. Permit to order the more critical elements. Simulation of possible scenarios.	Not considering impacts on users. Difficult to measure simultaneous interruptions.
RECOVERY APPROACHES	Consider resilience in terms of time, cost, and resources for recovery. Express the resilience loss.	Only post-disaster analysis. No emphasis on network properties.
OPTIMISATION APPROACHES	Set the best solutions and optimal allocation of resources. Allow for forecasting. The focus of capacity restrictions and congestion.	Hard application to large-scale networks. Difficult to measure simultaneous interruptions.
DATA-DRIVEN METHODS	Realistic analysis because real data are used. Based on spatial-temporal characteristics of traffic congestion.	Only ex-post analysis. Limits on data availability. No directly proposed solutions.
SIMULATION APPROACHES	Provide possible scenarios. Support the application of other methods. Useful for planning and construction of a more resilient network.	Necessitate sufficient data. Complex application.

2.6 Application for Urban Mobility: A Multimodal and Multilayered Context

Urban mobility is constantly evolving, characterised by improved interconnections and, consequently, increased complexity. This complexity lies in the intricate interactions between different modes of transport, which are increasingly shared. Transport modes are not independent (Baggag et al., 2017) nor isolated (Orozco et al., 2021), therefore it is necessary to implement the study of the system as a whole, instead of studying each mode in isolation, as they inherently always co-exist and influence one another.

The urban transport network can be investigated through the same categories already mentioned above (topological measures, recovery approaches, optimisation, data-driven methods and simulation), but it needs an extended analysis that considers its characteristics and covers the requirements for multimodality. We find that, in addition to the general setting, several studies offer more than one approach at the same time, resulting in a more effective combination of methods.

In urban settings, the behaviour of transport networks is influenced by the full multimodal and multilayered properties (Gallotti and Barthélemy, 2014), thus, the analysis of scenarios with only a single transport mode is not realistic and partially useful. Indeed, multimodality introduces new elements of complexity. It turns out that the representation of the transport system as a single-layer network is unrealistic and inadequate. Instead, multilayered network models are required, where each layer corresponds to a distinct transport mode (e.g., subway and bus) and not all transport modes share the same links.

Since multimodality implies switching from one mode to another, it needs MHs, as physically dedicated on-street locations where citizens can choose from different shared and sustainable mobility options.¹¹ Typically, subways and buses operate on dedicated paths (e.g., rails for subways, roads for buses), requiring a multilayered representation to accurately model their interactions.

Regarding these issues, Orozco et al. (2021) proposes an overview of the multimodality and multilayered frameworks, including modelling approaches and empirical evidence. For these authors, the combination of modes can be advantageous because it offers benefits and avoids the weakness of all modes (Orozco et al., 2021), facilitating more efficient and flexible mobility, especially in an urban environment.

This review invites us to reflect on the multilayered and multimodal approach in the case of disruption, where resilience assessment is required. We note that not all the measures dealing with the assessment of transport network resilience of the entire network are feasible when we deal with a multilayered approach because they fail to emphasise the benefits of having multiple transport options across different layers. Multilayered networks enhance resilience by providing alternative routes, enabling users to minimise costs and choose non-congested routes (Orozco et al., 2021).

The categorisation of approaches is not only built on their inherent differences but also on the discussion of urban mobility's evolving complexity. Thus, it is worth distinguishing methods limited to traditional single-layer networks and others feasible for more complex contexts. We categorise the selected papers also by the methods proposed, distinguishing them between: general approaches for transport network resilience, which have broad methods applicable to various contexts; and urban approaches (or applicable to urban), which are tailored for urban settings. This categorisation allows us to separate the studies into three groups, as in the following 2.4. This systematic breakdown underscores the growing importance of multimodal and multilayer frameworks in fostering resilient urban mobility systems.

¹¹<https://www.smartmobilityhubs.eu/>

Table 2.4: Approaches corresponding percentages

CATEGORIES	GENERAL	URBAN	APPL URBAN
TOPOLOGICAL	11%	67%	22%
OPTIMIZATION	25%	35%	40%
DATA DRIVEN + SIMULATION	43%	57%	0%
RECOVERY	33%	67%	0%
OTHER	50%	50%	0%

By analysing resilience through this categorisation, we can better identify which methods are most effective in addressing urban challenges. The three groups identified provide a clear distinction between generic methodologies and those designed or adaptable for urban applications.

2.7 Comparison of Results for Non-Urban and Urban Contexts

The proliferation of transport network resilience indicators during the period covered by this review underscores their importance as tools for decision-makers and transport planners to navigate the intriguing world of resilience assessment. In this chapter, we aim to present the results of our analysis and suggest the use of each method depending on factors such as initial conditions, interruption typology, observed variables and the scope of the research.

The studies featuring ‘general application’ (which means neither explicitly urban nor applicable to them) showcase a broad range of methods. This is because of the less complex nature of non-urban environments, which often lack the multimodal and multilayered properties of urban mobility. General studies typically refer to critical transport infrastructure [Titko et al. \(2020\)](#); [Liu et al. \(2023\)](#), single-mode network ([Verschuur et al., 2022](#); [Pagani et al., 2019](#); [Janić, 2018](#); [Zhang et al., 2023](#); [Wan et al., 2020](#); [Yao and Chen, 2022](#)) or to resilience assessment of the entire transport network, but focusing on the type of disruption event instead of its consequences ([Argyroudis et al., 2021b,a](#); [Martinez-Pastor et al., 2022](#); [Nogal and Honfi, 2019](#); [Gonzva et al., 2016](#); [Baxter et al., 2018](#)).

Based on the results, we advise that no urban contexts, such as regional, national, or international ones, usually do not involve mode substitution in the analysis of transport network resilience, thus limiting the application of methods which strengthen modes integration. In these cases, the transport network is often considered as a whole, and the analysis of disruptions and failures is conducted with respect to the entire network instead of the single components.

Natural hazards and extreme weather events are frequent scenarios for this setting, as these disruptions often paralyse entire networks. We find out that within of 24 general studies, 10 explicitly refer to natural hazards and extreme weather events as the starting condition for transport network resilience assessment. The reason is that weather-related events usually affect the entire transport network, and the solution is applied on a more general level than on each transport mode or specific nodes or links, in order to restore the initial condition of the network as a whole.

In this regard, recovery metrics dominate the methodologies in this context, as many studies present the recovery formula for transport network resilience to restore network performance ([Titko et al., 2020](#);

Argyroudis et al., 2021b; Janić, 2018; Tachaudomdach et al., 2021; Argyroudis et al., 2021a; Twumasi-Boakyee and Sobanjo, 2018). As a consequence, we observe that considering the transport network as a single entity always limits the resilience analysis and the consideration of multimodal and multilayered features.

On the contrary, in the urban case, the performance of transport networks is influenced by the full multimodal and multilayered properties (Gallotti and Barthélemy, 2014). The resilience assessments of urban transport networks, in the majority of the analysed studies, provide measures that include the multimodal aspects (63 over 109 cases) and belong to the category of topological models (44 cases). Indeed, a topological interpretation of multilayered and multimodal networks differentiates the layers for their nature, which are associated with nodes and links of the same transport mode (Aleta et al., 2017). In many cases, as synthesised by Orozco et al. (2021), the relevance of nodes is given by the overall centrality, depending also on the interplay between different transport options. Within this perspective, the scope of multilayered networks is also to offer the shortest and/or fastest path between origin and destination (Orozco et al., 2021; Strano et al., 2015; Nicosia et al., 2013; Baggag et al., 2017; Aleta et al., 2017).

One aspect of this multimodal literature is that most studies consider only the static multilayer network with no time-dependent characteristics (Orozco et al., 2021). The results show 30 papers of topological category pertaining to the static indicator typology, with no time variable in their formula, but aiming at absorbing the impacts of a disturbance and maintaining an acceptable level of service. Unlike static indicators, dynamic ones, in the case of urban transport networks, aim at restoring and balancing the regular operation within a reasonable period and cost (Goncalves and Ribeiro, 2020).

It is relevant to note that topological methods are, in many cases, combined with others, in particular simulation and optimisation, which enrich the analysis and give a comprehensive perspective of transport network resilience. The incorporation of simulation permits us to have a more realistic view of how the resilience indicators work and which are the different possible scenarios (Candelieri et al., 2019; Carmona et al., 2020; Bucar and Hayeri, 2020; Aparicio et al., 2022; Flores De La Mota and Huerta-Barrientos, 2017; Sohounou and Neves, 2021; Zhang and Ng, 2021a). On the other hand, optimisation techniques, when combined with the topological ones, enable to select the best coupled between different transport modes (Chen and Miller-Hooks, 2012; Thompson and Tran, 2019) or to suggest the optimum allocation of resources (Guo et al., 2021), distribution of flow (Wang et al., 2019) or an optimal network design (Jin et al., 2014; Gupta et al., 2018).

A significant insight derived from the findings is the critical role of cascading failures in urban resilience studies, particularly as they relate to the topological properties of transport networks. Indeed, the interconnected nature of multimodal and multilayered networks means that the failure of a single node can trigger widespread disruptions across multiple layers of the network. This phenomenon, caused by the removal of one node in a layer, produces the removal of any other connected nodes in other layers and removes also links not directly affected Boccaletti et al. (2014); Buldyrev et al. (2010). Consequent resilience strategies, based on topological methods, prioritise network redundancy, the robustness of interconnections between nodes, and the ability to isolate or mitigate disruptions before they propagate.

Other typical scenarios do not assume the cascading effect after the removal of one node but focus their attention on the node's importance inside the network, usually intended as hubs (Reggiani, 2022; O'Kelly, 2015; Kreutzberger and Konings, 2016). The importance of nodes acting as hubs is a recurring theme, as their failure can disproportionately affect the network's functionality.

Regarding the context-specific method selection, the choice also depends on the scope of the research and on what are the needs of a specific case study. There are different potential objectives related to the

transport network resilience analysis which can be identified, such as infrastructure enhancement, reduction of repair and operational costs, maintenance of connectivity and efficiency properties, allocation of resources, hub presence, and other network elements.

Another factor influencing the decision behind the application of a resilience indicator is the timing of the analysis. The approach taken to assess transport network resilience often depends on whether the analysis is conducted a priori (before an event occurs) or post-event (after an event has occurred). Usually, if the analysis is a priori or post-event, the transport network resilience approach utilised relies, respectively, on the network topology and simulation or on realistic data and time of restoring (data-driven approaches or recovery ability measures). Optimisation methods can be employed in both cases because they are usually added to one of the previous approaches. Whether working with network topologies or realistic recovery data, optimisation can be used to determine the most efficient strategies for improving resilience, minimising disruptions and expediting recovery. Data-driven methods or simulations are widely applied for their effectiveness in demonstrating the positive benefits of multilayered and multimodal networks, which are able to withstand disruptions better due to their redundancy, flexibility, and diverse routes.

As these multimodal and multilayered transport networks characterise most of the cities, it is reasonable to try and test the performance of the transport system with the introduction of MHs, with real or simulated data. From this perspective, the development of data-driven analytical tools helps evaluate the transport system and improve the customer travel experience and system efficiency (Ferretti et al., 2018).

An alternative direction for assessing network resilience focuses on the structural integrity of the network, particularly the size and connectivity of the transport network in the aftermath of a disruption. One common method is the Largest Connected Component (LCC) index, which rather than focusing on indicators that offer substitution tools, describes and compares the network size before and after the disruption. LCC emphasises the role of some links and nodes, highlighting their critical role in maintaining overall network connectivity, minimising service interruptions and maintaining network resilience (Chen and Miller-Hooks, 2012; Viljoen and Joubert, 2018).

2.8 Discussion and Conclusion

This review provides a systematic representation of the state of the art of transport network resilience indicators and contributes to categorising them based on different approaches. The synthesis of existing methodologies is not just an academic exercise, but it can be used for developing guidelines for decision-makers and public transport technicians, in order to direct them in addressing transport network resilience. By summarising and categorising approaches, we provide a pathway for stakeholders to align their analysis with specific conditions, disruptions, data availability and objectives.

Four main aspects need to be considered when we navigate transport network resilience: the condition at the beginning of our analysis (i.e., pre- or ex-post analysis); which kind of shock we want to study (i.e., extreme climate events, direct attack, infrastructure failure, random attack); which variables we want to include in the analysis and which data we have as well as which are missing; lastly, the objective of the analysis needs to be clear and can vary between many perspectives (i.e., assessing network performance, optimising resources and restoration costs, reducing the impacts of a failure). Some possible scenarios are suggested below (Table 2.5), with corresponding possible approaches based on previous results.

Table 2.5: Suggested scenarios and possible approaches for transport network resilience

SCENARIO	DISRUPTION /FAILURE	INTERRUPTED NETWORK'S ELEMENT	DATA/VARIABLES AVAILABLE	OBJECTIVE	APPROACH	INDICATOR/ METHOD	REFERENCES (examples)
Non urban	Extreme climate event	Entire system (transport, economic, social,etc.)	Time, measurable event's effects, geodatabase	1) Restore network functionality/ 2) Optimize adaptation-mitigation-readness/ 3)Calculate decline in network's territorial accessibility	1) Recovery models/ 2) Optimization/ 3) Data-driven+simulation	1) Resilience recovery formula/ 2) Bi-stage mathematical program/ 3) Dijkstra's algorithm	(Adams, Bekkem, & Toledo-Durán, 2012; Li, Liu, Song, Ye, & Liu, 2022; Beheshtian, Donaghy, Rouhani, & Geddes, 2019; Martin, Ortega, Cuevas-Wizner, Ledda, & De Montis, 2021; Yabe, Rao, & Ukkusuri, 2021)
	Directed attack	Node/ Hub	O-D pairs (city-city), geodatabase	1) Investigated the route redundancy/ 2)Assess Resilience of nodes	1) Topological/ 2) Optimization	1) Network-level route diversity/ 2) Integer programming model	(Chen, Cullinane, & Liu, 2017; Wang & Xu, 2022)
	Random failure	Node/s, Link/s	Network structure, road surface geometry and environment, O-D matrix	1) Enhance system-wide resilience, repair failure propagation/ 2) Prevention and managment7 3) Covering the performance of high exposure links.	1) Topological + economic/ 2) Data-driven/ 3) Optimization	1) Centrality measure+Risk analysis/ 2) Monitoring/ 3) Bi-objective model.	(Argyroudis, Achillopoulou, Livina, & Mitoulis, 2021; Bababeik, Khademi, & Chen, 2018; Segovia, Vila, Calle, & Marzo, 2012; Verschuur, Pant, Koks, & Hall, 2022)
Urban	Extreme climate event	Entire/portion of the network	Time, measurable event's effects	1) Individuate affected nodes and links and redistribute the passengers flow/ 2) Restore network functionality/ 3) Optimize adaptation-mitigation-readness	1) Topological / 2) Recovery models / 3) Optimization	Resilience recovery formula/ 3) Bi-stage mathematical program/ Performance index	(Li, Liu, Song, Ye, & Liu, 2022;Beheshtian, Donaghy, Rouhani, & Geddes, 2019; Khaghani, Rahimi-Golkhandan, Jazizadeh, & Garvin, 201; Wang, et al., 2017
	Directed attack	Node/s, Hub/s	N° of nodes and links, coordinates, critical nodes and links, passengers flow	Pre-event analysis to enhance network's structure and connectivity	Topological + Optimization	efficiency indicator/ Force-algorithms/ Dynamic phase selection + queue length dissipation	(Flores De La Mota & Huerta-Barrientos, 2017; Gao & Wang, 2021; Yao & Chen, 2022, Wang, Liu, Szeto, & Chow, 2016)
	Random failure	Node/s, link/s, Hub/s	O-D matrix, Traffic Analysis Zones (TAZ), GTFS data	Transfer passengers to available transport modes	Topological + Simulation	Centrality measures/ Mobility and accessibility metrics' behavior	(Aparicio, Arsenio, & Henriques, 2022; Azolin, da Silva, & Pinto, 2020; Bucar & Hayeri, 2020; Henry, Furno, & Faouzi, 2021; Zhang & Ng, 2021)

Given our findings, the first conclusion is that transport network resilience seems partially unexplored for multimodal and multilayered networks, even if most of the existing studies assume the urban transport network as a reference scenario. Despite this aspect, most of them are concentrated on the traditional transport modes, not even citing the more recent and sustainable ones that, certainly, are complicated to fit into classical approaches. Indeed, further development is required in this field to analyse the transport network resilience of interrelated transport networks, where different modes exist at the same time in the urban environment and the exchanges between them increase, especially thanks to the introduction of sustainable transport options (i.e., shared bikes, e-bikes, e-scooters).

Accordingly, the present review attempts to direct the analysis of transport network resilience, offering clear guidance on the methodologies and indicators that can be applied. At the same time, it encourages to reflect on adopting multilayered and multimodal approaches in case of disruption, when a resilience assessment is required.

A large and recent literature is available on the resilience of urban transport networks, but there is a lack of studies on the resilience of the hubs, which constitute the network's main urban element and a fundamental component of urban mobility, involving multiple transport services. Indeed, multimodal hubs characterise the new urban mobility, especially if distributed across the entire urban area, facilitating the interchange between modes, increasing the use of sustainable modes, improving the quality of services and reducing total travel time (Heddebaut and Di Ciommo, 2018). Physically, they represent the intermediate node between two or more end-nodes (Alibeyg et al., 2016), so it is interesting to investigate when the hub remains connected to the network and still allows connectivity through different layers. Resilience research must account for the interdependencies of hubs within multilayered networks. For example, a hub's functionality during disruptions determines its ability to sustain network connectivity across different layers. Beyond physical robustness, the resilience of hubs must encompass aspects such as accessibility, time efficiency, and cost-effectiveness, ultimately enriching the user experience.

Thereby, the future of network resilience research is to define more realistic transport networks, where, especially in the urban context, it is possible to analyse the interconnection between public transport networks and shared modes, efficiently integrated towards MHs. In summary, a most appropriate analysis of transport network resilience can be conducted if we include these two kinds of networks (the first static and the second dynamic), which allow us to assess transport network resilience by introducing a holistic approach and accommodating the evolving transport landscape.

For instance, flexible routes, enabled by shared services and well integrated with other modes, demonstrate significant potential in creating resilient alternatives to traditional fixed-route systems, like buses, metros, and trams. Incorporating these flexible systems into resilience assessments could lead to more adaptive and robust strategies, as they offer opportunities for substitution and integration with disrupted or disconnected public transport networks (as it will be explored in the next Chapter 3). However, this area of study appears to be in development (Saber et al., 2018; Schimohr and Scheiner, 2021; Radzimski and Dziecielski, 2021), but is still limited to specific case studies, scarcely generalisable to other urban contexts. Expanding these studies to cover diverse urban settings could unlock broader applications and strengthen the understanding of their resilience benefits.

Topological analysis, which, as it has emerged before, is the most widespread, is particularly suited to describe and analyse multilayered and multimodal networks because of its ability to capture the structural properties of complex systems, as well as to identify nodes able to maintain connectivity across layers. By the way, they can be enriched if weighted networks are considered. Unlike unweighted networks, which treat

all connections as equal, introducing weighted networks would enrich the analysis of resilience because they assign values to connections based on factors such as capacity, flow, or usage intensity. This dimension allows researchers to evaluate behavioural patterns under disruption scenarios with greater precision. Resilience indicators, supported by weighted network analysis, can help monitor and control these behavioural patterns in different parts of the network (Reggiani et al., 2015), even if it is still challenging to address and identify suitable implementation measures to diminish the negative consequences of external disruptions (Bešinović, 2020).

Concerning this aspect, greater attention can be given to additional socio-economic variables, which can be included in the assessment of transport network resilience, providing a more complete analysis. By integrating these variables, such as population density, income levels, and accessibility to essential services, resilience assessments can move beyond structural metrics to consider the human and economic costs of transport network failures. These issues should not represent a limit, but, even if increasing the complexity of transport networks, a stimulus to search for more robust analytical tools.

Ultimately, addressing these complexities requires a move away from traditional, mode-specific analyses toward holistic frameworks that incorporate dynamic interactions, sustainable modes and socio-economic factors. By bridging the gaps identified in this review, researchers and practitioners can design transport systems that are not only resilient to current challenges but also prepared for the demands of the future.

Chapter 3

An Analytical Framework Based on Network Resilience to Guide The Location of Mobility Hubs: The Integration of Bike-sharing and Public Transport

3.1 Motivation of the Study

This chapter develops an analytical framework to guide the location of mobility hubs (MHs), dedicating particular attention to transport network resilience analysis. This task continues the previous chapter, in which a systematic literature review was conducted to explore transport network resilience indicators. After an overview of the existing methods and approaches to assess the resilience of transport networks, this thesis focuses on a topological indicator as a metric for evaluating the criticalities of transport networks in an urban context.

The use of robustness metrics, with an emphasis on betweenness centrality, is motivated by several compelling reasons, grounded in both theory and practical application. Despite the number of different approaches, the topological one remains the best option for identifying critical nodes. Betweenness centrality can suggest which are the most important nodes for sustaining network functionality. Indeed, key junctions can be transformed into MHs in order to maintain network connectivity. However, when nodes with high betweenness are removed, they impact the overall network structure, providing information on vulnerabilities and reducing accessibility between different areas.

In a more practical application, employing these metrics facilitates scenario analysis and comparison without much effort to find the data. Several simulations can be performed to assess the impacts of different shocks on diverse transport networks. In this regard, these metrics can describe the integration of different transport modes into a multimodal network, including public transport (PT) and shared services, providing more realistic scenarios.

Furthermore, this kind of metrics enables the exploration of the temporal evolution of node importance, as the role of certain nodes may shift due to changes in traffic patterns, infrastructure development or demand. By tracking the betweenness centrality of nodes over time, decision-makers can identify emerging vulnerabilities and adapt strategies to enhance resilience. By doing so, mitigation strategies, such as enhancing the capacity or redundancy of critical links, can be developed.

These issues allow the inclusion of MHs as elements of urban public transport networks (PTNs) and the evaluation of their impacts on resilience. We focus on an additional aspect related to MHs that, as already introduced in the previous chapter, has received less attention in the literature, i.e., their ability to contribute to the robustness of the urban PTN. We argue that the redundancy offered by a mix of alternative transport modes, fostered by the presence of MHs, can mitigate the impact of the unavailability of PT due to disruptions of various kinds (failures, accidents, strikes, etc.), which often limit or impair its operation.

Henceforth, the transport network considered is the reproduction of a local urban PT supply with a station-based bike sharing service representing the additional mobility option. The context selected is the city of Munich (Germany), for which network metrics are computed, allowing us to assess the connectivity of the transport network both in the presence and absence of bike-sharing services. This computation permits the evaluation of bike-sharing impact in terms of the resilience of the entire transport network, where bike-sharing systems are intended as a substitute mode for PT. The presence of PT and a shared mode at the same location is the first step to develop MHs, and the efficient combination of them should orient the positioning of MHs as well (which will be the focus in Chapter 4).

This chapter aims to be a bridge between the literature review on transport network resilience and the computation and practical application of its indicator to be used in driving the decision of where to develop a new MH in an urban environment. This study lays a foundational framework for future research in urban mobility, emphasising the critical importance of assessing network resilience through the identification of critical points, PT stops, which need to be reinforced due to the creation of MHs where flexible shared modes

are available. These insights are particularly relevant for guiding the integration of PT and micromobility services, such as MaaS initiatives, as well as for promoting alternative and sustainable modes of transport.

3.2 Introduction¹²

Transport network resilience is the core issue of urban planning, given the increasing frequency of disruptions and interruptions caused by extreme weather events, attacks or failures affecting transport networks. Indeed, if we consider urban transport services as interrelated networks where different transport options are available, we can recognize that the functionality of its elements depends also on the interconnection between transport modes, that is mainly, the interconnection between Public Transport (PT) and Shared Transport (ST), such as bus, metro, tram, shared bike, e-scooter and so on.

In particular, a growing literature exists related to the combination of modes along the journey. Multimodal transport connections are essential for passengers because they improve the journey experience, also in case of interruption of one single mode ([Elshater and Ibraheem, 2014](#)). The focus of this chapter is on the interchange of PT and ST, which is intended to limit the use of more polluting options, i.e., private cars or scooters, but also as a way to increase the performance of the entire transport network.

In recent years, urban mobility has increasingly been developed around MHs, whose presence provides opportunities through the diversity of sharing mobility choices (bikes, scooters, electric cars, etc.). Therefore, MHs enable the combination of the original PT network (PTN) with more innovative, sustainable, and flexible ST, creating a complementary setting for urban transport systems ([Yang et al., 2019](#)). The development of such interconnections results in a more attractive and extended urban PTN ([Jaber et al., 2022](#)). The integration of ST is a challenge; it enlarges the choice set of users and is expected to cover the inefficiency of PT, overcome first and last-mile trips and facilitate the trip itself ([Garritsen, 2022](#)).

Considering the possibility of disruptions, PT and ST exposed to these events need to guarantee the functionality of the network through the connectivity of their component, which is the weighted measure of network linkage of a given node. In other words, the multimodal aspect of this kind of network can increase transport resilience.

In this context, MHs assume a significant role in assessing transport network resilience, allowing the connection between different transport modes, also in case of difficulties for the entire network. The disconnection of some important links or nodes of which a transport network is constituted can dramatically reduce its efficiency. Specifically, we look at how MHs presence enhances efficiency through alternative links and contributes to the network's ability to maintain connectivity. Moreover, through betweenness metrics, we analyse the criticality and vulnerability of these MHs, as they can become potential weak points in the network. By combining these factors, we assess the robustness of the urban PTN, focusing on its ability to withstand disruptions and ensure continued operation through alternative transport modes, even when some parts of the system are compromised.

In order to understand their role, we simulate different scenarios, one comprehending only the PTN and the other one with the introduction of a shared mode (shared bikes) that should enrich our resilience

¹²This chapter is based on [Malandri et al. \(2023\)](#) within the JPI Urban Europe - Smarthubs

evaluation. More precisely, we deal with these transport modes because we consider a specific kind of MH, composed of at least a PT stop and a bike-sharing station (BSS), whose relevance has been pointed out by several authors as an effective method for urban transport development ([Radzinski and Dziecielski, 2021](#); [Saltykova et al., 2022](#)).

We apply the topological method and network analysis for the city of Munich, Germany, for which we measure the robustness of the PTN by computing, respectively, the betweenness centrality of each PT stop and the global efficiency of the whole PTN, to see the impact of the presence of the bike-sharing service. Essentially, we assess the influence and changes derived by bike-sharing services on betweenness centrality, compared to when they are absent, as well as on global efficiency, in order to evaluate improvement or reduction caused by BSSs. The variation in global efficiency is useful to evaluate the broader impact of introducing a more flexible mode that provides alternative links to connect key nodes in the network.

Both analyses are ex-post, as bike sharing already exists in the reference scenario, but they highlight BSS effects on network efficiency. Indeed, these methodologies allow us to firstly list the most critical nodes in terms of their betweenness, and consequently propose them for MH implementation (as we will see in Chapter 4).

The computational results of such analyses are implemented in a programming code in R. This will reveal how PTN efficiency increases by offering a flexible transport mode and, combined with insights from betweenness metrics, the analysis identifies critical nodes within the network. These nodes, with high betweenness, will be further explored in the next chapter to inform the strategic placement of MHs, ultimately enhancing the overall efficiency of urban mobility networks and reducing PT vulnerability to potential failures.

Hence, the objective of this chapter is to understand if the availability of different mobility options, characterising MHS, can increase the ability of a transport network to withstand a given level of stress due to a disruption, which means increasing its resilience in terms of network robustness. Furthermore, the insights from this chapter are essential to provide indications, by means of sensitivity analyses, to be used for the choice of the most suitable locations for MHs in an urban context. This objective is achieved through the implementation of a multi-criteria analysis (MCA), which aims to evaluate different scenarios considering the resilience of the transport network as a variable influencing the decision-making process (see Chapter 4).

The structure of the chapter is as follows: Section 3.3 is a brief review of the literature on bike-sharing and PT systems integration; Section 3.4 introduces the main concepts and theories; Section 3.5 describes the employed methods and metrics; Section 3.6 illustrates the case study and results; Section 3.7 concludes the chapter.

3.3 Literature Review on Bike Sharing Systems Integrated with Public Transport Network

The first step forward to develop a MH is to combine at least two different transport options, one of them shared. To do so, we have widely explored the previous literature on this topic (partially exposed in this chapter and the remaining in the next one) and, thus, we propose the integration of PTN with bike-sharing service, given the widespread use of this option in recent years. Previous literature highlights the benefits that

the combination of these two modes brings to the whole travel experience (Elshater and Ibraheem, 2014).

Our focus on BSS is justified by several factors: the prominence of bike-sharing services in urban mobility, the extensive number of installations and the relatively easy availability of data compared to other shared mobility options. Bike-sharing systems, along with other shared mobility solutions, offer a variety of benefits to urban transport and society (Eren and Uz, 2020). From a transport perspective, bike-sharing adds a valuable option to the urban mobility mix, especially for underserved areas (such as industrial zones) or during off-peak times when PT frequencies are reduced. By doing so, bike-sharing systems offer bicycles for public hire, typically for short durations, providing an accessible and flexible transport option, often complementary to PTN (Zhang and Mi, 2018).

Some authors (Shaheen and Chan, 2016) describe this integration also in terms of integrated ticketing systems, which further enhance convenience by allowing users to use the same digital platform for both PTN services and bike-sharing. This integration simplifies travel planning, reduces barriers to multimodal use, and encourages the adoption of shared mobility options.

Additionally, placing BSSs near PT stops enhances the complementarity between modes of transport. This strategic placement encourages modal interchange, making bike-sharing an effective "last-mile" solution and providing greater connectivity to other PT services. This strategy aligns with what is supported by the study of Liu et al. (2015), who demonstrate that the optimal location of BSSs can significantly maximise accessibility and usage of both services, bike-sharing and PT.

More marginal, but no less significant, is the role of bike-sharing in alleviating pressure on crowded PT systems and reducing the need for car ownership (Teixeira et al., 2021). The same author states that bike-sharing, by providing a viable substitute for short car trips, contributes to a reduction in car dependency and ownership and consequently induces decreases in greenhouse gas (GHG) emissions and other air pollutants.

Moreover, bike-sharing systems can serve as a useful alternative when disruptions occur in the PTN, such as during strikes, delays, or service cancellations, offering a valuable contingency mode of transport for users (Cheng et al., 2021).

According to Cheng et al. (2020), there are two primary types of bike-sharing services: station-based (docked) and dockless (also referred to as free-floating). In station-based systems, bicycles must be borrowed and returned to designated docking stations. In contrast, dockless systems allow bicycles to be picked up and dropped off anywhere within the designated service area, without the need for a physical docking station. Station-based bike-sharing systems can significantly improve the integration of PTN by offering fixed and reliable points for bike pick-up and drop-off. Conversely, dockless systems are particularly advantageous for addressing the first and last kilometres of a journey, due to their flexibility, as they do not rely on physical docking stations. However, dockless systems come with challenges, including increased difficulty in operational planning, higher rates of vehicle vandalism and the problem of bikes being left in inconvenient locations.

These roles of station-based bike-sharing services as complementary and substitution options are particularly relevant to our study, which explores how they can enhance the resilience of urban transport networks.

3.4 Theoretical Background

This section takes up the main concepts of the previous chapter and completes them to form the foundation of this study: resilience and its intrinsic aspect of connectivity. These concepts serve as the analytical lens through which the performance of PTN is evaluated. The definition provided in this section does not pretend to be exhaustive, but is intended to clarify terms useful for understanding the chapter in a summarised and purposeful manner.

As already introduced in the previous Chapter 2 in Section 2.3.1, the term "resilience" first appeared in academia with [Holling et al. \(1973\)](#), who defined it as the property of the evolution of ecological systems. The definition of resilience used in this thesis, which is more suitable for our aims, 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 et al., 2018](#)). As can be inferred from the previous definition, resilience concepts can be divided into two main categories, already mentioned in Section 2.5 within the previous chapter: static and dynamic.

Static resilience refers to the ability of a transport 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 reorganise and evolve in response to changes and shocks, ensuring the continuity of operations even under adverse conditions ([Deloukas and Apostolopoulou, 2017](#)). In this study, the term resilience refers to static resilience.

In a transport network, connectivity measures the extent and operational links between different components of the network, enabling a seamless flow of people and goods. Connectivity encompasses both the quality and extent of these links, serving as a fundamental characteristic of efficient transport systems. A detailed definition of this concept is given by [Reggiani et al. \(2015\)](#), who describe connectivity as the ability to create and maintain a connection between two or more points in a spatial system.

Given its importance, graph theory and network analysis have become essential tools for studying connectivity. These methodologies offer metrics, such as node centrality measures ([de Stasio et al., 2011](#)), that help in evaluating the relative importance of specific nodes or links in maintaining the network's overall connectivity. Furthermore, these metrics encompass the density of transport links, the availability of transfer points and the ease of intermodal connections ([Hensher, 2009](#)), which describe how well-connected all network components are and determine the network's capacity to support multimodal and integrated transport systems.

In this study, after examining the indicators available for different contexts, we have oriented our research on that measure of resilience associated with the connectivity of the PTN because it better reflects how the network can adapt and recover from potential disruptions, given the levels of connectivity among its components. According to this, connectivity plays a crucial role in determining the robustness of the system, as it evaluates the structural interdependence of the network and its capacity to maintain service despite challenges.

By leveraging these concepts, this study provides a comprehensive evaluation of the PTN performance, offering insights into its ability to support sustainable and resilient urban mobility.

3.5 Methods and Metrics

The structure of transport services is usually depicted as networks, reflecting the notable similarities between them. If we restrict the study to the PTN, we note that it is composed of stations/stops and routes that are replicated, respectively, with nodes and links in graph theory; thus also their properties are the same. We apply graph theory and network analysis because we assume that PT can be described as a network.

Each node can be reached via multiple links that indicate the different urban transport modes (bus, tram, metro, etc). Once the network has been built, we study its connectivity using network analysis. First, we examine the structure of the PTN from a topological perspective, so that a preliminary study of the network structure can be provided. To this aim, we employ measures based on the shortest path and methods to calculate node/link centrality. Then, we add the network spatial features to the analysis, including the cost (in terms of time) a passenger suffers to travel through the network, which represents the weight assigned to each link. At this point, we study PTN connectivity through performance measures and scenario analysis, with and without aggregating bike-sharing services.

We can resume the phases of our methodology as follows:

- Selection of the context and generation of the PTN towards GTFS data, because of the information they provide about the interconnection of a PTN. They have further benefits derived from the standardisation of such data and a simple format (McHugh, 2013).
- Aggregation of single-mode networks (SMNs) like metro, tram, and bus networks in PTN: stops with the same name (including if different suffixes or prefixes) are aggregated, whether they belong to the same or different modes of transport. They are validated by the R code to be in proximity to each other.
- Integration of PTN and bike-sharing network: the latter is constructed for station-based service through fixed bike stations within a circular buffer, with a radius less than or equal to 200 m from PTN stops (García-Palomares et al., 2012; Aultman-Hall and Kaltenecker, 1999).
- Weight of integrated PTN and bike sharing with travel time, respectively calculated as the average time for each mode in the aggregated links, and as distance/speed, where the speed value is 15km/h (Fishman et al., 2013).
- Compute centrality measures to reveal critical nodes and compare the global efficiency with and without bike-sharing, in order to have an interpretation of network resilience for different scenarios.

To fully understand the assumptions stated before, we introduce basic terms and notation of graph theory and network analysis. We are mainly based on the study of Latora and Marchiori (2001) that introduces the concept of efficiency of a network, even if not directly referring to transport networks. We do not employ all these concepts in this specific study, but the extension of this research (Deliverable 5.4 by Malandri et al. (2023) for the SmartHubs project) is available and offers a comprehensive resilience analysis. Furthermore, the reason is that we only calculate the measurements we need to employ in Chapter 4, where a centrality measure (betweenness) is the indicator used for the resilience criterion in our multi-criteria approach.

3.5.1 Network Analysis

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

According to graph theory, a graph is defined as G and consists of the sets of nodes V and the set of edges or links E , so that a graph is a pair $G = (V, E)$. 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 nodes of node i . Under a topological perspective, we refer to hubs when nodes have large degrees, which means that they have many connections with other nodes in the network.

The adjacency matrix represents the adjacency relationship between nodes and is a non-negative $n \times n$ matrix A , where the entry is 1 if nodes i and j are adjacent, and 0 otherwise. A graph G is complete if all the nodes are pairwise adjacent. G is undirected if (i, j) and (j, i) represent the same edge, then it is also simple if there are no self-loops (edges starting from a node and ending on the same node) and only one edge can exist between each pair of nodes.

The density q describes how much the nodes are connected among themselves and is the ratio between the number of edges m and the overall possible number of connections among the nodes of G , denoted as $n(n-1)$, for directed G , or $\frac{n(n-1)}{2}$, if G is undirected (Freeman et al., 2002):

$$q = \frac{m}{\frac{n(n-1)}{2}} \quad (3.1)$$

A path between two nodes i and j is a sequence of distinct adjacent nodes starting from i and ending at j , where each node is visited only twice. If a path exists between each pair of nodes, the graph is connected; otherwise is disconnected. A disconnected graph is the case when some interruptions affect the link between a pair of nodes.

The number of edges of a path represents its length. The distance d_{ij} is the length of the shortest path between i and j . The average distance between two generic nodes is described as follows:

$$L = \frac{1}{N(N-1)} \sum_{i \neq j} d_{ij} \quad (3.2)$$

When some parts of the graph are disconnected, a subgraph $G' = (V', E')$ is created, where the connected components of G form the maximal connected subgraph.

Given the previous notation, we assume that a network is a graph that has some specific properties measured by a set of metrics, the centrality metrics (Albert and Barabási, 2002). The two main metrics that we consider in our study are the degree centrality and the betweenness centrality. Both are used to describe and give meaning of importance to the nodes of a network. The first (3.3) individuates the node i with the largest number of links to other nodes $k(i)$, and the second (3.4) quantifies how many shortest paths σ_{jk} between two given nodes j and k pass through node i , $\sigma_{jk}(i)$ (Latora and Marchiori, 2007):

$$Dc(i) = \frac{\kappa(i)}{N-1} \quad (3.3)$$

$$Bc(i) = \frac{1}{n(n-1)} \sum_{j \neq i \neq k} \frac{\sigma_{jk}(i)}{\sigma_{jk}}. \quad (3.4)$$

The betweenness centrality $Bc(i)$ is one of the pillars to pose some statements regarding the network analysis of transport networks. Indeed, it allows us to measure the importance of nodes, but also informs us how the performance of the network changes after the removal of some nodes.

In Figure 3.1, node B plays a key role in connecting several shortest paths, with a betweenness equal to 0.5. After removing node B, the graph becomes disconnected and there are only direct links between each node, thus none of them serves as an intermediary in shortest paths, and their betweenness measures drop to 0.

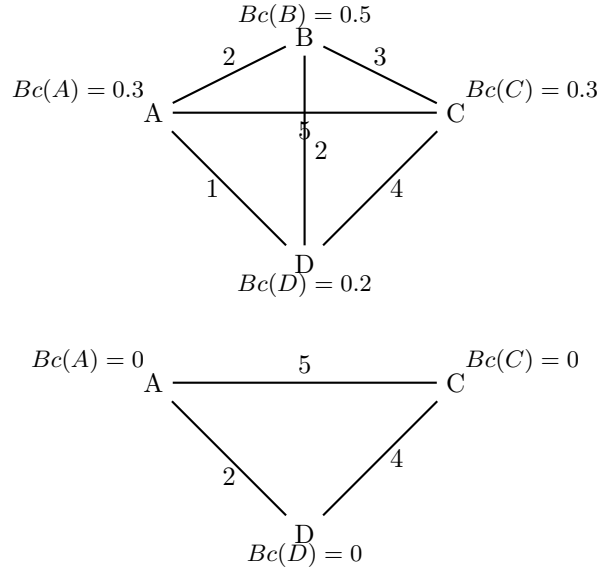


Figure 3.1: Examples of graphs with betweenness corresponding to each node before and after the removal of node B.

The removal can be caused by random attacks (failures and disruptions of one or more nodes with no intention) or targeted attacks (intentional removal of specific node or nodes, depending on their operating characteristics/functionality/importance). In both cases, the failure of a node is deemed through static and dynamic approaches.

We refer to the static approach when the removal of a node does not affect other nodes removal. Differently, the dynamic approach implies a cascading effect after one node is removed. In this case, the failure of one node propagates throughout the network, causing the failure of other interdependent nodes, which is called cascading failures.

Basically, the cascading failure model involves the transport network's volume of passengers being redistributed to other nodes not directly affected by the disruption, along the shortest path. Each node resists until its capacity is exceeded. When the load after the redistribution of passengers is bigger than the node's capacity, that node fails. The capacity ψ_i is the maximum load that a node can tolerate.

This occurrence is called inverse percolation and can be described as the removal of a fraction of nodes from a network (for example, PT stations), together with their corresponding edges (for example, rail connecting two metro stations). The effects of these phenomena are investigated through the changes in network performance, which correspond to the changes in network efficiency E (Latora and Marchiori, 2001). The latter is a metric used to obtain an indication of a network's ability to exchange information, which means that it describes how easily passengers can move from one node to another node in PTN. Nodes do not all transfer passengers in the same way, but usually the nodes at the borders of the network can not efficiently

communicate/exchange information, while the most central are more efficient and facilitate the connectivity.

Moreover, efficiency can be measured at a local scale (it depicts the quality of information between a node and its neighbours) and at a global scale (it refers to the entire network), as in the following formula:

$$E_{glob} = \frac{1}{n(n-1)} \sum_{i \neq j} \frac{1}{d_{ij}} \quad (3.5)$$

where d_{ij} is the distance between nodes i and j . Global efficiency E_{glob} is a value equal to or comprehended between 0 and 1 (Latora and Marchiori, 2001), where values close to 1 mean that the network is extremely connected. The change in network efficiency is intended as a change in network connectivity, thus in network resilience under the topological perspective. The connectivity analysis aims at evaluating the connectivity loss, which is the change in the sum of the inverse of the distance between all node pairs when excluding one or more nodes, with $i = 1, \dots, N$ (Latora and Marchiori, 2004):

$$\Delta E(i) = |E(G) - E(G \setminus i)| \quad (3.6)$$

where $E(G)$ is the efficiency of the original network, $E(G \setminus i)$ is the efficiency of the network after removing node i . $\Delta E(i)$ is the loss in efficiency caused by the removal of node i . Therefore, this formula also gives a meaning of node importance, based on their impacts on network efficiency, whether they are removed or implemented with a bike. Indeed, this formula can be used to compute any change in network efficiency, whether positive or negative. Specifically, in our case, it applies to measure the improvement in efficiency when integrating bike-sharing services, in other words, when we add flexible links to connect PT stops.

The removal strategy (inverse percolation) can be enforced in different ways:

- random, which means simulating random events such as accidents
- based on degree or betweenness measures, simulating attack strategies by removing nodes in decreasing order of such centrality measures
- cascading, when attack strategies are simulated by removing the node with the largest betweenness, recalculating the betweenness rank at each step.

The first strategy is the consequence of random disruptions, which can be earthquakes, floods (wide effects) or accidents, failures and temporary closures (delimited effects). While the other two categories are caused by targeted disruptions such as attacks, demonstrations or strikes, with wide effects for the connectivity of the network. In the further steps of this thesis, we will focus on the second option to decide which node needs to be reinforced through a BSS.

Another aspect of the connectivity loss is the evaluation of the generalised cost or travel time, which can substitute for the previous distance between nodes. The formula is as follows:

$$E_{glob} = \frac{1}{n(n-1)} \sum_{i \neq j} \frac{1}{T_{ij}} \quad (3.7)$$

To address the connectivity loss, we include the weighted analysis where a weight is attributed to the network efficiency based on OD flows of the shortest path. The weight F_{ij} is assigned to topological and

generalised cost analysis and represents the estimated flow between stops. Weighted global efficiency refers to how effectively a transport system moves passengers. The weighted efficiency is computed as the number of passengers moving between each pair of nodes over the distance between them:

$$E_{glob}^w = \frac{1}{n(n-1)} \sum_{i \neq j} \frac{F_{ij}}{d_{ij}^w} \quad (3.8)$$

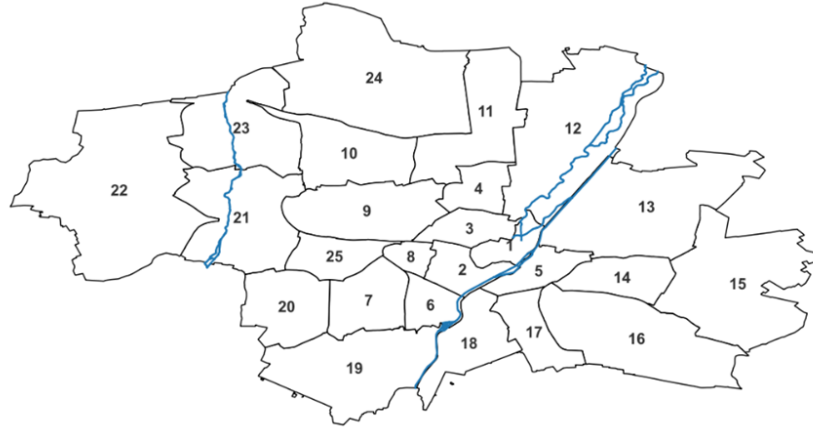
where F_{ij} represent the estimated flow between stops (Zhang and Ng, 2021b).

In our case study (Section 3.6), we will measure how global efficiency changes when we introduce and integrate bike-sharing services in a PTN.

3.6 Case Study: Munich

3.6.1 The city of Munich and Mobility Supply

The city of Munich is located in the south of Germany and is the capital of the Federal State of Bavaria. The city is situated in the administrative district of Upper Bavaria, and it forms the centre of the metropolitan region of Munich. With 1,561,094 inhabitants (as of March 31, 2021), Munich is the third-largest municipality in Germany (München-Landeshauptstadt, 2021). The city of Munich hosts international companies and is considered a cultural, political, scientific and media centre (Globalization and World Cities Research Network, 2017). The two major universities and various higher education institutions account for a total of 133,400 students. The high number of students is contributing to the relatively low average age of 41,6 years. It is divided into 25 administrative and political districts, as shown in Figure 3.2.



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 3.2: Munich borders and districts

Urban PT in Munich is primarily operated by the Münchner Verkehrsgesellschaft (MVG), which manages the subway, tram and bus services. The Munich Transport and Tariff Association is responsible for coordinating various PT services, including trams, buses, metros, suburban trains, and regional trains, within the city of Munich and the surrounding region. This area, which encompasses approximately three million inhabitants across 176 municipalities, ensures that public passenger and local transport are organised so that the network, fare system, and timetables are all properly coordinated. The Deutsche Bahn (DB), Germany's national rail operator, runs the S-Bahn network, connecting suburban areas and nearby towns in the Munich region to the city centre.

Concerning the infrastructure for active mobility, cycling in Munich has an above-average and strongly increasing share of 18% of the total traffic in 2020¹³. In addition, Munich is the city with the most bicycle lanes in Germany¹⁴. This context has favoured the development of several bike-sharing services. Among them, the MVG Rad bike-sharing system plays a significant role because it offers a hybrid model that allows users to return bikes at designated MVG stations or any publicly accessible location within the business area. Outside the business area, bike returns are only permitted at existing MVG stations, offering flexibility while ensuring proper infrastructure for service management (mvv-muenchen.de).

More details on city characteristics will also be given in Chapters 3 and 4, based on their specific objectives.

3.6.2 Data Description

In our general methodology, available in [Malandri et al. \(2023\)](#), we integrate three kinds of data: General Transit Feed Specification (GTFS), Geographic Information Systems (GIS), and Origin-Destination (OD) data, essential for analysing and optimising urban mobility systems.

¹³<https://www.sueddeutsche.de/muenchen/muenchen-radfahren-adfc-bilanz-1.4741451>

¹⁴Anlauf, T. (2017, October 20). KVR-Chef fordert schnellere Weiterentwicklung des Radverkehrs. Sueddeutsche Zeitung.

However, in the case of Munich presented here, we opted not to utilise the available OD data because it does not specify the mode of transport, encompassing flows from all transport modes, including private cars. Since our analysis is focused specifically on PTN and bike-sharing systems, the inclusion of car passenger flows introduces biases that are inconsistent with the goals of this study. Incorporating such data could misrepresent the dynamics of the PTN and its integration with bike-sharing systems, leading to skewed results. For the purposes of this thesis, we are solely interested in the structural approach to evaluate network resilience through measures of efficiency, independent of travel demand or user behaviour data.

The following sections provide detailed descriptions of the datasets employed in our analysis and their respective sources, including geospatial data for the PTN and bike-sharing systems, which form the foundation of our methodology.

3.6.2.1 General Transit Feed Specification (GTFS)

GTFS is an open standard designed to disseminate critical information about transit systems (McHugh, 2013). The GTFS schedule is easy to use and frequently updated because of its benefits in giving specific transit information to citizens and transport agencies. It includes static details about routes, schedules and geographic transit information, facilitating the construction of SMN, such as metro, tram, and bus systems. Each network comprises a series of nodes (stops) and edges/links (connections) arranged in a predetermined sequence.

However, GTFS data alone does not account for intra-network connections (line changes) or inter-network connections (changes in transport mode). This limitation is crucial for connectivity analysis, resulting in isolated networks for each transport mode. To address this, stops and connections can be aggregated to form a unified PTN. Departure and arrival times between nodes allow the calculation of in-vehicle time, while the frequency of PT at a node is determined by the number of vehicles passing through it. Additionally, GTFS data provides information on routes and modes, enabling the assignment of a transfer penalty.

In this thesis, Munich GTFS data are extracted from Deutschlandweite Sollfahrplandaten¹⁵ and the bike-sharing station locations from the MVG website¹⁶.

3.6.2.2 Geographic Information Systems (GIS)

GIS comprises integrated computer hardware and software systems that store, manage, analyse, edit, output and visualise geographic data. One of the most powerful aspects of GIS is its capacity for mapping and spatial analysis. By combining diverse data layers —such as demographic data, land use patterns, and transport accessibility— GIS provides a comprehensive framework for decision-making (Goodchild et al., 2005).

Within this study, GIS tools allow for the evaluation of connectivity between different modes of transport, the identification of mobility bottlenecks and the assessment of potential areas for improvement in bike-sharing and PT integration. GIS data are used to delineate the boundaries of the study area by integrating multiple spatial datasets, such as road networks, administrative zones and PT nodes. This ensures that the analysis is contextually accurate and geographically relevant.

Of our interest is the role of GIS in mapping and spatial analysis, enabling the integration of various data layers. This capability facilitates the spatial linkage between BSSs and PTN nodes, by mapping the

¹⁵urchgängige 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.

¹⁶<https://www.mvg.de/services/mvg-rad.html>. Retrieved on October 08, 2023.

locations of the latter and enabling the identification of gaps, overlaps and synergies between the two systems. The consequent integration supports the development of seamless multimodal transport networks. Such characteristics of the tool are employed to support the visualisation of diverse transport systems.

To ensure an accurate and comprehensive representation of the study area, the Munich dataset was extracted from OpenStreetMap (OSM) in 2023 through QGIS plugins. OpenStreetMap is an open-source, collaborative mapping platform that provides detailed geospatial data on a wide range of features, including streets, PTN, bike lanes, building footprints and points of interest. Its user-contributed nature ensures extensive coverage and regular updates, making it a reliable source for urban and transport studies.

3.6.3 Methodology

The assessment of resilience for Munich is focused on connectivity measures, motivated by the complete and usable GTFS schedule, as well as maps based on bicycle stations and a good supply of other interesting data for our analysis (to be supplemented in Chapter 4). This aspect allows us to generate a comprehensive and useful calculation of PTN connectivity for the purposes of our analysis, which has its focus on identifying the most critical points of the network in order to potentially turn them into MHs. However, we lack valid data on the OD matrix, which does not allow us to measure accessibility in a consistent manner and integrate the resilience indicator with this multidimensional aspect (as we did in Deliverable 5.4 by [Malandri et al. \(2023\)](#) for other case studies). This approach still offers valuable insights by examining the structural properties of Munich PTN and its overall performance.

To assess transport network resilience, we consider the PTN as a graph, wherein the nodes correspond to PT stops and the edges denote physical or operational connections between two successive PT stops, or stops equipped by a BSS. The graph-based approach allows for analysing the structural resilience of the PTN, focusing on metrics like connectivity, centrality and the overall efficiency of the network. By modelling different transport modes as separate and interconnected networks, the analysis captures both the individual characteristics and the interdependencies between layers associated with each transport option.

In our methodology, we first generate the general PTN of the city, as in Figure 3.3. Each mode is indicated by a different colour: blue, light red, green, and dark red. Their links represent routes of the bus, metro, train, and tram networks, respectively.

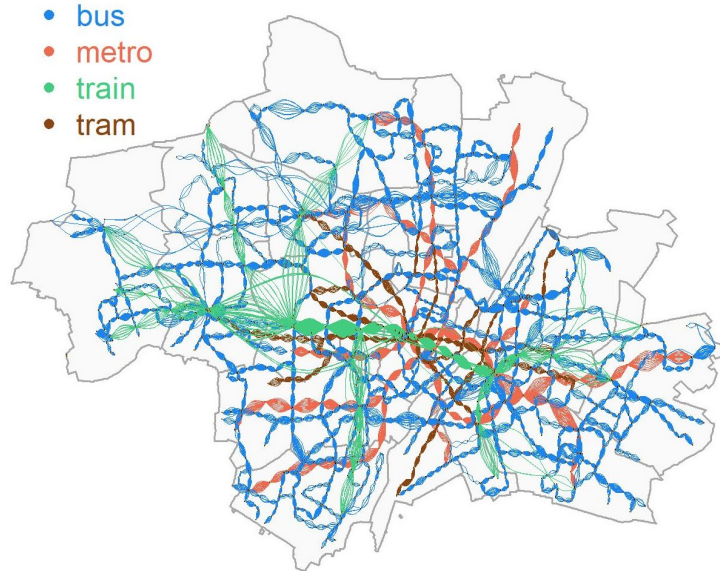


Figure 3.3: Detailed Single Mode Networks in Munich

Once we have all the individual SMNs, such as metro, tram and bus networks, they are aggregated into a single comprehensive network, the aforementioned APTN (Figure 3.4). This aggregation process is critical for creating an integrated representation of the city's PT infrastructure, allowing for the analysis of its overall efficiency and resilience.

During the aggregation, individual stops from different transport modes are combined based on specific criteria. The process involves merging stops that share the same name, even when variations exist due to suffixes or prefixes (e.g., "Hauptbahnhof" and "Hauptbahnhof Süd"). This ensures that closely related stops are considered as a single node in the aggregated network. However, name similarity alone is not sufficient to merge stops. Spatial validation, facilitated by geospatial data and R code, is employed to confirm that the stops are geographically in proximity and can reasonably be assumed to serve the same physical location or an area close enough to function as a single hub.

By incorporating spatial data, the methodology avoids errors such as aggregating stops with the same name but located far apart (e.g., "Hauptbahnhof" in different districts). All the aggregated stops fall at a distance below 150 mt from the geometric centroid of the stops identified by the same name. Almost 70% of the aggregated stops represent the aggregation of at least four individual stops with the same name.



Figure 3.4: Aggregated PTN

To understand the magnitude of the aggregation process, Figure 3.5 shows the percentage of aggregations concerning different modes: around 1% of aggregate nodes are served by all 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.

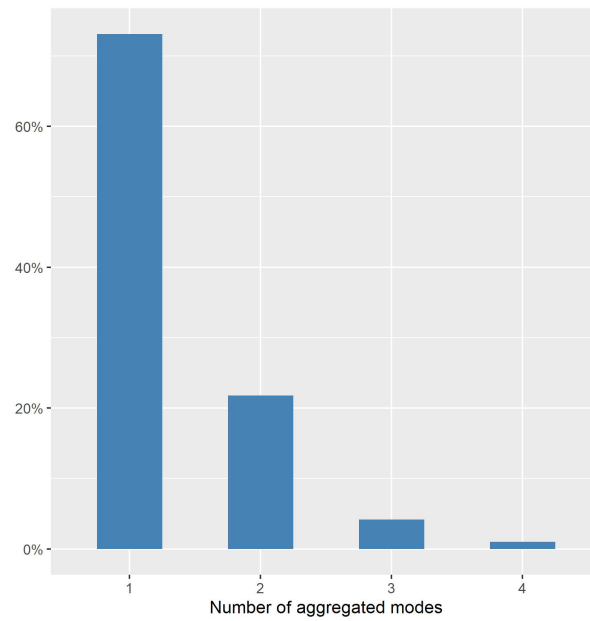


Figure 3.5: Percentage of aggregated modes

As already mentioned, we obtain BSSs from QGIS, as shown in Figures 3.6 and 3.7, where station-based bicycle systems are revealed by where bicycles are picked up and dropped off.

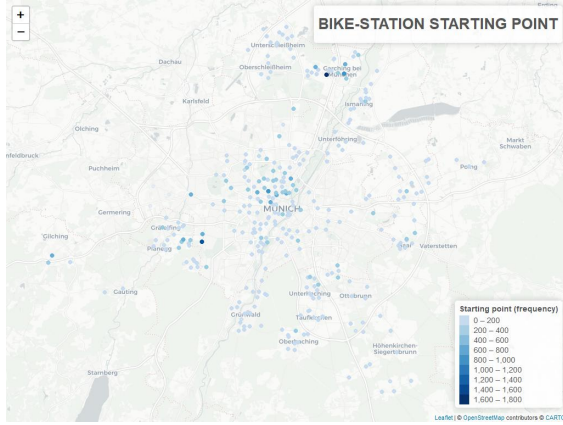


Figure 3.6: BSSs starting point (by frequency), extracted from QGIS.

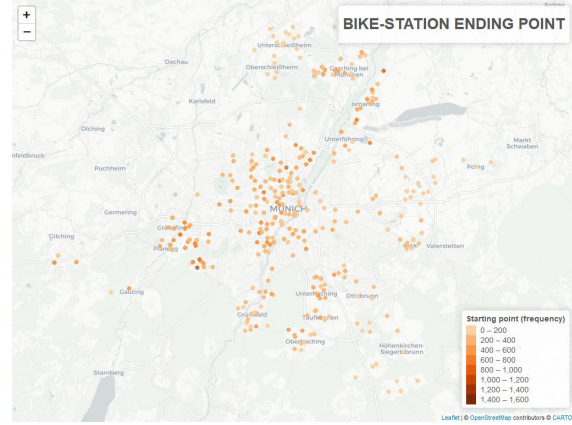


Figure 3.7: BSSs ending point (by frequency), extracted from QGIS.

From the previous points, we select only those BSSs within the considered borders and within 200m from PT stops. They total on 48 BSSs as in Figure 3.8. They are merged with the PTN, resulting in what we refer to as Aggregated Public Transport Network-Bike (APTNB in Figure 3.9). The integration of PTN and bike-sharing network follows similar principles to those used for earlier aggregation steps.

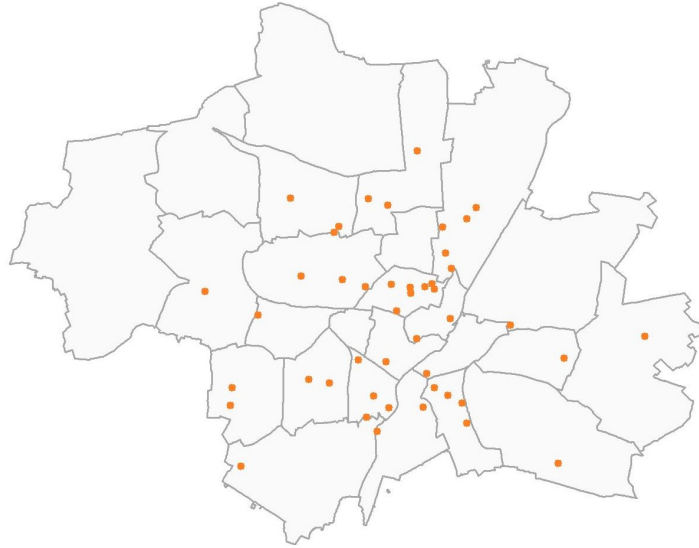


Figure 3.8: Munich Bike-sharing Stations



Figure 3.9: Aggregate Public Transport Network-Bike (APTNB)

For the bike-sharing network, a station-based service is established by considering fixed bike stations located within a circular buffer of 200 meters from PTN stops. This approach is in line with previous studies on bike-sharing network design, such as those by [Aultman-Hall and Kaltenecker \(1999\)](#) and [García-Palomares et al. \(2012\)](#). The BSSs outside this buffer are automatically excluded and are not included in the network, since they do not have the role of directly complement PT. The distance between PTN stops and integrated BSSs is calculated using the `osrm` package in R, a routing service that relies on OpenStreetMap data for accurate measurements.

Furthermore, the integration process also accounts for the connections between PTN and bike-sharing networks by ensuring that edges are formed where PTN stops and BSSs are located within a 3-kilometre radius of each other. This methodology, as proposed by [Böcker et al. \(2020\)](#), enhances the connectivity between the two networks and supports more flexible transportation options for users.

Once the PTN and bike-sharing networks are integrated, it is possible to assign weights to the edges of the resulting network. These weights represent the travel time required to move between connected nodes (stations or stops). Assigning such weights is a critical step in the analysis, as it transforms the network from a purely topological representation into a weighted graph, enabling the evaluation of travel efficiency.

The calculation of travel time is based on the geographic distance between two connected stations and the assumed speed at which a person is traveling. Specifically, for the bike-sharing network, we assume an average cycling speed of 15 km/h, following the observations stated by [Fishman et al. \(2013\)](#). This assumption aligns with the typical speeds observed in urban settings, where factors such as traffic conditions, intersections and the nature of bike-sharing systems influence average speeds. This speed provides a reasonable estimation for

calculating the time it takes to travel between stations via the bike-sharing network. Instead, travel time for PT modes is derived by the GTFS schedule, which provides departure and arrival times from and to each stop. So that, for the APTN, the resulting travel is the average among each PT mode.

The inclusion of travel time as an edge weight is particularly significant for analysing the integrated network's performance. It allows for a more realistic assessment of how users navigate the combined PT and bike-sharing system. For instance, shorter travel times between nodes indicate a higher level of efficiency and connectivity, while longer travel times may signal bottlenecks or areas requiring infrastructure improvements.

Moreover, the weighted graph enables advanced analyses, such as transforming the solely shortest-path computations from distance-based to time-based, providing insights into user convenience and overall system functionality by employing weighted connectivity measures. From here, the shortest path no longer refers to the shortest distance but to the shortest time, also defined as the minimum travel time between two nodes.

Once we have the APTN and APTNB weighted by time, we can provide some insights into urban resilience by computing node centrality and network connectivity for both scenarios. As previously stated, the analysis of betweenness centrality offers valuable insights into the role of each node within the transport network, and it gives an interpretation of resilience in the case of disruption, when one or more nodes are closed, based on their centrality. This metric quantifies the extent to which a node acts as a bridge or intermediary in the shortest paths connecting other nodes in the network.

By doing this, we identify which are the most critical and transit stops in our network. While their position makes them key junctions that consolidate traffic flow and enable efficient connectivity between disparate regions, on the other hand, their centrality underscores their vulnerability. Indeed, disruptions at these points can ripple through the entire transportation system, so that is important to strategically develop alternative connections at these points (Huang et al., 2024).

We compute the betweenness for each node of the APTN and APTNB, in order to understand which are the most critical nodes and where they are located in the Munich urban transport network. The comparison of betweenness centrality values before and after the integration of bike-sharing systems is crucial in assessing the impact of multimodal transport solutions. It highlights how combining transport modes can reduce the vulnerability of highly central nodes, while improving overall network connectivity and consequently network resilience. Aligning with these perspectives, we provide the main metrics for the APTN and its global efficiency, as well as for the APTNB. These computations allow us to compare the values corresponding to the different scenarios and derive some conclusions. The results of such computations are shown in the next section.

3.6.4 Results

The calculation of betweenness is instrumental in showing which nodes represent critical points, by quantifying how frequently they are traversed by the shortest/fastest paths connecting other nodes in the network. This aligns with the assumption that passengers' route choices are primarily influenced by travel time, with the expectation that they will consistently opt for the fastest available route (Cascetta, 2013). Nodes with high betweenness centrality values are often indispensable for efficient network operation, as they facilitate significant portions of passenger movement with a minimum cost in travel time.

In the case of Munich APTNB, the distribution of betweenness values is visually represented in Figure 3.10. Here, the size of the blue points assigned to each stop is proportional to the betweenness value of that stop. From this visualisation, it is evident that the nodes with the highest betweenness centrality are predominantly located along the S-Bahn lines, particularly in the corridor running parallel from Laim to

Ostbahnhof. This alignment underscores the critical role these stops play in connecting different parts of the city, as they are pivotal for the majority of the shortest paths in the network.

The concentration of high-betweenness stops along the S-Bahn lines can be attributed to the structural design of Munich's PTN. The S-Bahn network serves as the backbone of urban and suburban transit, linking outlying districts with the city centre and providing seamless connections to other modes of transport. Consequently, these stops become natural convergence points for passenger flows, amplifying their strategic importance.



Figure 3.10: Munich APTNB Betweenness Centrality

Among the most critical stops, several are key railway stations. For example, Hauptbahnhof, the central railway station, serves as the primary hub for regional and international travel, while Laim functions as a significant interchange station. Donnersbergerbrücke, the second-largest S-Bahn station after Hauptbahnhof, plays a vital role in connecting multiple routes. Marienplatz, located under the iconic square in Munich's city center, is a major interchange point for both the S-Bahn and U-Bahn systems. Similarly, Hirschgarten serves as an essential node on the S-Bahn's main line.

Analysing the top 6 critical stops, their high betweenness values underscore their importance as connectivity points. These values indicate that a significant proportion of the fastest paths traverse these nodes, meaning their disruption could severely impact the network's overall connectivity. The potential closure of such stops would dramatically reduce global efficiency, highlighting their vulnerability and the importance of maintaining their operational integrity.

Table 3.1: Betweenness centrality without bikes of the top 6 PT stops

Stop	Bet (without bikes)	Hub Bet Rank
Hauptbahnhof (S, U, Bus, Tram)	407969	1
Laim	384667	2
Donnersbergerbrücke	350629	3
Ostbahnhof	342853	4
Hirschgarten	326495	5
Marienplatz	318303	6

This is clearly demonstrated above, in the Table 3.1, which highlights the top 6 critical stops in the network. Betweenness centrality has been calculated for all stops in the APTN, which values show a wide range. The highest value represents the most critical stop, with a betweenness of 407969, while some stops have a betweenness centrality of 0. These low values are typically associated with stops located at the network's periphery, such as terminals or end-of-line stations. These stops primarily function as origins or destinations for trips rather than as intermediaries connecting other nodes. Consequently, they are not part of any shortest or fastest paths between other pairs of nodes within the network.

However, certain factors can further explain why some stops have low or zero betweenness values. If travel paths are weighted (e.g., by time or distance), stops with a higher "cost" associated with passing through them may be bypassed entirely in favour of more efficient routes. This weighting system can significantly influence the calculated betweenness, emphasizing stops that facilitate faster or shorter connections. Additionally, incomplete or sparse data about routes, connections or travel demand might misrepresent the actual role of some stops in the network. For instance, a stop might appear peripheral in the data but play a more critical role in real-world operations, such as serving as a local hub or accommodating high passenger demand outside the zone selected for our research.

To afford a comparison with the values in the previous table, we present values referring to APTNB nodes in Table 3.2. In general, betweenness is lower for stops across the network when bike-sharing systems are integrated. This reduction in betweenness highlights a significant finding: the availability of bike-sharing provides alternative paths for travellers, effectively redistributing traffic across the network. Stops that previously acted as critical hubs or "bottlenecks" experience less pressure, as some passenger flows are diverted to other routes facilitated by the bike-sharing infrastructure.

Table 3.2: Betweenness centrality with bikes of the top 6 PT stops

Stop	Bet (with bikes)	Hub Bet Rank
Hauptbahnhof (S, U, Bus, Tram)	406130	1
Laim	384467	2
Donnersbergerbrücke	350182	3
Ostbahnhof	342531	4
Hirschgarten	326037	5
Marienplatz	318282	6

Upon examining the rankings, we observe that the inclusion of bike-sharing systems does not consistently alter the rank order of stops. Notably, only Ostbahnhof and Donnersbergerbrücke have switched positions, indicating that the relative importance of these two nodes in the network shifts slightly when bike-sharing is introduced. This suggests that while the integration of bike-sharing systems influences the network's overall connectivity, maintained by stops with high betweenness centrality, individual stop rankings may vary depending on local network structure and spatial proximity.

Indeed, the incorporation of bike-sharing systems into the APTN not only enhances the efficiency of individual travel but also contributes to the robustness of the entire network. This improvement is particularly evident in the subsequent analysis of network efficiency and connectivity presented in Table 3.3, which further illustrates the quantitative impact of bike-sharing on overall system performance.

Table 3.3: Aggregate PTN metrics comparison, showing values for scenarios without and with bike-sharing integration

Metric	Without bikes	With bikes
Node	1076	1076
Length	2745	6951
Density	0.0025	0.0063
Average Path Length	1217.02	1201.02
Average Density	5.21	13.2
E_glob	0.00101825	0.00104051
ΔE_{glob}		0.00002226
$\Delta\%$		+2.2%

The value itself is relative and gains meaning when compared with other configurations of the same network, for this reason, we compare two different statuses of our network. All the metrics vary significantly because of the additional connections through bike-sharing links. The change in length, expressed in second, reflects a richer set of travel options as well as density, which means that nodes are more interconnected. Despite the increases, average path length is slightly less, because more direct or faster routes might exist. Similarly, the increase in average density indicated that each node is connected to more alternatives thanks to bikes. More importantly, we note that bike-sharing systems integration into these corridors has an impact on network resilience, enhancing global efficiency by the 2,2%. This means that, despite the critical role of stops with high betweenness, which makes them potentially vulnerable points, as disruptions at these locations could lead to cascading delays and inefficiencies, the network performance benefits from the existence of bike-sharing.

3.6.5 Discussion and Limitations

In this section we aim to discuss the results of our computations, offering insights into their implications. The findings emphasise the value of integrating traditional PTN analysis with visual mapping tools to uncover

patterns of vulnerability in urban transport networks. They also underscore the benefits of multimodal approaches, such as integrating bike-sharing systems to balance traffic flows and reduce pressure on critical nodes, like those along the S-Bahn axis.

To do so, one key methodological choice is to select only station-based bike-sharing services for their active role in directly substituting PTN shortcomings. This is widely recognised in transport planning, where proximity to PT stops is a critical factor in determining the integration of BSS with PTN, also influencing the use and number of trips made by a shared bike when it is accessible from a PT stop (Jaber et al., 2022). This may appear as a constraint, while it can represent a stimulus to have affordable and available bikes at fixed locations (Bachand-Marleau et al., 2012). The 200-meter radius threshold from a PT stop, instead of being a limitation, aims to include as many BSSs as possible for first- and last-mile trips. BSS outside the 200-meter radius can be relevant for certain users who travel further distances than the conventional ones (Noland et al., 2016), but this might overlook alternative travel behaviours that deviates from our study. The inclusion of BSSs that do not serve as effective first/last-mile solutions could lead to other infrastructural constraints.

Lastly, the limited field of station-based bike services also stems from the difficulty of modelling free-floating, which is not in line with our goal of measuring multimodal connectivity in spatial proximity.

Focusing on our case study, we note that Munich’s urban network has a considerable number of critical PT stops with high betweenness, which means that they serve as strategic hubs acting as obligatory transit points for travellers. In particular, they allow users to take the fastest paths between different zones in the city, ensuring efficient connectivity across the network. Their strategic position makes them key junctions for maintaining indispensable links between transport modes.

It is fair to mention that, in calculating travel time between PT stations, we use average travel time (derived from GTFS) without considering PT frequencies. Ideally, frequency data would enhance the accuracy of travel time estimations by accounting for waiting times and service availability. However, frequencies can be assumed to matter less if we hypothesise that users are able to plan their journey in advance, choosing the combination that minimises waiting time. By doing so, we focus more on network efficiency aspects rather than on passenger behaviour.

According to this, if we consider both scenarios (with and without bike sharing), we can highlight that the network heavily depends on these high betweenness nodes to sustain its robustness. Indeed, high betweenness centrality underscores nodes vulnerability, as disruptions at these points can ripple through the entire transportation system. Currently, these aspects suggest that these nodes are prone to congestion if the shortest paths have a high passenger flow, as many trips converge on them, representing potential bottlenecks.

Without supplemental infrastructure, such as BSSs or other sharing options, these nodes may struggle to handle high volumes of traffic efficiently. Indeed, mode diversification and effective integration introduce redundancy into the transportation system, creating more alternatives for completing trips. This redundancy decentralizes traffic patterns, reducing the centrality of individual nodes and fostering a more resilient and balanced flow.

Ultimately, the slight improvement in network efficiency, when bike-sharing is integrated, probably stems from inefficient placement of BSSs, which certainly bring benefits but must be optimally placed to achieve greater results. Another influencing factor to prove their advantages could be include real passenger flow in the analysis, which is not available for Munich PT and bike flows only because it is aggregated and generalised with private cars.

3.7 Conclusion

This chapter has addressed the need to analyse transport networks from a topological and network analysis perspective, in order to give a measure of resilience. To do so, after a detailed methodological section, we provide an exploration of the impact of the integration of bike-sharing systems into Munich's APTN, focusing on their effects in enhancing network efficiency and resilience. The scope is to establish a framework in order to develop MHs at critical points of the network, able to reduce its vulnerability and increase the connectivity.

Understanding the spatial distribution of betweenness centrality is essential for both operational and planning purposes. Stops with high betweenness are critical for ensuring connectivity, but they also influence the vulnerability of the network when exposed to disruptions. Indeed, the latter, such as delays or closures, if occurring at these locations, could have cascading effects, causing significant detours and inefficiencies in network connectivity. Conversely, integrating bike-sharing systems into these corridors enhances network resilience by offering alternative travel paths that alleviate the dependency on a few central nodes.

The proficient integration of PTN and bike-sharing network accounts for the efficient interplay between them. This has been demonstrated by comparing global network efficiency with and without considering bike-sharing system. The integrated network has shown a higher value for global efficiency compared to the solely APTN.

Despite this evidence, further research could enrich the analysis by including the passenger flow in the computation. By doing this, the results will be more realistic and directly approach the problem of traffic redistribution, which is excluded in our case. The decision to disregard this factor is motivated by the limited data, but, above all, by the interest in targeting the relevance of certain nodes in the network given their positions, as it will be useful to develop the next chapter.

Indeed, offering modal substitution and alternative flexible modes, such as bike-sharing options, has been proved to enhance network efficiency, but it could also be a way to reduce congestion and promote sustainable urban mobility. By integrating such modes into the analysis, future research could address the dynamic interplay between modal choices and passenger flow, providing a more comprehensive understanding of traffic redistribution and its implications for network resilience.

Additional advantages regards travel experience. Indeed, while PT edges may have a relatively fixed travel time due to schedules and operational constraints, bike-sharing edges can reflect the flexibility of direct, uninterrupted routes, offering an alternative to potentially congested or indirect PT options. By quantifying the temporal efficiency of these connections, planners and researchers can better evaluate the potential benefits of integrated mobility systems, optimising them in terms of resilience, reduced reliability on central nodes and enhanced user experience.

These findings provide a crucial foundation for the subsequent chapter, where a multicriteria approach is introduced to address the uneven distribution of BSSs across Munich's districts. This approach seeks to identify optimal strategies for improving the overall connectivity of the urban transport network. Specifically, it responds to the pressing need for enhanced integration of mobility systems by proposing targeted implementation of MHs. By strategically expanding the distribution of BSSs in underserved areas, the methodology aims to create a more cohesive and efficient network, fostering better resilience across the city.

Part III

STAKEHOLDER INVOLVEMENT IN LOCATING AND DEFINING MOBILITY HUBS

Chapter 4

Network Resilience for Mobility Hub Location: A Multi- Criteria Approach

4.1 Motivation of the Study

This chapter builds upon the previous one by presenting a practical application of the resilience indicators calculated earlier. Indeed, once we have collected the existing indicators and we have defined the most feasible one in the case of multimodal transport networks, we seek to demonstrate how betweenness centrality can be used to guide the optimal location choice for the implementation of a MH.

To achieve this goal, we explore various methods for resource and transport service allocation discussed in the literature. After reviewing these approaches, we determine that multi-criteria analysis (MCA) is the most suitable method for our context. Our choice is further supported by the work of our partners in the SmartHubs project, whose development of a multi-criteria tool for MH improvement influenced this chapter.

In this chapter, as well as in the previous one, we focus on a preliminary stage of MH development. We examine the steps required to facilitate MHs creation by implementing BSSs integrated with PT stops. This integration identifies shared mobility modes as a vital component of urban mobility planning, particularly when combined with the PTN.

For these reasons, this study aims to propose a new location choice framework for BSSs, incorporating a quantitative evaluation of PTN connectivity. We do so by using the analytic hierarchy process (AHP) and MCA. In our MCA, the alternatives considered as suitable locations for new station implementations are areas in the proximity of PT stops.

To determine the most suitable locations, we propose a set of criteria, some derived from the literature, which include proximity to points of interest (school buildings, green areas, tourism areas and entertainment/leisure facilities), socio-demographic characteristics (population density and employment rate), local pollution rates and a network-based criterion, measuring the importance of each PT stop within the network in order to increase transport resilience, namely betweenness centrality. This study is a direct extension of the work discussed in Chapter 3, where we calculated betweenness centrality for Munich. The values obtained from the previous analysis are incorporated into the criterion “Proximity to Critical PT Stop” and are weighted using the AHP. We submit a questionnaire to transport experts, which results in the weight assignment and drives our analysis, in order to introduce stakeholder involvement in addressing such criteria.

Finally, we emphasise that the Munich case study serves as a prototype for future applications in different urban contexts. The framework developed here can be adapted to other cities, both small and large, and can be used to foster greater integration between bike-sharing and PT systems, ultimately contributing to more resilient and sustainable urban mobility.

4.2 Introduction

Bike-sharing systems are attracting considerable interest in the literature due to their potential key role in encouraging the transition from car-based private transport to more sustainable mobility, particularly in the urban context. They were recently introduced in urban life as a means of PT, but their history started only in the Netherlands in the 1960s with the first bike-sharing program. The diffusion of BSSs has rapidly expanded in recent decades: from just five BSSs around the world in 2000 to over 1.914 by August 2022.¹⁷

¹⁷The bike-sharing world map. Retrieved March 11, 2024, from https://bikesharingworldmap.com/reports/bswm_mid2022report.pdf

Bike-sharing systems can be divided into three categories: station-based (docked), free-floating (dockless), and hybrid systems. The first option requires users to pick up and return bikes at specific docking stations, and the second allows users to collect and drop off bikes anywhere within a wider extended area. In the third case, bikes can be returned to designated locations that can be docking stations or clearly delimited virtual stations. When designing a bike sharing system, one of the first issues that directly affects the accessibility, attractiveness and efficiency of the service is where to locate the bike stations (Zhao, 2014). This choice is crucial for the success of a bike-sharing system as well as the connectivity of the entire PTN.

This chapter aims to guide decision makers in ranking alternative locations for installing physical docking stations by combining traditional planning indicators with an explicit consideration of transport network connectivity and robustness, two crucial properties that influence the resilience of urban transport networks (Ahern, 2011). To accomplish our objective, we use MCA, an approach to decision-making that facilitates the choice between multiple alternatives when various criteria are simultaneously considered. In our case, the alternatives — potential new locations for a BSS — correspond to the PT stops that currently do not have a BSS nearby. This choice is motivated by the idea of favouring the complementarity between public and shared transport, in order to obtain a more integrated urban transport system, which better responds to shocks and disruptions (D’este et al., 2003).

The criteria used are selected from those recommended in the existing literature: proximity to points of interest (POIs) (school buildings, green areas, tourism areas and entertainment/leisure facilities), socio-demographic characteristics (population density and area employment rate) and local pollution rates. The first contribution of this chapter is the inclusion of PTN robustness between the evaluation criteria. Robustness is defined here as the ability of a transport network to maintain its functionality under disruptions or failures (Li, 2014). It is a desirable transport network feature, which can be enhanced by bike-sharing, as the latter provides an affordable alternative to link PT stops when the network presents unexpected disruptions. However, to our knowledge, the role of robustness has not been explored so far in the academic literature on bike-sharing locations. The second contribution of this chapter is identifying the relevance of network robustness within the set of criteria commonly employed for this aim. To do that, we use the AHP on the basis of a questionnaire administered to a group of 17 experts in urban mobility.¹⁸ The method is grounded in mathematical and psychological principles, and offers a systematic approach to handling intricate decision-making scenarios through pairwise comparisons (Saaty, 2008). AHP employs opinions from experts and stakeholders to establish hierarchies of importance between criteria, ensuring a comprehensive and balanced evaluation.

After outlining our approach, we apply it to the city of Munich in order to address the following research questions:

- *What factors influence the choice of the optimal location for installing a new BSS? Consequently, which is the best location for a new BSS?*
- *Does the inclusion of PTN robustness in the MCA impact our decision?*
- *Within our approach, can we replicate the location of existing BSSs in the districts under analysis?*

These research questions are developed around the reason to investigate the influence of each weighted criterion, in order to develop MHs following expert suggestions. MCA allows for prioritising those stops

¹⁸The restricted number of experts involved is justified by the need to value their competence in the aggregation estimates, since, in large sample sizes, individual competencies impact the results to a less extent (Tsyganok et al., 2012).

that have higher values for the most weighted criteria and, consequently, to shape the final decision. This approach allows us to highlight the importance of expert opinions and the impact they have on strategic decision-making in urban mobility planning.

Furthermore, we want to assess if the ranking of the best alternatives to develop MHs varies according to the inclusion or exclusion specifically of the robustness criterion, to which we are interested in measuring the relevance. By doing so, we can identify whether the ranking remains stable or fluctuates under varying criteria.

Lastly, we explore a counterfactual scenario to investigate whether the initial location of BSSs prioritize the most critical points in the network. To do so, we hypothesise the effects on the rank of removing existing bike-sharing services and recalibrating the betweenness centrality. Essentially, we investigate whether the strategic placement of BSSs in the past was influenced by the same criteria we propose.

The rest of the chapter is organised as follows. Section 4.3 presents the related literature. Section 4.4 describes the methodology employed. Section 4.5 introduces network robustness in our analysis. Section 4.6 illustrates the application of our approach to the case study of Munich. Section 4.7 discusses the results, while Section 4.8 concludes and propose future research directions.

4.3 Literature Review on Transport Modes Integration and Multi-criteria Approach in Mobility

Our research is moved by the motivation that the location of BSSs is of critical significance for the integration of a bike-sharing system with the PTN, as claimed by [Lin and Yang \(2011\)](#). We are particularly interested in assessing the role of BSS, acting as a MH, and facilitating the connections between origin and destination through different transport modes. Particularly, this section is an expansion of Section 3.3, with a greater focus on the role of the BSSs, in addition to the benefits already mentioned.

We note that BSSs in the literature are considered to favour PT interchange, which determines their proximity to PT stops. The main literature that influences our study advocates that the bike-sharing system integrates the PT system and extends the accessibility to the final destination ([Lin and Yang, 2011](#)). Indeed, some authors ([Böcker et al., 2020](#)) argue that ridership is broadly higher around PT stops, which led us to include proximity to them among the location factors in our analysis. Moreover, a specific study on the integration between PT and bike-sharing systems is offered by [Campbell and Brakewood \(2017\)](#), which quantifies the interrelation between BSSs and bus ridership, assessing how bike-sharing complements bus trips. According to this literature, we remark that we deal with bike-sharing as an additional, integrated and substituted mode, which requires trips previously made by transit. It is the case of BSS as a facilitator for PT use, as an access-egress mode instead of walking ([Böcker et al., 2020](#)).

Wherever local access to PT is suboptimal, BSSs, even more than ordinary cycling, have also the fundamental role of enhancing flexibility, reliability and comfort ([Böcker et al., 2020](#)), but this certainly differs in relation to different population categories. For this purpose, we included socio-demographic characteristics to manage the BSSs position, also through these factors.

For the aforementioned reasons, the location problem constitutes a topic discussed in the literature from

different perspectives. In this section, we review only those relevant studies that use MCA to deal with this problem. The first group of studies approaches the more general transport system development through multi-criteria methods. An example that emphasises the role of bicycle facilities is [Rybarczyk and Wu \(2010\)](#), which encourages the development of a multi-modal transport system. The study presents a multi-criteria evaluation (MCE) analysis, including supply- and demand-based criteria for bicycle facility planning at two geographic levels (network level and neighbourhood level). While the focus for the previous studies is on the criteria selection, [Sayers et al. \(2003\)](#) is more interested in weighting the criteria of the MCA in such a way as to construct a flexible, transparent and user-friendly method of ranking transport investments.

Going deeply into the bike-sharing system topic, the review of [Bahadori et al. \(2021\)](#) proposes an overview of studies dealing with the BSS location problem under planning and operational viewpoints. Several of the studies reviewed propose a mixed approach between MCA and AHP in locating transport services. Among them, it is interesting to mention [Kanjanakorn and Piantanakulchai \(2013\)](#) because of the similarities with our study in ranking suitable locations for BSSs in the city of Bangkok, even if using different criteria. While the method is pretty similar, the contexts vary a lot. Munich is well-served by the PT system, whereas Bangkok is not and is characterized by traffic congestion problems. This is translated in the main difference that can be highlighted, which is the use of 'accessibility' to bike routes and walkability to destinations, instead of 'proximity' to POIs as we do. The latter implies an already existing bike-sharing system to be implemented and optimised, while the first one concentrates more on the strategies to encourage the use of bike-sharing mode.

Regarding this last matter, another group of studies reviewed deals with the benefits of integrating bike-sharing systems and PTN, emphasising the role of the BSSs location. A recent approach comes from [Kurniadhini and Roychansyah \(2020\)](#), which aims at implementing active mobility (walking and cycling) in cities due to the establishment of BSSs. For this reason, it gives emphasis and weight, in terms of AHP analysis, to "Proximity to bicycle lanes" and "Proximity to bus stops". In [Croci and Rossi \(2014\)](#), the focus is on the factors that attract users to use BSSs, based on their proximity and visibility.

An example of MCA and AHP together is [Ghandehari et al. \(2013\)](#), which reveals four main factors that influence the location of a BSS: closeness to the bicycle path, transport and networks, demand, and type of attractions. These criteria are also used to define the criteria employed in our study, where we avoid the distinction between criteria and subcriteria by assessing directly the weights of each of them compared to the others. The complementarity between MCA and AHP is also evident in [Kabak et al. \(2018\)](#), which attempts to evaluate and compare current BSSs and future stations. Additionally, this study combines the previous methods with GIS to address twelve conflicting criteria. These researches are behind our research to prove the consistency of our choice of criteria and methods, highlighting the gap in revealing the best location of BSS given the properties of the PTN, which is, in our case, the network robustness.

The cited literature approaches the BSS location problem by applying MCA on the basis of several criteria common to most studies. In our study, we selected the criteria by combining the above approaches. As a result, we include environmental, social and economic aspects, as well as transport network characteristics, which have not received enough attention in the past. Indeed, we note that there is no discussion about the influence of network robustness on the decision of where to locate BSSs. We propose to include the robustness properties of the PTN, which we believe are relevant in evaluating the impact of new BSSs and represent the innovative contribution that our study makes to this topic.

In the table below, we define a list of the most used criteria in the literature, which inspires us, but in some cases, they are included in the previous studies under different perspectives. Indeed, we combine and

transpose some already-used criteria into more comprehensive terms. All of them are intended to proceed by "Proximity to", because they refer to the distance and land use of the area around the BSS.

The studies in the columns represent the main contributions to the placement of BSSs or, more generally, to urban mobility design, integrating PT and bike-sharing systems with a multicriteria approach. We deliberately aggregate the sub-criteria, where multiple levels of MCA were present in different works, into individual criteria to allow for a more direct comparison of the weights. Although no study explicitly refers to the concept of robustness, aspects of network structure or proximity to transport stops are generally considered, such as "Proximity to bus terminal", "Proximity to train station" and "Proximity to bus stop" (Kurniadhini and Roychansyah, 2020), and we grouped them under the terms "Network structure and PT stops". Furthermore, for very similar terms, like "Proximity to subway stations" and "Distance from important intersections" (Jahanshahi et al., 2019), we also merge them under that criterion.

Table 4.1: Normalized weights of our criteria presented in previous literature.

CRITERIA	Ghandeari et al. (2013)	Sayers et al. (2003)	Cetinkaya (2017)	Kanjanakorn et al. (2013)	Kabak et al. (2018)	Rybarczyk & Wu (2010)	Kurniadhini & Roychansyah (2020)	Jahanshahi et al. (2017)
Green areas	0.3346	-	-	-	-	0.095	0.092	-
Sport centers	0.4545	-	0.014	-	0.115	0.195	0.283	-
Tourism areas	-	-	0.014	-	-	-	0.316	-
Schools	0.4743	-	0.018	-	0.017	0.142	0.091	-
Density population	-	-	0.065	-	0.098	0.047	0.392	0.107
Employment areas	-	-	0.007	-	-	-	0.115	-
Network structure and PT stops	0.5188	-	0.151	-	0.129	-	0.555	0.501
Bike lanes	0.3136	-	0.327	0.384	0.298	-	0.445	0.051

The normalised weights varies a lot across authors, with very low values in some studies with a larger number of criteria and sub-criteria compared to our study (an example is Cetinkaya (2017), where criteria in common have low weights). Higher values are assigned to "Bike lanes" and "Network structure and PT stops" (Cetinkaya, 2017; Kabak et al., 2018; Jahanshahi et al., 2019), which underlines the role of bike-sharing systems in combination with the entire transport network.

4.4 Methodology

4.4.1 Multi-Criteria Analysis (MCA)

MCA is a class of approaches aiming to rank alternatives or solutions based on several criteria. In particular, multiple-attribute decision-making includes a set of approaches to solve “ill-structured” problems in which the objective is complex and different solutions are possible. The best solution (or a set of preferred solutions) is proposed depending on attributes/criteria previously selected and weighted.

We consider the weighting of criteria a central part of our study. There are several options to assign values to criteria; in some cases, they can be equal for each criterion, and this does not require any additional input from decision-makers (Daugavietis et al., 2022). In our study, we apply the AHP in assigning weights, which allows us to differentiate the relative importance of each criterion and to give a rank order of weights. Subsequently, we apply the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) method to rank the alternatives. We explore the AHP in more detail in the next subsection because it represents the core of our analysis.

A general formulation for MCA is based on the weighted criteria, but the score attached to each criterion needs to be normalised first, allowing for a comparison between criteria with different measurement scales. The normalisation formula we use (for numerical criteria) is the following (Nardo et al., 2005):

$$\begin{aligned} \text{min_max_norm} : \mathbb{R}^n &\rightarrow \mathbb{R}^n \\ \text{min_max_norm}(x) &= \left(\frac{x - \min(x)}{\max(x) - \min(x)} \right) \times 100 \end{aligned} \quad (4.1)$$

where:

$$\begin{aligned} x &: \text{original data vector} \\ \min(x) &: \text{minimum value in } x \\ \max(x) &: \text{maximum value in } x \end{aligned}$$

This function scales the values of the input vector x to a range between 0 and 100. In summary, the Min-Max normalisation formula transforms the original data to a new scale where the minimum value is mapped to 0 and the maximum value is mapped to 100, while preserving the relative differences between the values. This normalisation technique is commonly used in data preprocessing to ensure that variables are on a comparable scale.

Collecting the alternatives and the normalised scores allows us to construct the weighted performance matrix, a structured representation of how each alternative performs across different criteria. In MCA we often encounter situations where certain criteria are more important than others. Weighted performance matrices allow us to take into account these varying levels of importance.

Table 4.2 shows an example of a performance matrix evaluating three alternatives over three criteria.

Table 4.2: Weighted performance matrix

Alternative	Crit.1 (w1)	Crit.2 (w2)	Crit.3 (w3)
Alternative 1	$x_{11}w_1$	$x_{12}w_2$	$x_{13}w_3$
Alternative 2	$x_{21}w_1$	$x_{22}w_2$	$x_{23}w_3$
Alternative 3	$x_{31}w_1$	$x_{32}w_2$	$x_{33}w_3$

4.4.2 Analytical Hierarchy Process (AHP) to Weight Criteria

Among a vast variety of multi-criteria methods, we apply the AHP in order to determine the weights. According to the literature, it is the most used approach in making decisions about transport infrastructure in urban areas and urban area development (Karleuša et al., 2013). Additionally, it is extensively used in decision-making processes related to transport design and optimum location for specific transport infrastructure (Karleuša et al., 2003).

The AHP can be considered as an appropriate tool for planning and design problems thanks to the characteristics it presents. It proposes ratio scales from paired comparisons, involving qualitative and quantitative criteria. The number of criteria simultaneously evaluated is recommended to be between 5 and 9 to avoid inconsistent results with higher numbers.

The analysis is typically conducted by employing a panel of experts/stakeholders who are tasked to assign a score to each pairwise criteria comparison. The scoring factors in AHP vary between a range of 1-9, where 1 means that the two criteria are of equal importance and 9 means that one criterion is extremely more important than the other (Saaty, 1987). Table 4.3 explains the intermediate scores and their meaning. The pairwise comparisons are reproduced in the reciprocal matrix A (Eq. (4.2)), that is a pairwise comparison matrix $n \times n$, where the diagonal is always 1. Each element a_{ij} represents the relative importance of element i compared to element j . The values on the right side of the diagonal are the actual judgment values, while on the left are the reciprocal values, which are the inverse of the judgment values.

Table 4.3: AHP scoring factors for pairwise comparisons

Numerical Value	Explanation	Interpretation
1	Equal Importance	Both criteria are equally important
2	Slightly Important	The importance of one criterion over the other is weak
3	Moderate Importance	The importance of one criterion over the other is moderate
4	Moderate Plus Importance	The importance of one criterion over the other is moderately strong
5	Strong Importance	The importance of one criterion over the other is strong
6	Strong Plus Importance	The importance of one criterion over the other is very strong
7	Very Strong Importance	The importance of one criterion over the other is extremely strong
8	Very, Very Strong Importance	The importance of one criterion over the other is almost absolute
9	Extremely Important	The importance of one criterion over the other is absolute

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \quad (4.2)$$

From the matrix in Eq. (4.2), it is necessary to compute a priority vector w , which is the normalised eigenvector of the matrix. It is obtained as the average across rows of the normalised relative weights of A .

Once we obtain w , we need to check the consistency of A . This property ensures that the judgments of the respondents are logically coherent and transitive (Saaty, 1980). A is consistent if $a_{ij}a_{ji}=a_{ik}$, for all i, j and k (Saaty, 1987). This condition is undesirable because human judgment does not perfectly respect the mathematical transitive property, so a certain deviation of consistency should exist. To test for consistency, we first need to estimate the principal eigenvalue $\lambda_{\max}$. This is the highest eigenvalue that satisfies the equation:

$$Aw = \lambda_{\max} w. \quad (4.3)$$

To estimate $\lambda_{\max}$, we multiply the pairwise comparison matrix A by w and set it equals to $\lambda_{\max} \times w$ (Saaty, 1987):

$$Aw = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix} = \begin{pmatrix} \sum_{j=1}^n a_{1j}w_j \\ \sum_{j=1}^n a_{2j}w_j \\ \vdots \\ \sum_{j=1}^n a_{nj}w_j \end{pmatrix}. \quad (4.4)$$

From Eqs (4.3)(4.4), we derive the formula for $\lambda_{\max}$, which quantifies the overall priority or importance of the criteria being compared (Saaty, 1987):

$$\lambda_{\max} = \frac{\sum_{i=1}^n \left(\sum_{j=1}^n a_{ij}w_j \right)}{\sum_{i=1}^n w_i}, \quad (4.5)$$

where n is the dimension of A , which is the number of criteria considered in the pairwise comparison; w_i is i -th component of the eigenvector w , which represents the relative priority of the i -th criterion. The sum in the denominator normalises the priorities such that w sums to 1. The numerator calculates the aggregated weighted influence of all criteria j on each criterion i , considering the pairwise comparison values a_{ji} .

If A is consistent, then $\lambda_{\max}=n$. Because of the previous explanation, we have to compute an index of deviation from consistency as $\lambda_{\max} - n$, which is the consistency index (CI) and the consistency ratio (CR) (Saaty, 1987):

$$CI = \frac{\lambda_{\max} - n}{n - 1}; \quad (4.6)$$

$$CR = \frac{CI}{RI}, \quad (4.7)$$

where RI is the Random Index for a given matrix of size n .

CI is an average value and measures the deviation or degree of inconsistency. A higher value of $\lambda_{\max}$ indicates better consistency, which means that the priorities w derived from A are well-aligned and accurately capture the relative importance of criteria. The ratio of CI over RI gives the meaning of an acceptable level of inconsistency, which must be smaller than or equal to 10%, otherwise we need to revise the subjective

judgements (Elboshy et al., 2022; Goepel, 2018; Saaty, 2008). Indeed, a certain level of inconsistency can be tolerated without invalidating the judgments (Saaty, 1980). This consideration underscores the importance of limiting the number of compared elements. When the number of elements is large, the relative priorities among them become very small, making the results highly susceptible to distortion from minor errors. In contrast, when the number of elements is smaller and their priorities are relatively comparable, minor errors have less impact on the overall ranking, thereby preserving the consistency of the relative priorities (Saaty, 1987).

In light of this, our study will first implement the AHP within our MCA exercise, following a structured approach consisting of six main steps. This method will help ensure that the relative priorities are maintained throughout the analysis.

1. Definition of the problem;
2. Generation of the alternatives;
3. Selection of the criteria;
4. Assignment of the weights;
5. Filling the evaluation matrix;
6. Presenting the results of the evaluation.

While the steps from 1 to 5 are presented in Section 4.5, the results of the weighting phase and the consequent final ranking of alternatives (step 6) are presented, for the Munich case study, in Section 4.6.

4.5 Introducing Network Robustness as a Location Factor

4.5.1 Problem Definition and Survey Design

As mentioned in Section 4.4, the problem we want to tackle is selecting the location of a new BSS based on criteria suggested by the literature and introducing network robustness in order to develop MHs which better align with transport resilience goals. To do so, we weigh the selected criteria through the AHP, by directly involving a panel of experts in transport and urban mobility.

To determine the degree of importance of each criterion in our analysis, we consulted, in October 2023, a group of 28 experts through an online survey provided via Microsoft Forms (see Annex 2: Bike Sharing Location Survey (example questions)). Specifically, all members of the panel were participants in the "SmartHubs" project (ERA-NET Urban Accessibility and Connectivity, JPI-Urban Europe). We collected 17 valid answers, which we analysed individually to check for consistency. The gender distribution of the experts is balanced. In terms of their profile, most respondents (15) were in academia, while two more were classified as either urban planners or else. The age of the respondents was rather heterogeneous, ranging from 25 to 60 years.

The value of the answers of this group of experts lies in the fact that they are mostly experienced researchers on a specific topic, the integration of different PT and ST, aimed at the development and creation of urban MHs.

As there are nine criteria (described below), this results in 36 pairwise comparisons. Each of them allows the respondent to decide which criterion is preferred over the other, or to select "equal importance". When the latter option is selected, the respondent is shifted to the next pairwise comparison; otherwise, he/she is asked to indicate, with a value from 1 to 8, how much important the selected criterion is in comparison to the other ¹⁹.

4.5.2 Alternative Generation and Criteria selection

Within our approach, in a first stage, the alternatives of the MCA are selected: these are the PT stops that do not already include a BSS. To define them, we use a catchment area of 200m from each PT stop. Those which do not have any BSS within such a catchment area are selected ([Aultman-Hall and Kaltenecker, 1999](#); [García-Palomares et al., 2012](#)). To answer our third research question, instead, we take into account all PT stops, assuming that none of them provides a BSS. This allows us to prove if the current location of BSSs is coherent with the criteria used in our analysis.

We select nine criteria, which take into consideration the proximity to POIs, environmental issues, social and economic aspects, and the robustness of the PTN. Specifically, the criteria cover five main dimensions:

- C1. Urban Life Dimension/Points of Interest
 - C1.1. Proximity to green areas (PGA)
 - C1.2. Proximity to sport/recreation centres (PSC)
 - C1.3. Proximity to tourism areas (PTA)
 - C1.4. Proximity to schools (PS)
- C2. Demographics
 - C2.1. High-density areas (HDA)
 - C2.2. High-employment areas (HEA)
- C3. Environment
 - C3.1. High polluted areas (HPA)
- C4. Equity
 - C4.1. Low-income areas (LIA)
- C5. Robustness
 - C5.1. Proximity to a critical public transport stop (CPT)

¹⁹The choice of the scale from 1 to 8 derives from the limitations of the online form, and is meant to count as the range from 2 (slightly more important) to 9 (extremely more important) in the original AHP evaluation scale, where instead 1 means "equal importance".

The concept of proximity to POIs regards accessibility, referring to the possibility of reaching relevant activities and amenities within a threshold in terms of time or distance (Silva et al., 2023; Kanjanakorn and Piantanakulchai, 2013). As postulated by Banerjee et al. (2020), the closer POIs are, the higher the likelihood of increased bike-sharing use in accessing these locations. Consequently, the success of BSSs varies according to the characteristics of the area in which they are located. Sports activities, attractions, parks and schools have been identified as factors positively influencing the selection of BSS locations and the subsequent ridership at stations (Zhang et al., 2016).

Demographic attributes play a pivotal role in influencing BSS utilisation, as elucidated by Zhang and Zhang (2018), which uses a recent population-based nationwide survey conducted by the U.S. Department of Transportation. High-density areas are particularly significant when viewed through the lens of service user volume, a perspective endorsed by Burden et al. (2009). Furthermore, the income profile of residents is a crucial consideration, focusing on economic exclusion from PT services or the acquisition of a private vehicle. Poor access to transport services, including shared modes, exacerbates social inequality by limiting opportunities to reach services and other POIs (Giuffrida et al., 2023).

Giuffrida et al. (2023) highlights that BSSs help socially include communities, particularly by reaching those who are more excluded and marginalised. Additionally, BSSs contribute to reducing the environmental footprint of private vehicle use by providing a sustainable and accessible alternative. These goals align closely with the environmental and equity dimensions of our study, which emphasise the importance of addressing pollution levels and fostering equitable access in areas where BSSs could be implemented.

The potential of bike-sharing systems to mitigate air pollution has been extensively recognised in the literature, with many studies highlighting their capacity to replace private vehicle trips and, in doing so, reduce GHG and particulate matter. For instance, the deployment of BSSs and MHs has been shown to play a significant role in decreasing air pollutants such as PM_{2.5} and NO_x. Recent research demonstrates the optimisation of such systems to maximise environmental benefits: Xanthopoulos et al. (2024) and Stadnichuk et al. (2024) explore innovative strategies for the placement of MHs to reduce urban pollution, while Kang et al. (2023) examines the quantifiable impacts of reduced vehicle emissions resulting from increased bike-sharing service use. Similarly, Aydin et al. (2022) highlights the role of careful planning and integration of sustainable transport systems in achieving cleaner urban air. This background has influenced the choice of "High polluted area" as one of the key criteria to be weighted.

Regarding the last two dimensions, Anderson et al. (2017) provides substantial insights relevant to this study, in particular with regard to the evaluation of the MH location problem by means of the AHP. Notably, Anderson et al. (2017) introduces the equity dimension into the transportation optimisation problem. Thus, the equity dimension is intricately linked to the urban life dimension, wherein the concept of proximity plays a pivotal role. According to Wang et al. (2022), bike-sharing systems have a significant impact on decreasing inequalities in commuting time and work accessibility, at both the individual and spatial levels.

Moving to the last dimension, robustness refers to the potential resilience of the PTN, assessed through network analysis. The connectivity and accessibility of each PT stop determine the PTN resilience in terms of maintaining its functionality and a certain level of accessibility to the surrounding areas when disruptions are applied to the network. Several studies establish a link between the structural properties of bike-sharing systems and the properties of the entire PTN, underscoring the role of BSSs in enhancing overall connectivity (Wu and Kim, 2020). Thus, centrality measures, as employed in our study and in Wu and Kim (2020), are used to evaluate connectivity, highlighting the role of BSSs in facilitating interconnections between different stops and modes, even in the event of disruptions. We consider PT stops with high centrality as critical

within the network. We seek to understand how this criterion influences the BSS location problem and whether it is perceived as relevant according to expert opinions.

4.5.3 Assignment of Weights and Pairwise Comparison Matrix

In the AHP survey, after we present the criteria, the respondents are asked to assign the relative weights to each of them. In the first stage, for each pairwise comparison, the respondents are asked to answer which of the two criteria is preferred when considering the implementation of a new BBS. For instance, one question is: "Which is more important between 'Proximity to green areas' and 'Proximity to sport/entertainment centers'?".

Then, the respondents have to establish the degree to which one criterion is more important than the other, using a range from "slightly more important" to "extremely more important". Alternatively, they can attribute to the two criteria "the same importance".

The judgments are transposed into a format useful for the AHP application (see Annex 3: AHP template and results), and the resulting weights are used in the MCA. To do so, the judgments are reported in the Excel tool created by [Goepel \(2018\)](#). The spreadsheet tool is already coded to calculate all required parameters, including consistency values for both individual judgements (matrices) and aggregated arrays. Indeed, this tool provides the results of individual weights, which are calculated using the row geometric mean method (RGMM), including the consistency of their answers. Goepel's tool aggregates the individual judgments of a maximum of 20 stakeholders and 10 criteria, so it fits our needs.

In the Goepel tool, the CR is calculated according to the formula 4.7, and improvement possibilities are suggested for CR values higher than 0.1. The tool evaluates the three most inconsistent answers and proposes the corresponding judgement, resulting in lower inconsistency. The aggregated expert opinions are given in the normalised matrix, and normalised principal eigenvectors are computed.

Table 4.4 displays the aggregated priorities for our nine criteria after assessment through the CR adjustment procedure.

Table 4.4: Aggregated pairwise comparison matrix

Matrix	PGA	PSR	PTA	PS	HDA	HEA	HPA	CPT	LIA
PGA	1	2.0878	0.8200	1.2605	0.5166	0.6587	0.9354	0.5146	0.9097
PSR	0.4790	1	0.6536	0.9898	0.4090	0.4451	0.8597	0.4151	0.6119
PTA	1.2195	1.5299	1	1.1245	0.5098	0.6033	0.9051	0.5513	0.9026
PS	0.7933	1.0103	0.8893	1	0.5502	0.8069	1.3212	0.4922	0.9097
HDA	1.9358	2.4448	1.9614	1.8177	1	1.6642	1.7605	0.7971	1.8683
HEA	1.5182	2.2469	1.6574	1.2394	0.6009	1	1.4084	0.5218	1.4229
HPA	1.0690	1.1632	1.1048	0.7569	0.5680	0.7100	1	0.5161	0.8238
CPT	1.9432	2.4090	1.8138	2.0319	1.2546	1.9165	1.9377	1	2.3595
LIA	1.0993	1.6343	1.1080	1.0993	0.5353	0.7028	1.2139	0.4238	1

4.5.4 AHP Results

From the table above, we derive Table 4.5, which shows the weights resulting from the AHP. The criteria are ranked by their weights and corresponding standard deviation. The inclusion of standard deviation provides an important measure of variability or dispersion of the judgments made during the pairwise comparisons. A lower standard deviation indicates a high degree of agreement among the evaluations, reflecting consistency

in the prioritisation of criteria. Conversely, higher standard deviations may signal discrepancies or a lack of consensus, which could merit further examination to understand the underlying differences in stakeholder perspectives.

The CR accounts for 0,8 per cent, which means that the computed weights are within the acceptable threshold for consistency. This low CR indicates that the pairwise comparisons used in the AHP process are consistent and that the derived weights are robust. Together, the weights, standard deviations, and CR offer a comprehensive view of the prioritisation process, illustrating not only the relative importance of each criterion but also the reliability of the data and judgments used to calculate them.

Table 4.5: Criterion weights and +/- values

Criterion	Weights	+/-
CPT	0.188	± 0.028
HDA	0.169	± 0.018
HEA	0.124	± 0.019
LIA	0.095	± 0.009
PGA	0.093	± 0.018
PTA	0.092	± 0.012
PS	0.087	± 0.014
HPA	0.087	± 0.012
PSR	0.065	± 0.013

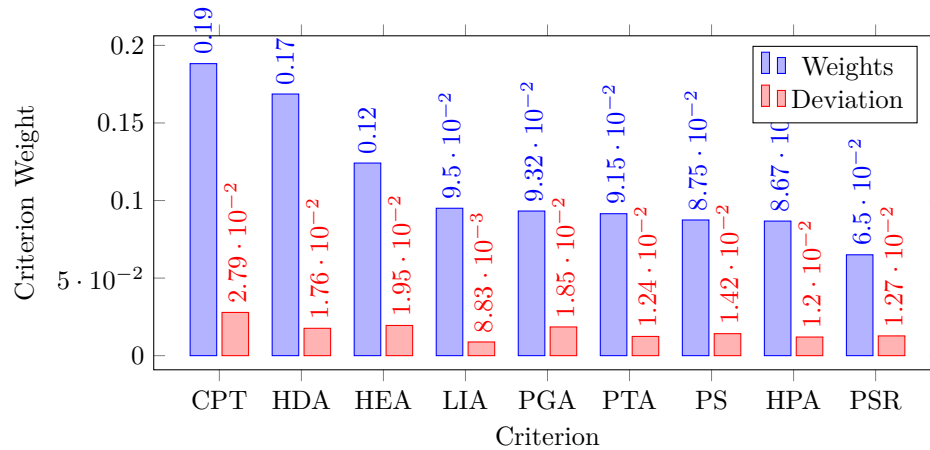


Figure 4.1: Criterion weights with deviation

As we can see from the results, the "Proximity to critical public transport stop" (CPT) has the highest weight of 0.188, so it seems to be the preferred criterion, but it also presents the highest variance (Fig. 4.1). This is due to heterogeneity in the evaluations, with a higher share of maximum importance scores than the average.

This result might respond to the need for the affordability of different transport modes in those areas where more people live and work, but also to the certainty of having means at their disposal to allow users' trips in case of problems on the PTN. To this extent, BSSs can act as a flexible alternative in case of unavailability of PT at a stop, thus transforming critical points into more resilient ones, which are able to promote alternative

modes and to allow them to continue the trip.

The second most important criterion is the "Location in high-density areas" (HDA), followed by "Location in high-employment areas" (HEA), which suggests that demographic criteria are of relevance. According to some authors (Burden et al., 2009; Ferrando et al., 2007), the density factor (in our case with a weight of 0.095) is recommended to drive BSS location decisions, which implies locating them first in the city centre, and then extending them to the peripheral areas. This aspect could conflict with the equity criteria, because it may favour richer areas at the expense of low-income areas.

The criterion that appears as the least important is the "Proximity to sport/recreational areas" (PS), with a weight of 0.065 only. The other criteria all have similar weights, around 0.09. It can be noted that the proximity to POIs is generally evaluated as scarcely relevant, but it depends on the POI considered: for example, proximity to green areas and tourist attractions assumes greater relevance if compared to proximity to schools and sport/entertainment attractions.

This could imply some issues regarding the importance of having substitute modes not only for residents and citizens, but also for visitors. The latter ones could be more interested in reaching green and tourism areas by using a BSS. Given this potential dual usage of bike-sharing services, it is necessary to distinguish between the general bike-sharing system, which targets commuters, and rentals for recreational cycling, which are more oriented towards tourists (Banerjee et al., 2020).

4.6 Case Study: Munich

4.6.1 Presentation of the Area and Methodology

Bike-sharing services in Munich are offered by a variety of providers, with the MVG Rad bike-share system, a hybrid model managed by Münchner Verkehrsgesellschaft mbH (MVG), playing a significant role. The MVG Rad system is a blend of free-floating and station-based models. Within the designated (central) "return zone" bikes can be rented and returned at BSSs or any other location. However, outside this zone, bikes must be returned to BSSs.

For Munich urban PT, the primary provider is also the MVG, which operates subway, tram and bus services. In addition, the S-Bahn network, which links suburban areas and small towns in the Munich metropolitan region to the city centre, is operated by Deutsche Bahn (DB), Germany's national rail provider.

To apply our MCA approach to the Munich case, we use the following procedure: first, we select the alternatives, namely the urban PT stops suitable for the implementation of a new BSS. Subsequently, we discuss the indicators used to operationalise the criteria described in Section 4.5.2; then, we construct a performance matrix that contains the alternatives' evaluation for each criterion, and we associate each criterion with its corresponding weight (Section 4.5.3).

Finally, we employ the TOPSIS to derive a ranking of the most appropriate locations where to establish a new BSS. TOPSIS is one of the most used methods in MCA (Behzadian et al., 2012), and is based on compensatory aggregation, comparing a set of alternatives based on multiple criteria. It is applied in particular in transport and mobility policy evaluation, because of fewer rank inversion problems compared to other MCA methods (Macharis and Bernardini, 2015). The method, developed by Hwang et al. (1993),

ranks the alternatives that simultaneously have the shortest (geometric) distance from the positive ideal solution (representing the best possible performance) and the farthest distance from the anti-ideal solution (representing the worst possible performance).

4.6.2 Data

In our application, we use several datasets that we merge depending on the objective. The selection of Munich as the case study is also driven by the availability of the following required data: BSS data, PT data, GIS data on POIs, sociodemographic data and environmental data.

The BSS dataset includes all bike-sharing trips in the year 2022, carried out using the MVG fleet.²⁰ The PT dataset is a nationwide GTFS dataset²¹ that combines local, regional, and national PT services operating in Munich. It contains information about stops, routes, schedules and geographic transit details.²² Given the volume and complexity of the bike-sharing and GTFS data, these need to be preprocessed in order to be manageable within our procedure.

The BSS dataset is populated by anonymised records of trips between all return zones and stations. Since we consider only a station-based bike system, because of the perspective of its integration with PT, we derive the 327 fixed bike stations, excluding the return zones. Moreover, once limiting our selection within the city borders of Munich, the number of stations is reduced to 168. Because we focus on the role of the bike-sharing system integrated with PT, we exclude from our dataset all the BSSs at a distance higher than 200 from a PT stop. This is a reasonable walkable distance, as also stated by Radzinski and Dziecielski (2021) and largely explained in the previous chapter. These are the cases we can consider as the first step for the MH implementation. The result of this procedure is 48 BSSs (for their locations see Figure 3.8).

GTFS data allows the construction of the PTN for each mode (metro, tram, bus, etc.). However, to evaluate the robustness of the APTN as a whole, we need to integrate the single-mode networks (as we have also previously done in Section 3.6.3). We propose a summarised version of the process for the sake of clarity.

A way to create an APTN is by aggregating the stops of different modes (or different lines of the same mode) within a short walking distance from each other, to allow transitions between them. Here, we aggregate stops that have the same name, whether they belong to the same or different modes of transport. The underlying hypothesis of this choice is that PT stops sharing the same name are in proximity to each other. In the case of Munich, the fact that all the aggregated stops fall within a maximum distance of 150m from the geometric centroid of the stops identified by the same name validates our hypothesis.²³

²⁰Source: <https://www.mvg.de/services/mvg-rad.html>.

²¹Source: www.govdata.de/daten/-/details/deutschlandweite-sollfahrplandaten-gtfs. Retrieved on June 17, 2023.

²²Since the availability of stops and routes depends on days and time intervals, in our example we select the PTN service between 7:00 am and 8:00 am of a random workday.

²³This choice has the advantage of eliminating the need for a predefined (arbitrary) radius within which stops must be considered for aggregation. An alternative method would involve establishing interlinks between stops associated with distinct routes, as well as intralinks connecting stops within different network modes. These links are interpreted as walkable paths. In this scenario, selecting stops for adding these new links becomes crucial, and proximity serves as the guiding criterion.

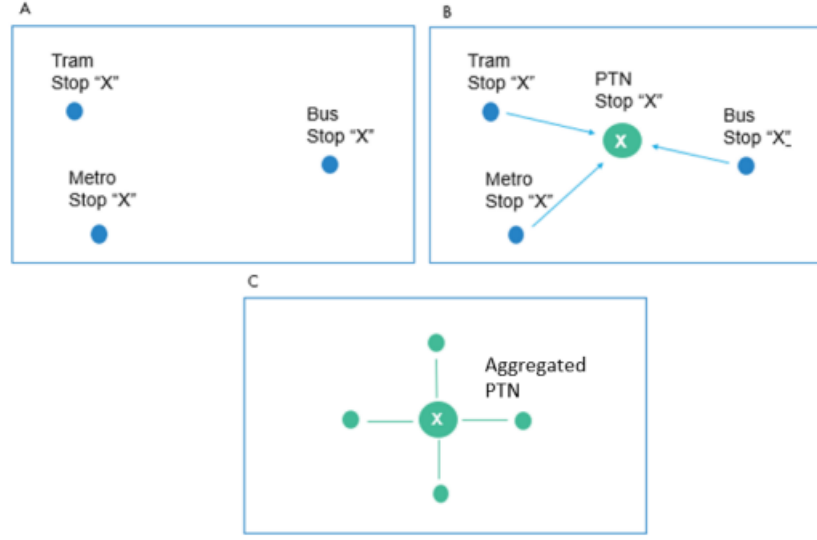


Figure 4.2: Procedure to aggregate PT stops

Figure 4.2 shows the stop aggregation procedure. The single-mode stops (blue nodes), all having the same name “X”, belong to three different transport networks (metro, tram, and bus). In our procedure, these stops converge into a single (aggregated) stop (green node) whose geographical coordinates fall at the geometric centroid of the involved stops.²⁴ After this procedure, we obtain 1076 aggregated stops within the city borders.

As mentioned in Section 4.5.2, we subsequently integrate the 48 BSSs, resulting in the APTNB. The figure below illustrates spatial relationships between BSSs and PT stops. Figure 4.3a depicts the local integration of BSSs (represented by the orange circle) with individual PT stop (indicated by the blue circle) within a predefined radius of 200 meters. With the aggregation, this points corresponds to a single one (the blue circles in Figure 4.3b).

Figure 4.3b highlights a broader integration strategy where links (depicted as blue lines) are established between multiple PT stops aggregated with BSSs within a larger 3 km radius. The central PT stop (represented by a larger blue circle) serves as a hub, linking to other PT stops with bike stations within a 3 km radius. This means that the connection between PT stops with BSSs incorporated are allowed for a maximum distance of 3 km.

²⁴In 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.

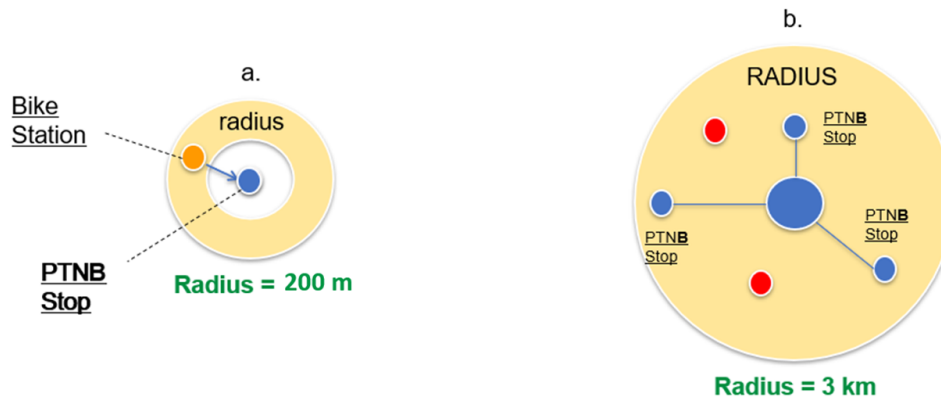


Figure 4.3: Bike aggregation procedure

The other set of data we employed is extracted from GIS. The GIS dataset includes the geographical location of green areas (open-space areas reserved for parks and other "green spaces"), sports/entertainment centers (cinemas, theatres, stadiums and sports facilities) and tourism areas (monuments and archaeological sites). Data refers to the location of the monuments or access points to buildings and parks. They are geographical points determined by longitude and latitude, which are extracted from openstreetmaps.org (Figure 4.4).

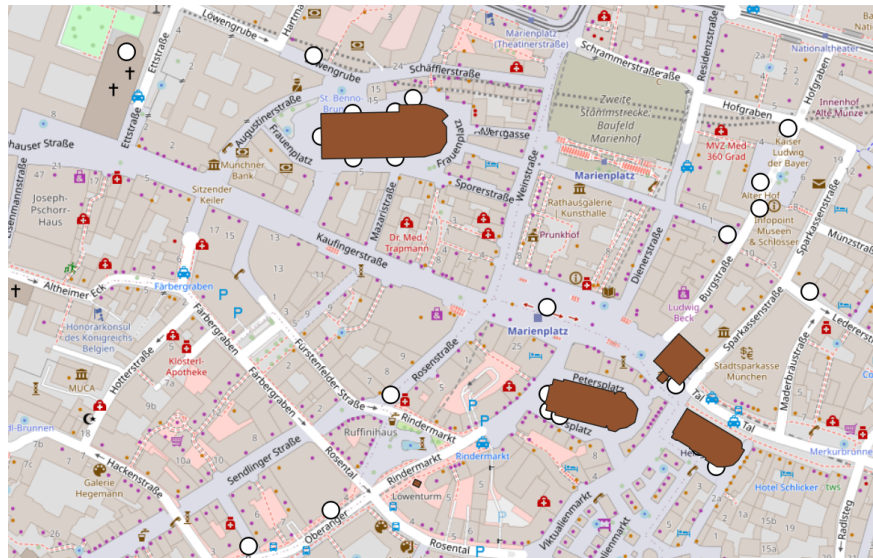


Figure 4.4: Examples of POIs in Munich, extracted from openstreetmap.org

The socio-demographic dataset is the result of the collection of data from different sources. Population density is extracted from the Landeshauptstadt München - Indikatorenatlas, for the year 2022. The income variable is defined by Data-Driven EnvirLab as GDP per capita, expressed in USD. The unemployment rates come from the Münchner Armutsbericht 2022, available within the publications of the Social Services Department of the city. All data are referred to city districts.

Finally, the environmental dataset contains a normalised index for the average exposure to PM2.5 (fine particulate matter measured in micrograms per cubic meter ($\mu\text{g}/\text{m}^3$)). This index, extracted from the Data-Driven EnviroLab, ranges from 1 to 100, providing a comparative measure of air quality across different regions.

We decide to measure this criterion with the PM2.5 indicator because it refers to particulate matter with a diameter of 2.5 micrometres or less, which is approximately 30 times smaller than the width of a human hair. Due to its small size, PM2.5 can easily penetrate deep into the lungs and even enter the bloodstream, leading to serious health effects. Prolonged exposure to PM2.5 is linked to a variety of health issues, including respiratory diseases, cardiovascular problems, and an increased risk of lung cancer. The World Health Organization (WHO) highlights PM2.5 as a major environmental risk factor, estimating that exposure to high levels contributes to millions of premature deaths worldwide each year ([World Health Organization et al., 2021](#)).

From an environmental and urban planning perspective, monitoring PM2.5 levels is particularly important as these particulates are primarily generated by vehicular emissions, industrial processes, construction activities, and residential heating ([Tucker, 2000](#)). Urban areas, characterised by dense traffic and limited green spaces, are often hotspots for PM2.5 pollution ([Koolik et al., 2024](#)). Consequently, reducing PM2.5 exposure is a critical objective when designing sustainable transport networks. This motivated us to include this criterion in order to determine the location of BSS, also with the aim of reducing air pollution.

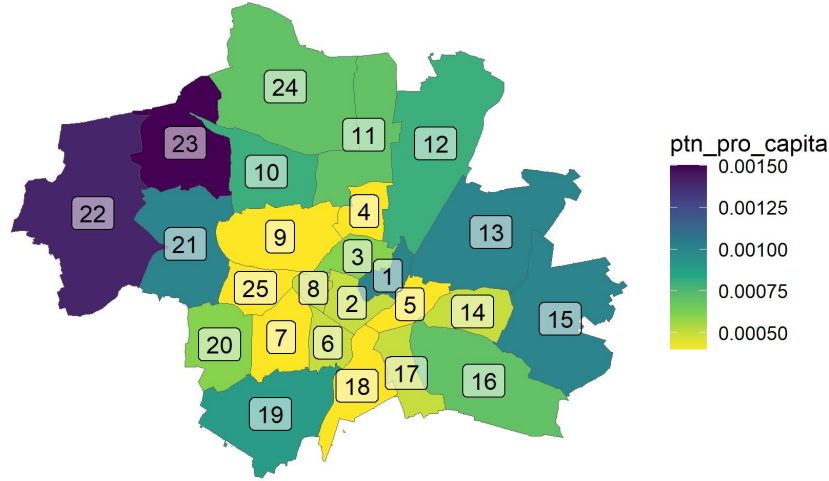
4.6.3 Selection of Alternatives

The next step of our approach is to select the areas where to consider potential new BSSs. In the case study applied to Munich, we assume that a policy-maker is committed to enhancing the bike-sharing service in areas where the availability of PT (measured as the number of stops) is limited compared with the number of residents. In other words, we assume the implementation of a policy to improve the distribution of mobility options available to the residents, especially in districts where PT availability is scarce, affecting the opportunity to move without private vehicles. The establishment of a new BSS near a PT stop can be seen, in this sense, as an element that enhances the connectivity of the broad PTN, which also includes bike-sharing. Moreover, it can be viewed as a way of facilitating communication between PT stops when a direct line is not present or mobility through PT is inconvenient.

For this purpose, we select those PT stops (aggregated as described in Section 4.6.2) which are located in the three Munich districts with the lowest number of stops per resident. We consider only three potential districts in different city zones for the intervention because we assume budgetary and logistical constraints faced by the policy-maker when implementing BSSs. However, the model we apply allows us to accommodate additional districts and more alternatives, with results adjusting accordingly.

Based on the results shown in Figure 4.5, the districts that correspond to our restriction are Untergiesing-Harlaching (18), Laim (25) and Schwabing-West (4). The three selected districts are fairly central, the first one being located in the southern part of the city. In these areas, PT stops are 75, where three of them already have a BSS nearby and 72 do not. Therefore, the list of alternatives (new potential BSSs) is 72

locations.



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-Hasenberg, 25.Laim.

Figure 4.5: Number of PT stops for residents

4.6.4 Criteria Measurement

Among the criteria considered in the MCA, those classified as "C1. Urban Life Dimension/Points of Interest" and "C5. Robustness" are stop-related i.e. each stop, potentially, shows a different value for each alternative, while those labelled as "C2. Demographics", "C3. Environment", and "C4. Equity" are district-specific, since more granular data are not available, therefore alternatives belonging to the same district, show the same value.

Recall that on the "C1. Urban Life Dimension/Points of Interest" we find C1.1. Proximity to green areas (PGA), C1.2. Proximity sport/recreation centres (PSC), C1.3. Proximity to tourism areas (PTA), C1.4. Proximity to schools (PS), data for these criteria are extracted using the "osmdata" package in R, which provides a convenient way to access the underlying data from OpenStreetMap (OSM).

Then, we subset these data defining the concept of proximity as the condition wherein a given entity (such as a school, park, etc.) is situated within a buffer radius, denoted as $r = 417\text{m}$, which is also an acceptable

walking distance rather than driving (Aultman-Hall and Kaltenecker, 1999). This distance is equivalent to the span traversed in five minutes at a walking speed of 5km/h.

To evaluate the criterion "C5.1. Proximity to critical public transport stop (CPT)", where, with the term "critical" concerning APTNB, we mean stations that have a high centrality in the network, as determined by robustness-related centrality metrics (e.g., betweenness centrality). These are the stops whose non-availability (during a disruption) causes extensive damage to network connectivity, leading to significant fragmentation and reduced accessibility across the network. Identifying these critical stops requires applying appropriate indicators that accurately capture their centrality and influence on the overall robustness of the APTNB (as we have largely discussed in the previous two Chapters 2 and 3). Such indicators should account for the structural properties of the network, enabling the assessment of their impact under various scenarios of disruption. Moreover, they are also central stops for users' operation, as they allow numerous and fast connections so that they can be seen as potential places to develop MHs, with further mobility options at the same stop.

Among the metrics developed for this scope, we selected betweenness centrality BC . It plays a crucial role in assessing the robustness of APTNB, identifying critical nodes, and measuring how often a node lies on the shortest paths between other nodes. In a transport network, nodes with high betweenness centrality act as critical hubs. These hubs facilitate efficient passenger movement and connectivity. By identifying these critical nodes, transport planners can focus on strengthening them to enhance overall network robustness. We expect to have high betweenness in stops highly connected and within many shortest paths, but that do not provide a BSS, differently from those that integrate PT and bike-sharing, where the sharing mode offers a higher level of robustness, with alternative and flexible links.

In the formula, B_c is used to describe and give meaning to the importance of nodes in a network, quantifying how many shortest paths (σ_{jk}) between two given nodes (j) and (k) pass through a node (i) ($\sigma_{jk}(i)$):

$$B_c(i) = \frac{1}{n(n-1)} \sum_{j \neq i \neq k} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \quad (4.8)$$

In this case, we compute the B_c for the APTNB, because the Munich transport network already provides a bike-sharing system, and we want to identify those nodes with high betweenness and still missing a BSS.

To compute betweenness centrality in a multimodal transport network, we incorporate travel times specific to each mode of transport. For PT, the travel time between two consecutive stops is calculated using the GTFS data. Specifically, the travel time is the difference between the arrival time at the destination stop and the departure time from the origin stop. This approach allows us to capture the schedule-based variability of PT, reflecting realistic transit conditions.

For cycling, we assume an average speed of 15 km/h to estimate travel times between nodes connected by bike links. This speed is chosen as a representative value for urban cycling, balancing typical travel conditions across diverse users and environments.

The resulting network is a weighted multimodal graph, where the links are assigned weights corresponding to travel times. These weights ensure that the shortest path calculations prioritise realistic, time-efficient routes.

Using the weighted graph, the R code computes the optimal routes for each pair of origin and destination nodes in the network. The algorithm dynamically accounts for the mode-specific travel times to determine the most convenient paths. These paths may involve one or more PT modes and/or bike-sharing.

After identifying the optimal paths, the **R** code calculates betweenness centrality for each stop by evaluating how frequently each node is included in the shortest paths across all OD pairs. This measure highlights the criticality of specific nodes and links in facilitating efficient travel within the network.

The table below (Table 4.6) lists the indicators used for each criterion in order to construct the performance matrix for the Munich case study. The indicators can vary depending on the context and data availability.

Table 4.6: Criteria indicators

Criterion	Indicator
CPT	Betweenness Centrality
HDA	Density
HEA	Employment rate
LIA	Average income rate
PGA	N. of green areas [#]
PTA	N. of tourism attractions [#]
PS	N. of schools [#]
HPA	Average exposure to PM2.5
PSR	N. of sport/recreation centres [#]

[#] Within a 5-minute radius of a buffer where the alternative is the centre.

4.6.5 Results

Once we define criteria weights and alternatives, we combine the AHP with the TOPSIS method, in order to have the results for our case study. The aim is to have a ranking of alternatives within the three districts previously selected — Untergiesing-Harlaching (18), Laim (25), and Schwabing-West (4) — where we attach to each alternative the weighted and calculated criteria of Sections 4.5.2 and 4.5.3. Figure 4.6 presents the outcome of applying the methodology to the districts, where, for the sake of brevity, we show only the first top ten choices (in Annex 4: Rank of 72 alternatives (PT stops) for $r=5$ minutes, the entire ranking of alternatives is available).

This allows us to address our first research question: *What factors influence the choice of the optimal location for installing a new BSS? Consequently, which is the best location for a new BSS?*

Box “A” displays the rank of the top ten best options for the location of a new BSS. In the context of our case study, when faced with the decision of selecting one alternative, our choice would be the Laim stop, since it obtains the greatest score. If we wanted to place two BSSs, we would need to recalculate the performance matrix, excluding Laim from the options. Additionally, we would need to recalibrate the betweenness of the stops, taking into account the presence of an extra BSS.

Box “B” shows the contribution of each criterion to the overall score, expressed in terms of weighted normalised values. The height of the bars shows the score of each alternatives in various criteria. In the case of Laim, for instance, what ‘propels’ this stop to the top of the ranking is the value of the indicator associated with the CPT, as highlighted by the height of the blue bar, while the criteria associated with proximity (PGA, PS, PSR, PTA) provide a lower contribution.

A potential constraint of our analysis may be the sensitivity of the outcomes to the value of the parameter r . This sensitivity implies that small variations in r could lead to substantial changes in the results, potentially limiting the generalisability of our conclusions. Such sensitivity might arise due to the range of r , or the

empirical context in which r is applied. To address this issue, further analysis involves a detailed sensitivity analysis to quantify the extent of this dependence.

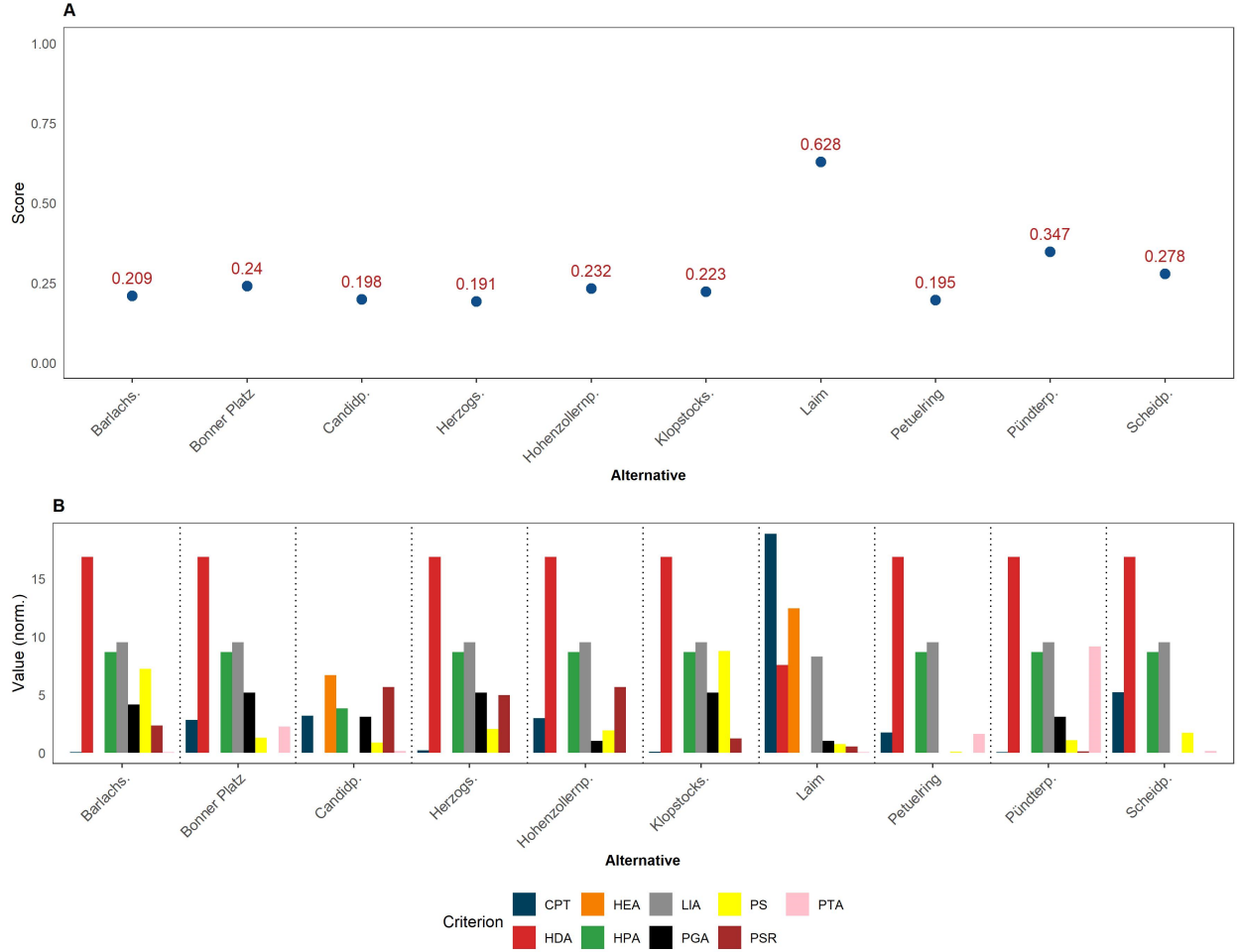
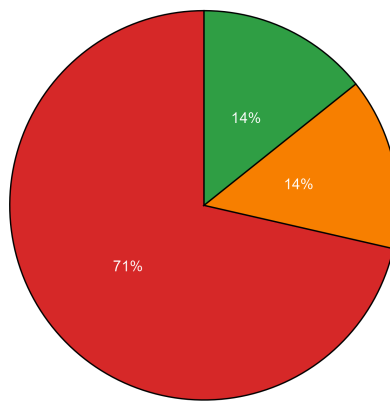


Figure 4.6: Final rank (top ten)

Note: 's' means Straße and 'p' means Platz

Figure 4.7 illustrates the outcomes of this analysis, revealing key insights into the solidity of the rankings. Out of the 72 alternatives considered, 20 appear at least once in the top ten across the different values of r (1 to 10 minutes), suggesting a moderate degree of variability in the rankings. However, three of these alternatives (Hohenzollernplatz, Laim, and Scheidplatz) remain consistently present in the top ten, regardless of the value of r , highlighting their relative stability and importance within the network.

Figure 4.8 provides a detailed comparison of the three ranking scenarios, emphasizing the relative consistency among the top-ranked alternatives. Specifically, the top four options exhibit substantial stability across different parameter values, highlighting their robustness as critical nodes in the network. Among these, Laim consistently emerges as the optimal choice, maintaining its position as the highest-ranked alternative in all scenarios. This finding reinforces the reliability of Laim as a strategic focal point in the network, even for different values of r .



N. of times an alternative is included in the top 10

Figure 4.7: Frequency in the top ten rank alternatives (number of times)

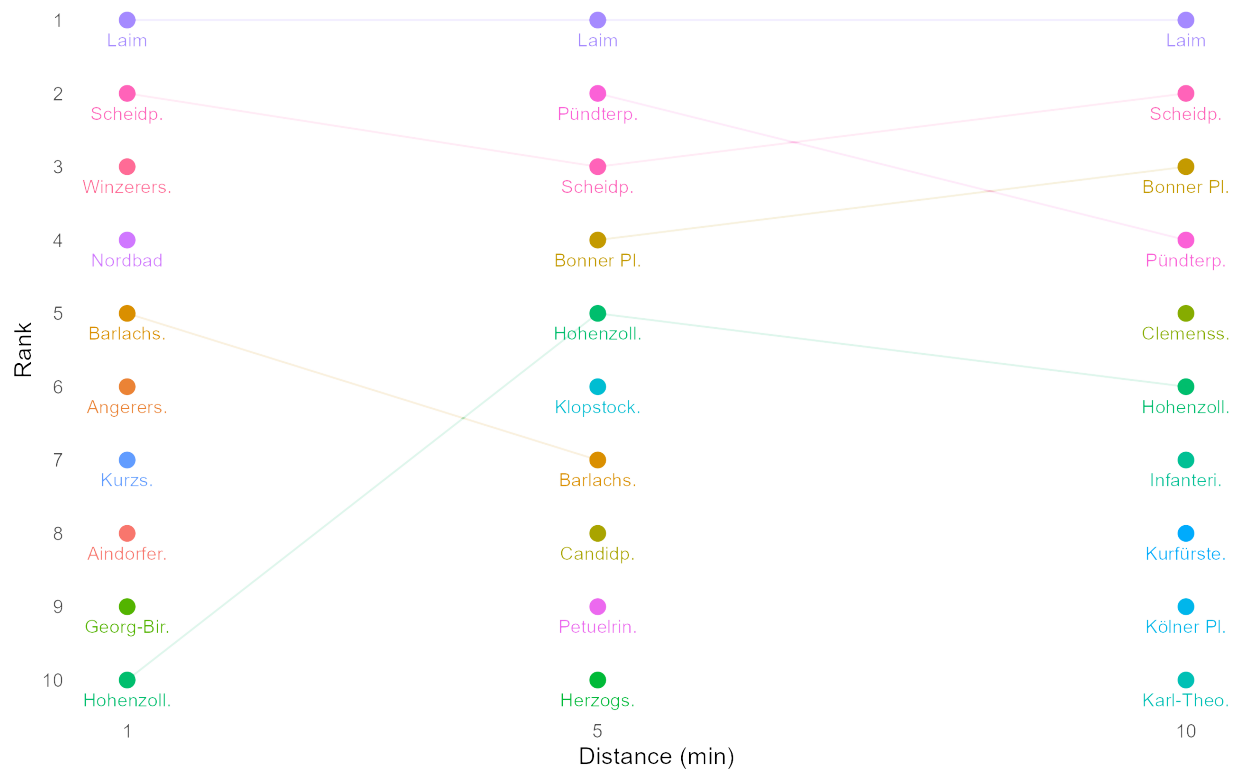


Figure 4.8: Top ten alternative ranked by r

Note: Alternative names are truncated to the ninth character

At this point, we turn our attention to the second research question: *Does the inclusion of PTN robustness in the MCA impact our decision?* This question is critical for understanding the extent to which robustness-related criteria shape the ranking of alternatives and whether their exclusion would lead to significantly different results.

To address this, we replicate the MCA using again the TOPSIS method. For this analysis, we exclude the criterion associated with PT network robustness — specifically, "C5.1. Proximity to critical public transport stop (CPT)" — to isolate its impact on the rankings of alternatives. If the rankings remain largely consistent, it may suggest that the other criteria dominate the decision-making process. Conversely, substantial changes in the rankings would underscore the key role of robustness, emphasising the importance of including this criterion to ensure comprehensive evaluations.

This is made possible by the unique capability of the AHP to assess the relative importance of criteria through pairwise comparisons. Because of this approach, AHP permits the computation of a new vector of weights excluding one or more criteria and focuses on relative prioritisation rather than absolute values. As a result, the absence of a specific criterion from the questionnaire does not compromise the integrity of the evaluation process. Moreover, the modular nature of AHP facilitates seamless updates or modifications to the framework, allowing for dynamic adjustments based on evolving priorities or data availability. The weights associated to the remaining criteria are shown in Table 4.7.

Table 4.7: Criterion weights when CPT is excluded

Criterion	Weights	+/-
HPA	0.310	± 0.062
PGA	0.252	± 0.094
PTA	0.120	± 0.053
PSR	0.098	± 0.037
HDA	0.068	± 0.023
HEA	0.068	± 0.023
PS	0.045	± 0.017
LIA	0.041	± 0.015

As we can see in Figure 4.9, the exclusion of the CPT criterion alters significantly the ranking of the top ten alternatives. The previously favoured one, "Laim", now falls out of this ranking. Given the new set of criteria and weights, the alternative we would select is now "Pündterplatz". The criterion "Proximity to green areas" likely plays a more prominent role in ranking alternatives, as it varies more significantly across stops than the one with the greater weight in the new vector, "High polluted areas". At the same time, the pollution levels are almost uniform for PT stops within the same district and exhibit only minimal variation across the three selected districts, ranging from 9.96 $\mu\text{g}/\text{m}^3$ to 10.21 $\mu\text{g}/\text{m}^3$ of PM2.5, which already exceed the WHO's annual guideline.²⁵ For this reason, the "High polluted area" criterion has limited influence on the new ranking, and "Proximity to green areas" actually determines the rank of alternatives.

²⁵<https://iris.who.int/bitstream/handle/10665/345329/9789240034228-eng.pdf>

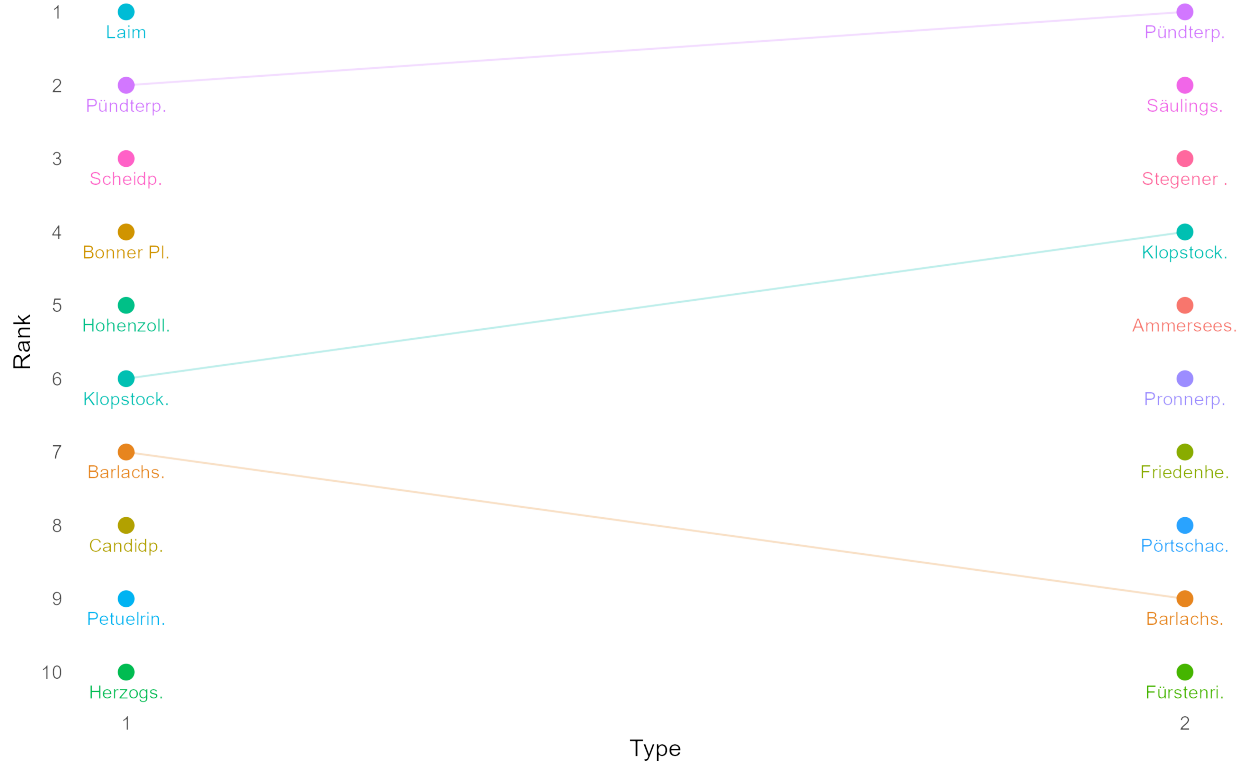


Figure 4.9: Top ten with CPT (Column 1) and without CPT (Column 2) for 5-minute radius.

Note: Alternative names are truncated to the ninth character

We can also observe a considerable shift in the ranking of the top ten alternatives when comparing the two rankings presented in Figure 4.9. When comparing the two rankings, we notice that only three out of ten alternatives remain in the top ten. This outcome highlights the substantial influence that the inclusion of the CPT criterion — representing the robustness of the public transport (PT) network — has on the decision-making process for selecting the optimal locations for new BSS.

Lastly, we answer our third research question: *Within our approach, can we replicate the location of (three) existing BSSs in the districts under analysis?* This question aims to verify the alignment between our MCA outcomes and the real-world decision-making processes that led to the current location of BSSs. Specifically, this issue can be formulated as follows: assuming no BSS is currently present, would applying our methodology and weights identify one or more of the three PT stops where a BSS currently exists as optimal locations?

This analysis serves a dual purpose. First, it acts as a validation mechanism for our approach, allowing us to assess whether the criteria and weights we employed align with the factors that likely informed the original placement decisions. Second, it provides insights into the effectiveness of current BSS positioning in meeting the network’s needs based on our robustness-oriented framework.

However, it is important to note that BSSs were first introduced in 2015, but their number has increased over the years. We do not have precise information regarding the specific moment when the three BSSs were installed or the exact conditions and characteristics of the transport network at that time. Nevertheless, it is

reasonable to assume that the overall road and PTN configuration has not undergone significant changes since then. As such, the criteria and framework employed in this study likely provide a reliable approximation of the factors influencing both past and current decision-making processes.

If the results converge, this could reinforce the validity of both our methodology and the initial placement strategy. Conversely, significant discrepancies could highlight opportunities for improving the decision-making process or suggesting that different priorities (e.g., cost, accessibility, or demand patterns) influenced the original decisions and could be added to our MCA.

To perform this analysis, we recalibrate the methodology to simulate a counterfactual where no prior BSS infrastructure exists, ensuring an unbiased evaluation. Applying our methodology, we have 75 alternatives, including the three stops of Willibaldplatz, Wettersteinplatz, and Kolumbusplatz / Humboldtstraße. We recompute the betweenness centrality because it is affected by the elimination of three BSSs, and we recalibrate the model.

The result for the 5-minute radius from the PT stop is a slightly different ranking (Table 4.8), where seven stops out of ten remain the same, with only two positions switched.

Table 4.8: Ranking of alternatives

Alternative	Ranking
Laim	1
Pündterp.	2
Scheidp.	3
Bonner Platz	4
Klopstocks.	5
Hohenzollernp.	6
Barlachs.	7
Willibaldp.	8
Herzogs.	9
Infanteries.	10

Willibaldplatz, one of the PT stops which actually has a BSS, occupies position 8, while the others are in positions 30 (Wettersteinplatz) and 41 (Kolumbusplatz / Humboldtstraße). These results appear to suggest that different criteria have been used to implement the actual BSSs, that will be discussed in the following section.

4.7 Discussion

The aim of this research was to assess the relevance of the BSS location problem in order to develop an urban MH, within the context of enhancing transport network resilience. This is not the only factor to be included in the policy-making process, but it represents a requisite step to direct decision-makers to value alternative

mobility options, offering a more sustainable and flexible mode, such as bike-sharing.

Given our results, we elaborate on some policy directions that can improve the performance of multimodal integration and reduce the negative effects of missing transport services. Under our hypothesis that a policy-maker is required to optimise the location of BSSs, and given some criteria selected from the literature and weighted by experts in mobility, three main factors have been identified. These are the proximity to PT stops, population density, and the robustness of the PTN.

In particular, we underline the significance of network robustness, which is scarcely considered in the literature. Indeed, we note that including a network-based criterion in determining where to provide an alternative and flexible transport service in case of disruptions, significantly influences BSS location.

In the Munich case study, the top-ranked option, Laim, emerges as the most suitable location due to a combination of its structural and functional attributes. It is a key PT stop along the S-Bahn, acting as a vital hub and transfer point for commuters travelling across the city. It can be accessed from both sides of the urban rail. As shown in Figure 4.10, Laim does not provide BSS within 200m. The closest BSS is at a 18-minute walking distance north of the Laim station, within another district, and another is aggregated to Willibaldplatz, at 24 minutes of distance, according to GoogleMaps.

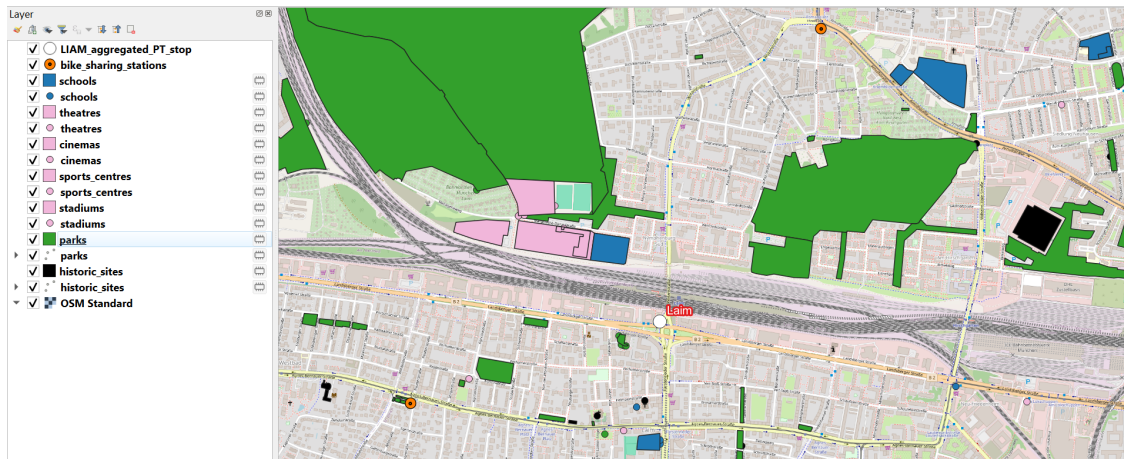


Figure 4.10: Laim location from QGIS

Laim is located in a densely populated and well-connected area of Munich, characterised by substantial foot traffic, residential neighbourhoods and commercial activity. The station serves both residents and commuters from the surrounding areas, making it an ideal candidate for a BSS. Additionally, its position within the urban fabric allows for seamless integration of bike-sharing with PT, further promoting sustainable mobility.

All these aspects may influence the high betweenness value of Laim, which is the second highest in the whole Munich APTNB (see Table 3.2 in Chapter 3). This metric describes Laim as one of the most critical PT stops, with high centrality and high demand, but lacking a BSS.

Based on these results, our policy suggestions are defined in order to implement BSSs, with a wide array of potential benefits, but also presenting specific limitations and risks that must be carefully considered in urban planning and policy development. Table 4.9, inspired by [Teixeira et al. \(2021\)](#), summarises a

set of aspects to be considered in planning MHs, including environmental, social equity, economic, modal shift, PT integration, and cycling promotion to POIs. Each category highlights potential benefits and associated challenges, emphasising the need for tailored policy interventions. This overview serves as a basis for identifying strategies to maximise the advantages of BSSs while addressing potential drawbacks, particularly in relation to the local context, user demographics and urban infrastructure. By considering these factors, cities can develop more effective and equitable bike-sharing policies that align with broader goals of sustainability.

Table 4.9: Policy suggestions for bike-sharing systems implementation

Category	Potential Benefits / Risks	Policy Suggestions
PT integration with share modes	Improved catchment areas and last-mile connectivity, enhanced resilience / Competition with PT	Integrate ticketing systems, install stations near PT stops and increase their number.
Environment	Reduced air pollutants / Short trips have small impacts	Promote car trip replacements, reduce parking spots and monitor environmental impacts.
Equity	Reduced accessibility gaps for disadvantaged groups / Limited socio-economic resources	Subsidise low-income users, deploy in underserved areas, prevent gentrification effects
Demography and Economy	Provision of services to high-demand areas, travel time savings, reduced congestion / Short-term vision, weather conditions and easy turnaround	Partner with local businesses, highlight economic benefits, perform cost-benefit analyses
Cycling Promotion	Encouraged cycling culture and diversity to POIs / Critical availability of a large number of bike-sharing at attractive places	Build safe cycling lanes, promote cycling awareness, focus on outreach to new users

Despite these ideal features characterising the best candidates for new BSSs, at this point, it is fair to note that we face some limitations regarding different aspects of our analysis.

One of them regards the number of experts involved, which was sufficient for the AHP, but did not include other kind of stakeholders from the administration and PT operators. The prevalence of academics in the expert group influences the interpretation of our results. However, this choice was guided by the specific focus of the study, which aims to establish a theoretical and methodological foundation for integrating BSSs. The experts were not made aware of the context in which this method would have been applied, which might have influenced their opinions on the relevance of the criteria. We point out that the same survey could be disseminated to a broader or different range of experts for specific contexts. Indeed, broadening the expert panel, including also bike-sharing and PT operators, transport authorities, policymakers, and private sector actors, could offer diverse perspectives, which, on the other hand, require a remarkable synthesis work. Future refinements of this research could explicitly integrate these voices to balance theoretical insights with operational expertise, ensuring a more comprehensive understanding of BSS integration within transport networks.

As already mentioned, the accuracy of our calculations depends on several factors, including the availability

and quality of data on service schedules, vehicle speeds and passenger behaviour. For betweenness centrality measures, several assumptions have been made, regarding aspects such as average passenger arrival rates or standardised transfer times, which, if different, could introduce variability in the results. Nonetheless, this approach provides a robust framework for assessing PT efficiency and its impact on network performance.

The added value of the network resilience criterion is also shown by the omission of the latter. It allows us to determine whether the rankings of the alternatives are significantly altered, thereby shedding light on the relative importance of incorporating PTN robustness into the decision-making framework. Additionally, this approach ensures a deeper understanding of the trade-offs and interdependencies among the criteria, thereby enhancing the robustness and reliability of the final recommendations. The findings reveal whether the inclusion of our selected criteria—such as proximity to CPT or other measures—would have led to similar decisions.

Beyond replication, this exercise offers insights regarding future network expansion or optimisation. For these reasons, we also provided different scenarios in which we tested the influence of the r parameter. By doing so, we can also aim to uncover the strengths and limitations of the current BSS locations, as demonstrated in the counterfactual. This would be impossible by considering the free-floating option, which, furthermore, is overcome in some contexts where the incorporation of designated BSSs have created a much more reliable and theft-resistant bike-sharing system (Shaheen et al., 2010).

Another possible counterfactual analysis could be carried out by applying our methodology to the entire Munich area instead of restricting the field to the three districts with less PT stops per inhabitant. This choice is deliberate and influenced by the need to identify the mobility supply gap, ensuring that the study focuses on less accessible areas and on where improvements in BSS could have the most impact. We acknowledge that the non-selected districts are already well served by PT stops, so we prioritise areas where the bike-sharing has a potential complementary role for daily short PT trips (Shaheen et al., 2010). Thus, rather than distributing BSS in an area already well-served by PT, we adopt a strategy that aims to fill accessibility gaps and balance the distribution of new BSSs across districts that need them more. Indeed, transport disadvantages, in terms of sparse PT stops, can increase social exclusion or the reliance on private cars (Jaramillo et al., 2012). From this perspective, it might be interesting to test different selection criteria for the neighbourhoods to analyse. Given the outcome of the criterion used in this thesis, which selected fairly central neighbourhoods based on PT stop density, a more detailed measure of the supply of PT (such as the average number of potential rides per stop) might help identify areas affected by transport poverty.

We acknowledge that the scarcity of transport services is not the only factor influencing the social exclusion and marginalization of some zones, but there are several others, such as income levels, digital access, cycling culture and safety perception, which can shape significantly the use of PT together with bike-sharing (Piatkowski et al., 2015). These elements are not directly modelled in our analysis, but could influence the extent to which BSS expansion in low-PT areas translates into higher usage rates.

Our methodology offers several key advantages that contribute to its applicability and relevance in both research and practice. First, it is firmly grounded in the literature that advocates for the use of MCA in the development of bike-sharing services. By building on established frameworks and integrating best practices, our approach ensures methodological consistency with proven strategies in transport planning and sustainable urban mobility. This foundation enhances the credibility and reliability of the results, making the methodology a valuable tool for decision-makers and urban planners.

Second, the methodology leverages data that are readily accessible, reducing barriers to implementation. By relying on publicly available or easily obtainable datasets, such as transport network data, demographic

information and socio-economic data, the approach minimises the need for costly or time-intensive data collection processes. This accessibility makes it particularly suitable for cities or regions with limited resources, ensuring that the benefits of bike-sharing services can be extended to a broader range of contexts.

Third, our framework, with appropriate adjustments, is highly adaptable, allowing it to be customised for diverse urban settings and tailored to specific objectives. The flexibility to adjust criteria, weights, and evaluation techniques ensures that the methodology remains relevant across varying geographical, socio-economic and cultural landscapes. This adaptability is critical in addressing the unique challenges and priorities of different cities, from improving last-mile connectivity in densely populated urban centres to promoting sustainable transport options in smaller towns or rural areas.

4.8 Conclusion

This chapter introduced a comprehensive methodology for identifying suitable areas for locating new BSSs in order to develop new MHs, addressing the pressing need for sustainable, well-integrated and resilient transport solutions in urban areas. By employing a combination of AHP and TOPSIS, our MCA integrates multiple criteria into a coherent methodological framework. This dual-method approach not only builds upon existing research but also advances it by providing a structured, adaptable and context-sensitive tool for decision-makers.

A key feature of the methodology is the inclusion of a preliminary list of criteria derived from an extensive review of the literature, to which we add the resilience criterion as the core of the proposed approach. Resilience, defined in this study as the robustness and adaptability of the PTN, reflects the increasing focus on transport systems' ability to withstand and recover from disruptions. The inclusion of this criterion is both timely and essential, considering the growing challenges of urbanisation, climate change, and the need for equitable transport access. The results of the methodology emphasise the significant influence of resilience, as demonstrated by its weight derived from expert opinions, and its measurable impacts at each PT stop. This unique focus sets our approach apart from similar studies and reinforces its contribution to sustainable transport planning.

The practical utility of the methodology is demonstrated through its application to the city of Munich, chosen for its comprehensive PTN, data availability, and unique urban characteristics. Munich's seemingly well-connected PTN provided an ideal testbed to assess the lack of BSSs and the alignment of current BSS locations with the identified suitable areas. The analysis revealed several key insights, including a noticeable scarcity of BSSs in three districts, highlighting the need for a more strategic distribution of stations. These findings underscore the potential of the methodology to guide improvements in both the placement and density of BSSs, ensuring they better serve the needs of residents and align with the city's sustainability objectives.

Furthermore, the results illustrate how the methodology can capture urban peculiarities, such as areas with high transport demand but inadequate BSS coverage, offering a nuanced understanding of spatial dynamics. The ability to translate these insights into policy recommendations, partially discussed in Chapter 3.7, demonstrates the methodology's value as a practical planning tool.

In addition to these advantages, the methodology provides a transparent and structured approach to decision-making, which is crucial for engaging stakeholders and fostering public trust. The explicit incorporation of multiple criteria allows for a balanced consideration of economic, environmental and social factors, aligning the outcomes with broader goals of equity and sustainability.

Future research could expand the number of criteria considered, provided that the increase in complexity does not compromise the consistency of results. For instance, incorporating additional factors such as user behaviour patterns, land use characteristics and emerging mobility trends could refine the analysis and offer deeper insights. Moreover, involving a broader range of stakeholders, including mobility service providers, local authorities and potential users, could enrich the process by incorporating diverse perspectives and priorities.

Overall, this methodology not only supports the strategic placement of BSSs but also contributes to the advancement of research in transport network planning. Indeed, it can be scaled up to support the evaluation and strategic positioning of MHs, which contribute to shaping multimodal and resilient transport networks. These aspects expand the BSS location problem to a broader goal of fostering sustainable urban mobility and achieving integrated transport solutions in a wide range of contexts, thanks to the key role of MHs.

The next chapter will assess the needs and expectations surrounding MHs, by conducting a pilot study in Munich with surveys and interviews of diverse groups, in order to combine our quantitative approach with the qualitative evaluation of MHs.

Chapter 5

Needs and Expectations Towards a Mobility Hub: A Mixed-Methods Approach for the case of Munich

5.1 Motivation of the Study

The methodology presented in the previous chapter provides an approach for selecting the best location for a BSS as a first step in the implementation of a MH. As established in the thesis from the introduction, the efficient and optimal integration of at least two different modes, one of which is shared, can be recognised as the setting for new MHs. After the incorporation of such insights from the BSS location problem, the next critical step is to define the core components that make MHs successful. One key aspect that remains to be addressed is understanding the needs and expectations of the various stakeholders involved. These stakeholders, each with different interests and profiles, play a fundamental role in shaping the success of MHs and ensuring their acceptance and effective use. Therefore, this chapter delves into the expectations of these stakeholders and highlights how their input contributes to the design and attractiveness of MHs.

A central element of this study is the partial introduction of a co-design method, a collaborative approach widely used in urban mobility planning across diverse contexts. Co-design enables us to integrate stakeholder input directly into the planning phase, ensuring that the resulting MHs meet both functional requirements and user expectations. This method is particularly useful for achieving broad acceptance and fostering user engagement, making it indispensable for MH development.

For this research, we again focus on Munich as the primary case study, building on the collaboration with the Chair of Urban Structure and Transport Planning at the Technical University of Munich. The ongoing research conducted during a research visit to this chair, combined with findings from the SmartHubs project, allows us to draw comprehensive insights into the design and operation of MHs. This partnership provided a valuable opportunity to validate the proposed components of MHs and consider how they could be tailored to the local urban context.

In this chapter, we emphasise the role of MHs in offering a diverse range of integrated mobility services, as well as their potential to provide attractive alternatives to private car use. A key objective here is to understand how MHs can encourage a shift toward sustainable mobility practices. This requires a deeper investigation into the factors that influence users' mobility choices, particularly in the context of evolving technological advancements such as shared mobility services and integrated digital platforms. These advancements are rapidly transforming urban mobility, especially in European cities like Munich, where plans are in place to implement 200 MHs by 2026.

To meet our research objectives, this study adopts a mixed-methods approach grounded in the co-design framework. This includes conducting surveys among residents of the Maxvorstadt neighbourhood in Munich, as well as expert interviews with representatives from the city administration and the private sector. These insights help validate the study's findings and ensure that the MH components reflect both user needs and expert perspectives.

Finally, this chapter advocates for more inclusive and user-centric approaches to the planning and development of MHs. The involvement of stakeholders in the design phase is essential not only for ensuring that MHs meet their intended objectives but also for fostering long-term adoption. Looking ahead, future research should focus on scaling this co-design process to different geographic contexts and urban size. Replicating the approach in smaller, medium-sized, or polycentric cities will be critical for broadening its applicability and ensuring that MHs can be successfully implemented across diverse urban landscapes.

5.2 Introduction²⁶

Climate concerns require an effective change in urban mobility, increasing the adoption and attractiveness of sustainable mobility. This challenge should be mitigated with policy-centred approaches that involve civil society (Bartenberger and Szescilo, 2016; Puerari et al., 2018). Cooperative approaches regarding mobility issues are not extensively discussed in the literature and are far from becoming standard practice (Sanders and Stappers, 2008). Such approaches must also incorporate the stakeholders' needs and expectations regarding sustainable mobility projects, defining a bottom-up process, fundamental to achieve public acceptance (Evans and Terrey, 2016; Steen et al., 2011). Despite this, there is a knowledge gap in incentivising providers to align their services with users' needs and expectations (Hanson, 1999).

This study contributes to the existing literature by highlighting the importance of participation through co-design, a process that can contribute to the success and acceptability of transport planning. Specifically, this research focuses on the user-centred design of MHs and how this can increase their accessibility, attractiveness, and overall acceptance. The approach based on stakeholder involvement, such as the civil society, can help to bring together a variety of knowledge and to drive transformations based on the needs of a diverse range of actors (Bell, 2019; Puerari et al., 2018), which is also the core of this study. Urban and transport planning must encourage people to switch from cars to more environmentally friendly and convenient alternatives. In the context of intermodal MHs, this research argues that a well-designed MH, grounded in the needs and expectations of stakeholders, can play a pivotal role in promoting multimodality and reducing dependence on private cars (Geurs et al., 2024). In the context of this research, a MH is a physical place with a well-visible on-street location that serves as a mobility node, where to shift between shared mobility options, and PT (Anderson et al., 2017). It also provides benefits to user experience and attractiveness of different transport modes (Bell, 2019), promotes multimodality, and has the potential to reduce dependence on the private car (Aydin et al., 2022).

To increase acceptance and usage of MHs, the main contribution of this research is to identify the diverse needs and expectations of different stakeholders for co-designing MHs. The aim is twofold: 1) to analyse needs and expectations towards a MH in Munich, in terms of transport opportunities and digital and non-digital services, and 2) to explore spatial factors where stakeholders think MHs should best be located. We took a case study of the surrounding area of the campus of the Technical University of Munich (TUM). The high travel demand, due to the university and further points of interest, makes the TUM main campus in Munich an interesting area to analyse the needs and expectations toward a MH. The methodology employed to achieve the objectives is a mixed-methods approach rooted in the co-design approach. This entails employing a survey of citizens as an exploratory research design to gather quantitative data and conducting interviews with practitioners to qualitatively understand deeper and validate the survey results.

Given the aims of this research, the following research questions were formulated to guide the study:

1. *What are the specific transport needs and expectations of different stakeholders regarding MHs in Munich, particularly in terms of the digital and non-digital services they should offer?*
2. *Which spatial factors do stakeholders believe are most important when determining the optimal locations for MHs in the Munich area, with a focus on the area surrounding the university campus?*
3. *How can the insights from stakeholder needs and expectations be used to co-design MHs that increase their acceptance and usage among different stakeholder groups?*

²⁶This chapter is based on Duran-Rodas et al. (2025) forthcoming in the Journal of Urban Mobility

The chapter is structured as follows: in Section 5.3, we briefly conceptualise MHs and the co-design approach, referring to the main previous literature on the topics. Section 5.4 defines the methodology we apply to conduct the survey and interviews. The main results are shown in Section 5.5 and discussed in Section 5.6, where we also propose recommendations for mobility planners and define the limitations of our study. Finally, in Section 5.7, we present some conclusions and suggest further research based on this study.

5.3 Literature Review

The literature review summarises contributions in the field of MHs, avoiding repetition with the previous chapters and broadening the definitions not only by referring to its characteristics due to the PT and ST offer, but also we are interested to assess how this research topic is adapted for the mixed-methods approach, as well as introducing the co-design approach specifically. It aims to define these concepts within the scope of our research and to contribute to expanding the application of such terms in future studies.

5.3.1 Mobility Hubs and Mixed-Methods Approach

In the literature, as we have already pointed out, there is no fixed and generally accepted definition of the term MH. [Geurs et al. \(2024\)](#) is one of the first systematic contributions to the topic, providing a literature review on the definition and categorisation of shared MH. After reviewing previous studies on the topic, they provide a comprehensive definition: “A shared mobility hub is a physical location where different shared transport options are offered at a dedicated, non-temporary and recognisable location, and public transport is available within walking distance (pag. 118)” ([Geurs et al., 2024](#)). It is worthwhile to evolve this concept with the description given by [Aydin et al. \(2022\)](#), where MHs are dedicated locations to comfortably and safely switch between modes of transport. In this research, we take these definitions as references, and when we mention MH, we essentially mean this. Beyond the absence of agreement on the term MH, there is neither an agreement on which types of mobility ultimately constitute a MH, which is why we gathered previous literature on the subject and proposed the various components of MH in the survey. Some authors ([Ambroz et al., 2016](#)) define minimum requirements, for example, having at least one shared mobility and at least one PT option nearby ([Geurs et al., 2024](#)), which is a fundamental requirement in our research. To give a broader sense to the term, we have also accepted the definition given by [Miramontes et al. \(2017\)](#), which refers to MHs as places where multimodal transport options are simply offered at close distances. Indeed, one of the key points of this study is defining which are the transport services offered at MHs. We differentiate between means of transport and mobility-related services.

Regarding the services available and the goal of MHs, we agree with [Aono \(2018\)](#), which defines an MH as a place where connectivity is promoted thanks to different sustainable integrated transport modes. We are also interested in the integration of technologies as suggested by [Aydin et al. \(2022\)](#), which is another key issue of our research. Indeed, MHs are enriched through new mobility services, especially digital technologies that are becoming increasingly important, for example, digital pillars for trip planning, booking, and payment of shared modes ([Geurs et al., 2024](#)). These elements are usually considered optional, and we are interested in understanding how citizens perceive them.

The reasons why we concentrate on the development of MHs are therefore the benefits they create in terms of connectivity of transport users and convenience of travel (MaaS, 2021²⁷), as well as counteracting the first and last-mile problem. In this way, they also act as gap fillers in the PTN. Despite these advantages, we need to consider that passengers are also resistant to changing modes during a trip (MaaS, 2021). It seems to them to be inconvenient and a loss of time and connection, which requires designing MHs that ensure smooth changes. Geurs et al. (2024) argues that this limitation can be overcome with the implementation of a co-design approach, which can ensure user-centred universal design principles. For this reason, we introduce this approach to our research in order to reduce discontent and collect opinions from citizens and experts. This allows us to reflect on the limitations due to the different needs of socio-economically disadvantaged groups and physical impediments that can decline the attractiveness of MHs.

This study draws on already concrete examples of MHs in the Dutch provinces of Groningen and Drenthe, the Flemish Region in Belgium or the German city-state of Bremen, where regional networks of MHs were created. At a city level, The Hague and Munich also plan to develop several MHs in the metropolitan area. At the moment, the corresponding municipalities have delineated mobility transition strategies that include the promotion of different types of MHs (The Hague 2040²⁸; Mobility Strategy 2035²⁹). According to this plan, Munich is planning to have up to 200 by 2026, but has already established around 53. These ongoing policies represent an incentive for our research in assessing the needs and expectations of stakeholders over existing or new MHs in the city of Munich.

Another valuable example comes from Vienna (Austria), where the creation of 16 MHs in August 2022 was promoted, with an interactive online map to show different available services and mobility options at any hub (Wiener Linien, 2022³⁰). These projects are aligned with the support of the European Commission on European Cities in tackling urban mobility challenges. MHs implementation can be embedded and adapted into the broad SUMP (Sustainable Urban Mobility Plans³¹), as provided in the plan for the city of Vienna, where special attention is given to potential MHs³². The latter literature and cases were instrumental in outlining the scope of the research and future steps.

In order to enhance the role of MHs and the characteristics outlined above, we have decided to apply the mixed-methods approach based on applications in previous literature, which emphasises its usefulness especially in the field of transport projects in which several stakeholders are involved. This methodology combines two phases, quantitative and qualitative, to obtain a more comprehensive overview of a research problem, which are respectively organised as survey, data collection and results, while the second as interviews, questions and results.

The survey, as a quantitative research method, offers the possibility of collecting data on the needs and expectations of citizens in a profound way (Creswell, 2009). The method provides the opportunity to collect a comprehensive range of data on the subject of the study in a detailed way (Kuckartz, 2014). The interviews permit the elaboration of causal mechanisms for the specific findings of the survey and the observation of mechanisms from the perspective of the interview partners (Döring and Bortz, 2016). This mixed-methods approach allows us to highlight different aspects of MH and the establishment of a profound understanding of the needs and expectations of various stakeholders for MHs through verbal descriptions (Diekmann, 2021).

In the research landscape, there are studies on the needs of PT users (Stradling, 2002), on intermodal

²⁷<https://mobility-as-a-service.blog/mobility-hubs/>

²⁸<https://www.government.nl/binaries/government/documenten/reports/2019/05/13/public-transport-in-2040/>

²⁹<https://muenchenunterwegs.de>

³⁰<https://www.wienerlinien.at/wienmobil/stationen>

³¹<https://transport.ec.europa.eu>

³²<https://sumps-up.eu>

MHs (Bell, 2019; Gebhardt et al., 2016), or on the expectations for transport in general (Elmashhara, 2021; Kurniawan et al., 2018; Vandebona and Tsukaguchi, 2013). There is also literature on smart components such as MaaS in the context of mobility (Jittrapirom, 2017; Liao and Correia, 2020; Papa et al., 2017) or on the location factors that influence the use of mobility services (Ambroz et al., 2016; Aono, 2018; Murray, 1998; Roberts, 2019). However, there is not enough research on location factors, transport options, and digital or non-digital services in the context of an MH. To fill this gap, qualitative research is appropriate to investigate this phenomenon, as new insights can be gained inductively (Lin, 1998). At the same time, qualitative research allows a deductive review of the literature findings (Creswell, 2009), which are combined in this chapter with new insights from data collection, with a focus on empirical data collection (Mayring, 2015).

According to Kuckartz (2014), a mixed-methods research design is appropriate for the research gap under investigation, characterised by its complexity and the need for both qualitative and quantitative insights, in order to gain a multi-perspective understanding. Indeed, from a quantitative approach, it is possible to have objective analysis and evaluate measurable aspects regarding MHs, which can define their performance in terms of connectivity, efficiency and demand. On the other hand, it is worth associating qualitative methods to capture the user perspective, behavioural trends and experiences. This combination strengthens the role of MHs and their social acceptance as new mobility services in place of private vehicles.

By doing so, we can achieve a more complete view of the phenomenon, as well as generate in-depth knowledge about MH adoption and perception. Based on these explanations, it can be stated that the problem of lack of integration of different perspectives identified in the literature, as well as the novelty of the object of study, were decisive for the decision to carry out the mixed-method approach.

5.3.2 Co-design Approach

Co-design can be defined as a methodology that seeks to empower and guide users to design, refine, or invent products (Buchanan, 2001). This definition is intentionally broad in order to cover a wide range of participatory practices. The approach is embedded in the citizen-centric approach of the "New Public Governance", meaning the shift from a goods-dominant to a service-dominant logic. Co-design thus shifts the focus from the product itself to the design process, which helps to address complex societal problems (Sanders and Stappers, 2008). Bovaird (2007) describes this mechanism by emphasising the active participation of end users in the design development process, treating them as equal contributors alongside the designers (Pirinen, 2016). It is precisely this last contribution that is an inspiration in the elaboration of the research method for this chapter, where we consider citizen participation on a par with that of experts.

It is worth highlighting that this research primarily focuses on identifying the needs and expectations of civil society during the design process (co-design) of a MH, rather than during the implementation process (co-creation) itself. This distinction is crucial because the study serves as a pilot exploration to inform and guide future development of MHs (in Munich as well as elsewhere). Indeed, we exclude the possibility to immediately create a MH given the long-term planning, the significant resources and the institutional coordination required. By the way, the core of the MH co-creation process can be inspired by our results and can benefit from the initial collaboration between citizens, researchers, and mobility experts, which remains open and can be scaled up in subsequent stages. We employ the term co-design in this chapter to refer specifically to the initial phase of establishing a broader participatory framework for MH planning.

However, it must be considered that there are different degrees of participation in co-design. Based on Arnstein's public participation ladder with eight levels of participation (1969) (Arnstein, 1969), they can

range from manipulation of citizens (first ladder) to citizen control (eighth ladder) (Figure 5.1).

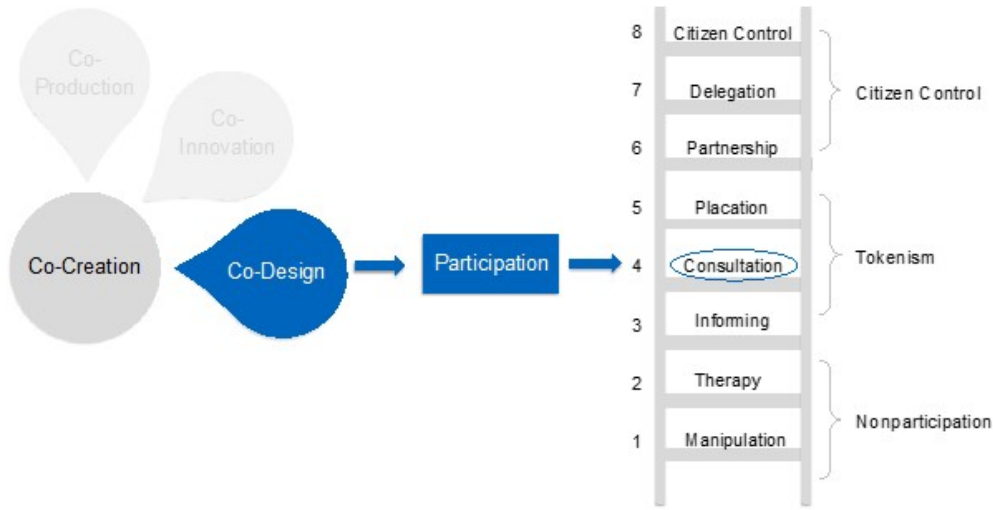


Figure 5.1: Conceptual framework of participation based on the co-design approach by Bovaird (2007) and Arnstein's ladder (1969)

In our study, the concept of co-design serves to better adapt services to the needs of citizens and create acceptance of the services provided (Bovaird, 2007). Opinions and needs from citizens and experts are the foundation for shaping a more structured co-design process in future implementation phases. Civil society involvement plays a crucial role in increasing the legitimacy of projects and promoting a trust-based relationship with citizens (Bartenberger and Szescilo, 2016; Evans and Terrey, 2016). Moreover, such local knowledge, collected through a co-design method, improves the quality of decisions (Newig and Fritsch, 2009). Concurrently, the OECD (2011) also highlights cost reductions, better service quality, and improved user satisfaction with the involvement of citizens in public service delivery.

Regarding the specific contribution of earlier literature to this study, we focus on those that have centred their research on the needs of PT users, as Bell (2019) and Stradling (2002). Other more in-depth contributions that helped define the terms and components of MHs used in this research are Gebhardt et al. (2016), which gives an overview of "intermodality", which means a combination of different modes during one journey, at specific points, namely intermodal MHs. In this research, the authors point out that a key factor for a sustainable urban transport system is a well-working intermodal supply. But this study gives also considerable attention to users' daily decisions, which is part of our research to individuate which factors and needs influence the citizens in adopting an intermodal MH.

Expectations regarding individual transport modes have been identified to define the potential expectations of MHs (Elmashhara et al., 2022; Kurniawan et al., 2018; Vandebona and Tsukaguchi, 2013). As integrated mobility, the concept of MaaS is closely linked to MHs as a key concept for both physical and digital integration. This concept represents a shift from the traditional ownership-based transport system towards an access-based approach, offering user-customised and convenient mobility solutions (Jittrapirom et al., 2017; Liao and Correia, 2020; Papa et al., 2017).

Regarding the selection of location factors for MHs, Ambroz et al. (2016) reinforces the idea that an MH

should be situated in areas with a high concentration of employment, educational facilities, shopping, housing, and recreational spaces. In this research, we aim to understand, from the public's perspective, which location factors users consider beneficial, as well as the influence of digital services. To investigate this phenomenon, interviews are carried out for the inductive generation of potential new insights in the local case study of Munich.

5.4 Application of Mixed-Methods Approach

In this study, the mixed methods approach is used to elaborate causal mechanisms for specific findings of the survey, thanks to the interpretive approach. We have designed the survey based on [Diekmann \(2021\)](#), which illustrates effective methods in modern empirical social research, including experimental planning, sample research, measurement and modelling problems, experimental and quasi-experimental design, as well as online questionnaires. In our approach, we retrieve and use verbal descriptions to establish a deep understanding of the needs and expectations of different stakeholders for a MH.

The method involves a two-phase, sequential mixed-methods approach to analyse the needs and expectations of different stakeholders for a MH in terms of location, transport options, and digital or non-digital services. In the first phase, quantitative research in the form of a survey addresses the research question of where a MH should be located and what kind of transport options and digital or non-digital services should be offered. The information from this first phase has been deepened in a second qualitative phase.

The methodology of this chapter is composed of three main phases: 1) conceptualisation, 2) data collection and 3) data analysis (Figure 5.2). The conceptualisation is assessed through a literature review to define the research gap about MH and related needs and expectations, defining a case study for the investigation of the research objectives. The first phase is then supported through an exploratory phase during which a previous pilot survey, a survey, and interviews are conducted to collect data on the needs and expectations of Munich citizens about a MH, its transport options, digital and non-digital services, and the location of a MH. In particular, the quantitative results from the survey are validated and enriched through semi-structured interviews with partners from the private sector and the administration of the city of Munich. The interview results constitute the qualitative data. The analysis of the interview data was computer-assisted with the qualitative data analysis program MAXQDA to ensure an efficient and structured data analysis.

This chapter aims to use the methodology, specifically, surveying citizens and interviewing experts, as a co-design approach for the conceptualisation of MHs. In this chapter, we apply the "Consultation" stage of the co-design approach, based on Arnstein's ladder of citizen participation (1969), which is employed through the survey and interviews. This stage, which involves gathering the community's opinions, is utilised to demonstrate how the needs and expectations for a MH can be collaboratively collected from both citizens and experts ([Arnstein, 1969](#)).

Both quantitative and qualitative data are further explored and analysed to derive the final results. The analysis follows the circular principle, whereby intermediate results of the data analysis inform the subsequent stages of qualitative data analysis. The analysis also followed the case-based principle, which means that the data material is processed sequentially from front to back ([Döring and Bortz, 2016](#)). After the interview data

had been reviewed for a first pre-analysis, a two-step coding process was carried out.

In summary, this kind of analysis of quantitative and qualitative data corresponds to a mixed-methods research approach, which involves a survey as an explorative research design to collect quantitative data and interviews to qualitatively understand the survey results.

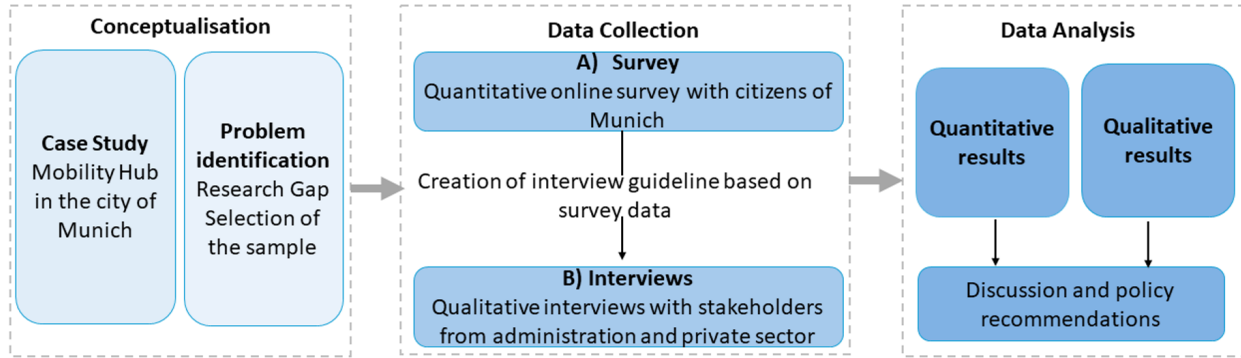


Figure 5.2: Methodology framework

5.4.1 Conceptualization

5.4.1.1 Case Study: Munich Mobility

Munich is an important transport hub for national and international transport. 537,928 private cars are registered in the city of Munich (as of 2021), resulting in 34 cars per 100 inhabitants³³, which is significantly lower than the German average of 58 vehicles per 100 inhabitants³⁴. As of 2020, there are 341,698 in-commuters and 130,429 out-commuters³⁵. Munich is thus one of the cities with the most commuter traffic in Germany.

Looking at the PT system, as already mentioned in Chapter 3, the various S-Bahn and U-Bahn lines, as well as bus and tram networks provide a well-developed transport network in the city. Despite the increasing share of cycling, the escalating competition for space and the environmental repercussions of traffic resulting from the continuous expansion of the city are leading to agglomeration disadvantages that increasingly constrain the quality of life. In a nationwide comparison, the state of Bavaria ranks last in the transport sector on topics such as climate protection, land consumption, and air quality (pro Schiene, 2021). Thus, Munich offers great potential for shaping a modal shift in Germany toward sustainable mobility.

Among the mobility plans for the city of Munich, we noted that the Mobility Strategy 2035³⁶ for the city of Munich has set several of these recommendations as the core of the plan by 2035. Specifically, the goal is to achieve at least 80% of inner-city traffic using emission-free vehicles, public transport, cycling, or walking by 2025. As part of this plan, up to 100-200 MHs will be established in the municipal area of Munich by 2026, aiming to ensure that the walking distance to access a shared mobility service is no more than 5

³³<https://stadt.muenchen.de/dam/jcr:08c1aecc-5191-4824-9f80-1c8c381c47e1/jt160705.pdf>

³⁴<https://www.umweltbundesamt.de/daten/private-haushalte-konsum/mobilitaet-privater-haushalte>

³⁵<https://www.stmwi.bayern.de/landesentwicklung/raumb Beobachtung/daten-zur-raumb Beobachtung/>

³⁶<https://muenchenunterwegs.de/2035>

minutes. Additionally, it is expected that shared modes will potentially lead to a modal shift away from private car usage of 8.3%.

To align with this plan, the area chosen for the location of the MH in this study is the Maxvorstadt district, covering an area of 0.59 km², with its centre being the main campus of the TUM. The study area is inhabited by 3,700 people and was selected due to its significant relevance to traffic management in Munich, enabling comparisons with the entire city. A radius of approximately 300 meters around the centre of the study area represents the acceptable distance ([Aono, 2018](#); [Sarker et al., 2020](#)).

5.4.1.2 Problem identification

The literature highlights a concern regarding limited stakeholder involvement in the design and planning of MHs. To enhance participation, a co-design approach was employed in this study, actively involving users in the process of consultation. To gather citizens' input, the study began with a quantitative analysis. It required the selection of a target population, in our case, all citizens who live within the 25 city districts of Munich, to express their needs and expectations over a MH. The target population accounts for 1.5 million people, which requires a reduction of the sample. We decided to use a "convenience sample", which is a non-probabilistic sample, that responds arbitrarily to our objective.

5.4.2 Data collection

5.4.2.1 Survey

The cornerstone of the quantitative data collection is the survey, which underwent a pilot phase to test its duration and gather feedback from a group of 13 individuals, comprising students and staff of the TUM. Following the review process, the survey was distributed in both German and English in December 2022 (Annex V). The survey comprised closed-ended questions (featuring multiple-choice options or Likert scales ranging from "very important" to "irrelevant"), open-ended questions (intended to capture subjective responses), and hybrid question types (providing answer options alongside open questions in the form of text fields). The sequence of questions followed the guidelines for questionnaire construction outlined by [Berger \(2010\)](#) and [Diekmann \(2021\)](#).

The content of the questions was based on the research gap identified to accurately capture the needs and expectations of MHs. To capture respondents' needs, questions were primarily focused on the perceived individual importance within each component category ([Miramontes Villarreal, 2018](#)). Furthermore, explicit questions were asked about expectations. In addition, based on the topics retrieved from the literature review, the survey aimed at identifying different transportation opportunities, mobility-related services, and digital and non-digital services that can be found or should be included in a MH. The literature also provided information on location factors and design that influence the attractiveness and use of a MH, these components are also included in the questions of the survey. This approach ensured that all key aspects of the literature were addressed in Figure 5.3.

To depict the question of where the MH should best be built in the area around the TUM main campus, the geoinformation platform QGIS was used. All longitude and latitude data that could be collected in the survey were exported from the Excel data sheet and imported into QGIS. The questions showed a map of the case study, selected in the conceptualisation phase, where respondents were asked to place a pin

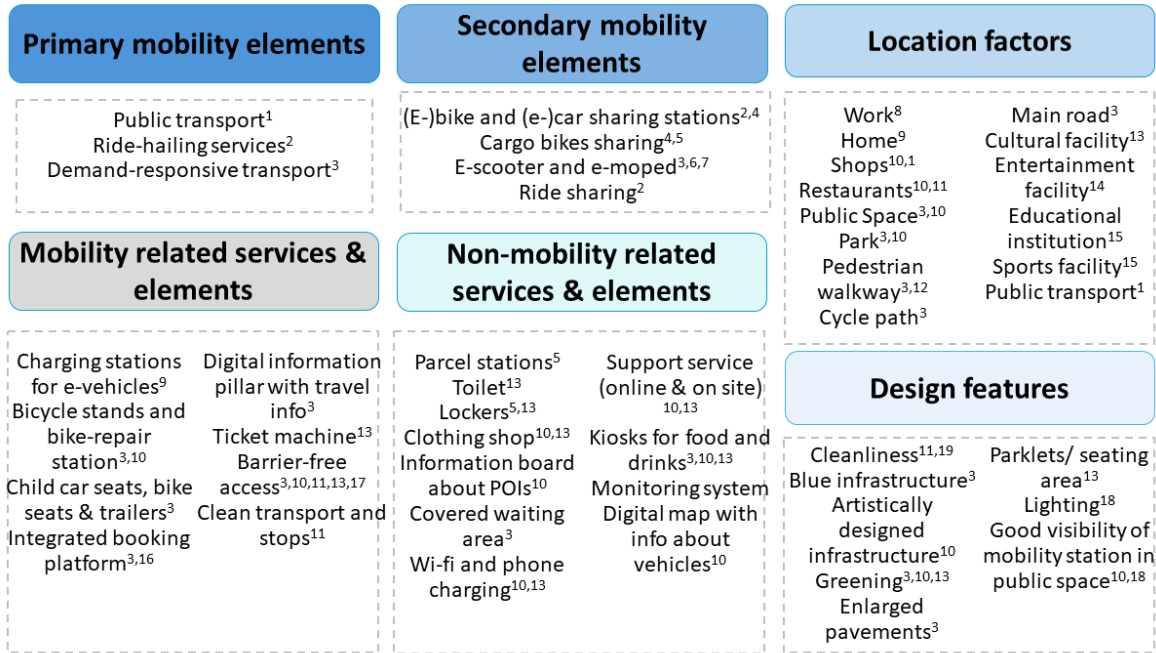


Figure 5.3: Components of mobility hubs based on literature

¹Miramontes et al. (2017), ²Anderson et al. (2017), ³Roberts (2019), ⁴Shaheen Christensen (2013), ⁵Bruzzone et al. (2021), ⁶Laa Leth (2020), ⁷Tuncer Brown(2020), ⁸Frank et al. (2021), ⁹Liao Correia (2020), ¹⁰Ambroz et al. (2016), ¹¹Chiadambra (2019), ¹²Tavassoli Tamannaei (2020), ¹³Aono (2018), ¹⁴Monzon-de-Caceres Di Ciommo (2016), ¹⁵Blad (2021), ¹⁶Jittrapirom et al. (2020), ¹⁷Conticelli et al. (2021), ¹⁸Murphy (2019), ¹⁹dell'Olio et al. (2011).

they considered as the most suitable MH location. The question aimed to document the frequency of the preferred locations. Building upon the previous question, respondents were then queried about the factors that influenced their choice of location.

The components from the literature were assessed in the survey by segmenting questions into units of analysis, using the following thematic blocks: 1. General mobility behaviour, 2. Transportation opportunities, 3. Digital and non-digital services, 4. Location factors, 5. Expectations, 6. General attitude towards a MH.

5.4.2.2 Interviews

The qualitative phase is applied as the sequential procedure of the mixed-methods approach, which involves quantitative data as a basis for qualitative data collection (Kuckartz, 2014). This phase is characterised by semi-structured online interviews with experts from the private sector and administration to obtain specialist knowledge on the data collected in the survey. They are selected through a "purposive sampling" depending on their involvement in the implementation of a MH. In this way, individual aspects of a MH that were identified in the survey can be examined from other perspectives and thereby studied more comprehensively (Kuckartz, 2014; Döring and Bortz, 2016), adding expert contribution and experience. The semi-structured method is flexible and adapted to specific contexts and respondents. It fits better with explorative research because the data collection strategy derived from open-ended questions allows for an interpretive approach and subject-based understanding (Diekmann, 2021; Flick, 2021).

We posed two primary questions to the experts: the first sought to contextualise the survey results and

gain insights into what these findings imply for the planning of a MH from the expert perspective; the second question aimed to explore potential strategies for implementing the implications derived from the results. The expert opinions regard the survey blocks of questions on "primary mobility elements", "secondary mobility elements", "mobility-related services", "digital services", "location factors", and "expectations" towards a MH. The interviews are concluded with practical advice for MH implementation.

5.5 Results

5.5.1 Survey results

The results of the survey come from 211 accepted observations, but they are influenced by the affiliations of participants to the main campus of TUM. Data were processed in R, Excel, and QGIS.

The participants in the survey are mainly under 35 years old (53.1%). Only 3.1% were older than 65, and the rest are in between. The different genders participated in almost the same amount (47.5% male, 51.8% female and 0.6 diverse). The most consistent group of participants was indeed with a university education level (85.6%). They also represent the majority groups in the employment status, which are students (40.6%) and full-time employees (38.8%).

In this study, after cleaning the data set, an explorative data analysis of the survey data is carried out using descriptive statistical methods, such as the relative frequency of the respective attribute of a variable is evaluated as a percentage. For example, the percentage of all respondents who are either male or female is calculated with respect to all answers to this specific question.

In order to prepare the data for a graphical representation of all closed questions, they are imported as CSV files into the statistics programme R, where the data are cross-tabulated and filtered. For instance, the socio-demographic variable "age" is crossed with the variable "use of mobility-related services". Attributes are given in relative frequencies and percentages for the respective question. The resulting data tables are, in turn, imported into Excel and presented there as bar charts or tables using pivot tables. The form of the graph in which the data is presented depends on the scale level of the data. The data have a nominal (e.g. question on gender) or ordinal (e.g. Likert question) scale level (Diekmann, 2021).

Regarding the "general mobility behaviour" of respondents, data shows that the large majority (77%) travel four days or more per week (Figure 5.4).

In the literature, bar charts are usually suggested for both scales, but it is also pointed out that tables are suitable for socio-demographic data (Döring and Bortz, 2016). Stacked bar charts are particularly suitable for a visually appealing presentation of Likert-type questions, as the individual items of the respective variables can be compared directly. The bars represent the proportion of the respective answers depending on the total number of answers. The bars of the stacked bar plots always add up to 100% (Figure 5.5).

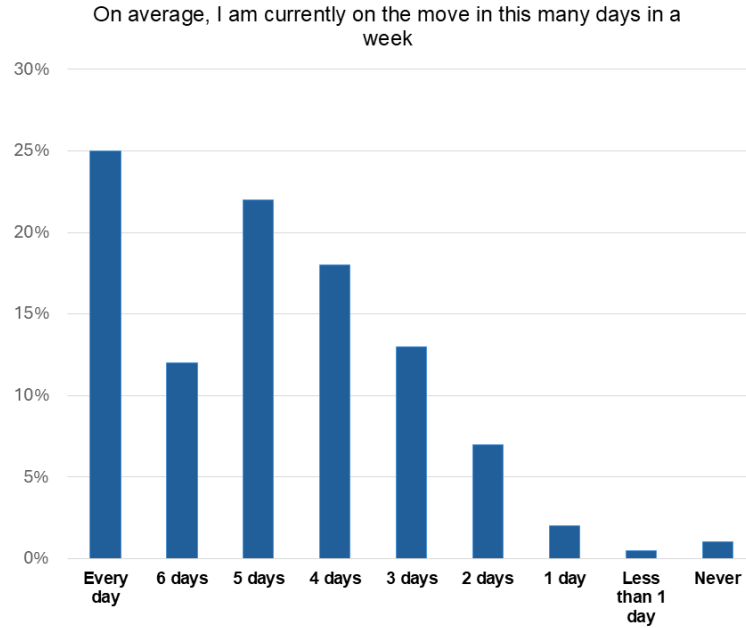


Figure 5.4: Frequency of mobility per week

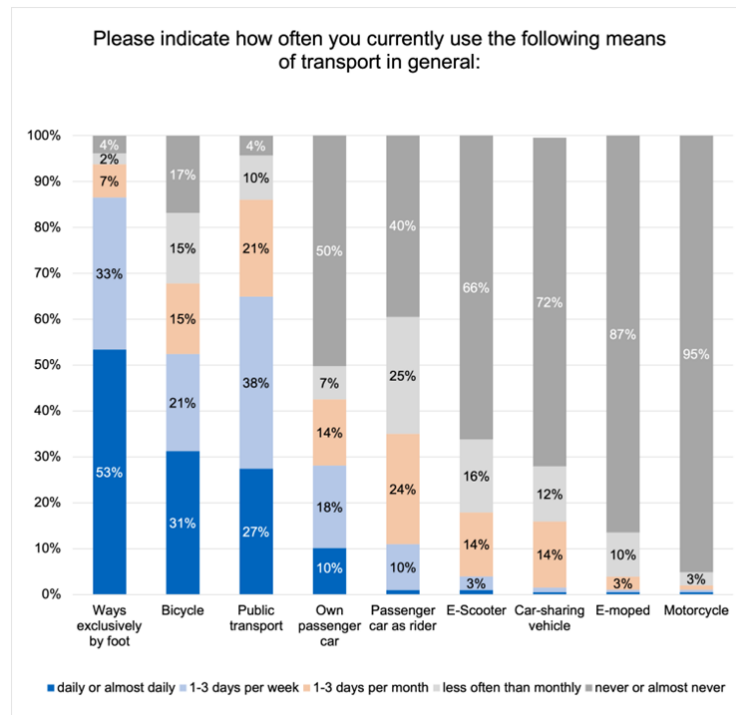


Figure 5.5: Frequency use of different transport mean

Most people travel daily (25%) and five days a week (22%). More than half of all participants (53%) walk every day or almost daily. This is followed by travelling by bicycle (31%) and PT (27%) daily or almost daily. Respondents rarely travel by car-sharing vehicle, e-moped, or motorcycle. Based on both kinds of results, we

can note that a significant number of respondents are on the move every day or many days a week and travel mostly by foot, PT, or bicycle. Regarding the use of mobile devices for mobility, most respondents (76%) have a basic knowledge of digital services and use mobile devices for timetable information, ticket purchase, or route planning.

5.5.1.1 Mobility hub needs

The thematic block "transportation opportunities" includes public transportation-related needs as "primary mobility elements", where 73% of all respondents mention the subway most frequently as a 'very important' means of transport at a MH (Figure 5.6b). In second rank is the bus as a 'very important' means of transport (41%), followed by the tram and rapid-transit railway. Mobility service providers such as 'Uber' or cabs are most frequently named as 'rather unimportant' or 'irrelevant'. The need related to public transportation features are preferred and considered 'very important' in order: mobility station's lighting (73% of respondents), covered waiting areas (70% of respondents), cleanliness of transportation means, and the mobility station (68% of respondents) (Figure 5.6a). If we cross the results with the gender characteristics of respondents (Figure 5.7a), we can highlight that 60% of all female respondents find the item 'lighting' at MH important, while only 40% of male respondents do so. Furthermore, the results for 'monitoring systems' are differentiated by gender: 20% of male respondents find monitoring systems very important, but 80% of female respondents do. Additionally, digital features (i.e., digital information pillar with departure, delays, and sharing vehicles' availability), as well as transfer time, are crucial needs to be considered in the MH planning process. Concerning transfer time, the majority of respondents (83%) would spend one to a maximum of five minutes walking to change from one mobility option to another. Five minutes is the time most respondents would use to switch from one option to another (43%).

The "secondary mobility elements" are those referring to shared services, and respondents consistently considered 'very important' only bicycles stand (74%), while the charging station for e-mopeds or scooters is considered 'rather important' or 'irrelevant' (Figure 5.6c). The survey data showed that the older the age group was (between 51 and 65 years old or over 65 years old), the more likely they were to describe the item "e-scooters" as 'rather unimportant' or 'irrelevant' compared to other age groups. This result is of particular importance because it shows large differences in various age groups and respective needs for sharing systems.

The second thematic block "digital and no-digital services" includes the mobility-related services at a MH, among which there is a clear need for bicycle-related services. Indeed, respondents rated services involving bicycles as 'very important', namely 65% state secure parking facilities for private bicycles and 74% indicate bicycle racks, followed by bicycle repair stations and charging stations. The mobility-related services for the rental of equipment for transporting children show rather ambivalent results, so it is interesting to cross the socio-demographic variables. Indeed, a gender difference appears among the respondents who select 'very important' for "rental of car seats for children", where 65% are female and 35% male, as well as for the rental of bicycle seats for children and rental of bicycle trailers. The digital needs resulting from the survey show that 65% of all respondents generally classify all listed items as 'very important' or 'rather important'. An

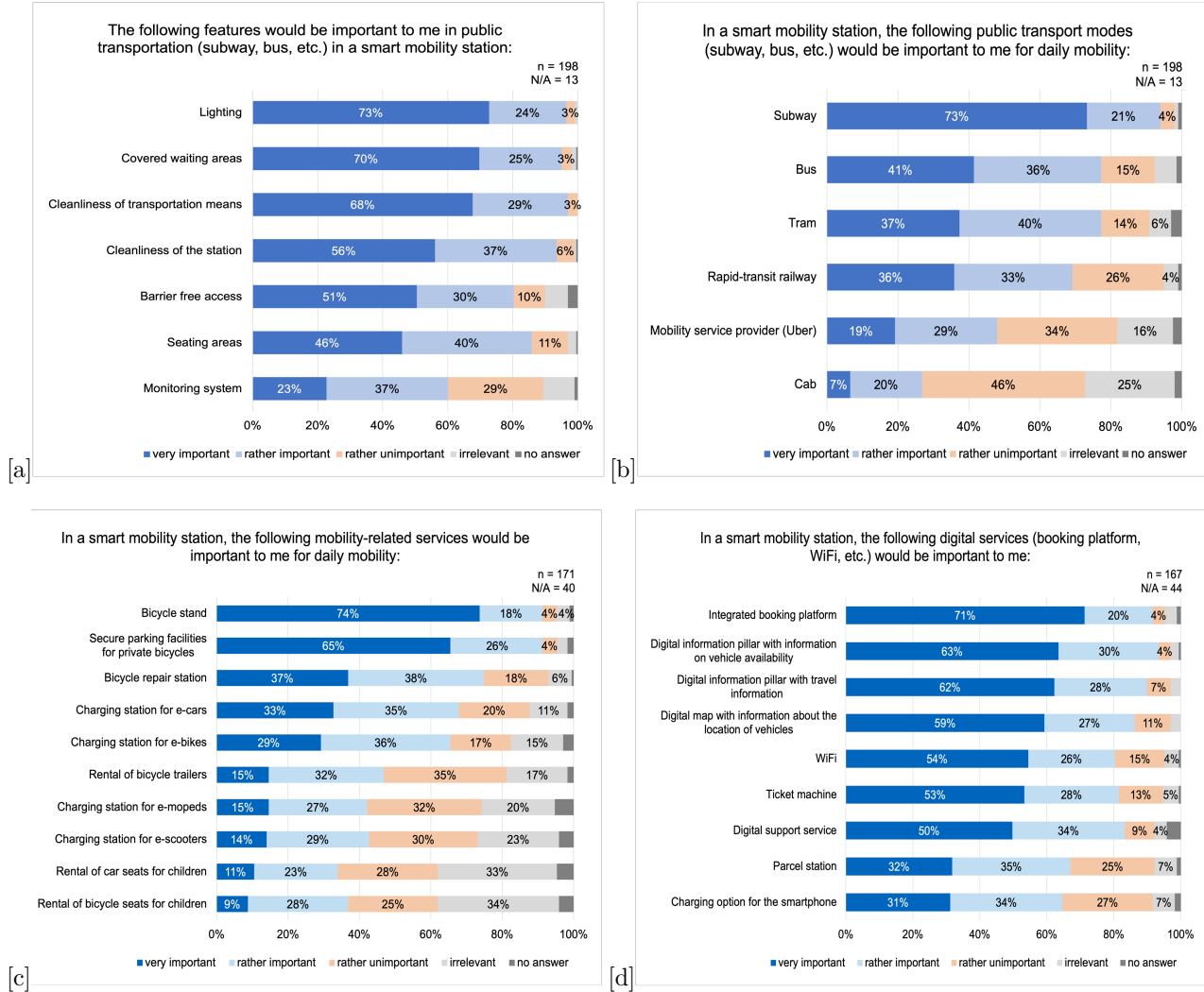


Figure 5.6: Survey results for needs: a) Needs in terms of features of public transportation; b) Needs in terms of public transportation; c) Needs for sharing services; d) Needs for digital services

integrated booking system and the provision of information in the form of a digital information pillar or digital map are the most important needs of the respondents regarding digital services at a MH (Figure 5.6d).

The third thematic block on "location factors" presents different results depending on the posed questions (if focused on the importance of closeness to specific places or on influencing factors for the location). Respondents were presented with a set of points of interest and infrastructural features without showing a map. They were asked to indicate the locations where they would like to see a MH built. Survey participants were then asked to select their desired location for a MH on a map and what factors they considered when selecting their preferred location. The results before and after showing the map differ, except for "proximity to an educational institution", "proximity to public spaces" and "proximity to public transportation", which were relevant factors in both cases. Before showing the map, 67% of all respondents indicated that the MH should be located close to their homes and 64% indicated that proximity to work was important. Survey participants were then asked to select their desired location for an MH on a map and indicate the factors influencing their choices. In the second option, the proximity to home (14%) and work (27%) was much less

	Gender	
Item	female n [%]	male n [%]
Covered waiting areas	65 [58]	47 [42]
Seating areas	41 [57]	31 [43]
Lighting	69 [60]	46 [40]
Cleanliness of transportation means	60 [56]	47 [44]
Monitoring systems	28 [80]	7 [20]
Barrier-free access	44 [57]	33 [43]
Cleanliness of the station	49 [54]	41 [46]

(a) Gender rating item as "very important"

	Agegroups (years)				
Item	18-24 [%]	25-34 [%]	35-50 [%]	51-65 [%]	+65 [%]
Rental of cargo bikes	14 [44]	38 [45]	7 [32]	7 [44]	4 [80]
Rental of bikes	5 [16]	25 [29]	6 [27]	4 [25]	2 [40]
Rental of e-bikes	14 [44]	48 [56]	10 [45]	6 [38]	3 [60]
Rental of e-scooters (Lime, Tier)	16 [50]	39 [46]	17 [77]	12 [75]	4 [80]
Rental of e-mopeds (Emmy)	22 [69]	61 [72]	19 [86]	11 [69]	4 [80]
Car rental	18 [56]	52 [61]	16 [73]	9 [56]	4 [80]
Rental of e-cars	13 [41]	31 [36]	12 [55]	9 [56]	3 [60]
Ridesharing services (Uber)	10 [31]	38 [45]	13 [59]	9 [56]	5 [100]

(b) Age group in years rating as "rather important" and "irrelevant"

Figure 5.7: Survey results categories (item) crossed for genders and ageing

frequently chosen by the participants for determining the location of an MH (Figure 5.8a). A heat map was then created to display geographically clustered data (Netek et al., 2018). The different colouring of the heat map shows differences in the frequency of selection of the preferred location for a MH, with dark red sites being selected frequently and light red to beige points being selected less frequently.

The frequently chosen points on the preferred location of a hub are near the TUM main campus (Figure 5.8b), or a PT stop. The chosen locations (in red in the figure) are also all on traffic roads and often at crossings. This means that the respondents express a strong need for a MH to be located on a street or even an intersection and close to a PT stop, an educational institution, a public space, their home, or their workplace.

5.5.1.2 Mobility hub expectations

The block regarding "expectations" aimed at capturing what impact respondents expect from a MH in terms of shared services. Respondents state that sharing services save resources and, thus, have a positive impact on the environment. The results demonstrate that the majority has positive expectations on the provision of sharing services: 61% of all respondents expect to result in less car traffic due to the provision of alternative transport options at a MH; 58% expect fewer harmful emissions (58%), 42% in less road traffic noise. Surprisingly, respondents were least likely to expect sidewalks or bike lanes to become congested as a result of sharing services offered at a mobility station (15%). In addition, only 18% of all respondents believe that social exchange is promoted by a MH.

Even if positive expectations clearly prevail, negative expectations appear only in open-ended questions, mainly represented by shared service congestion/traffic. Moreover, respondents claim that the offers are easy to use and easy to book and that there are cheap offers. The focus of the expectations is therefore strongly on a convenient usage of the offers. In addition, the respondents frequently stated that they expect mobility

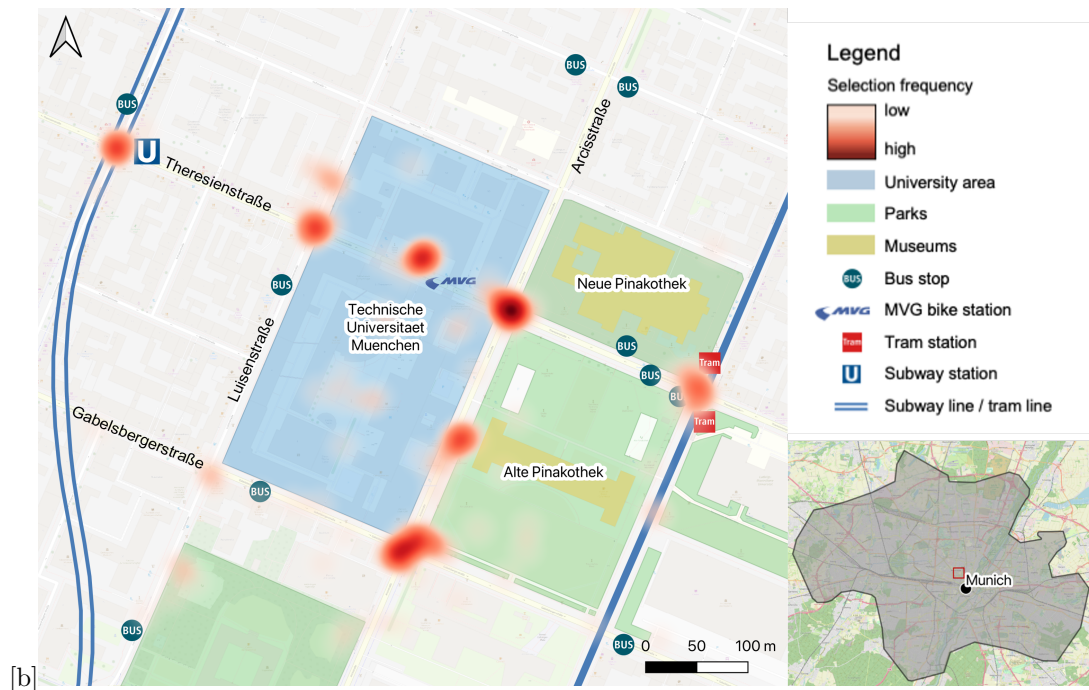
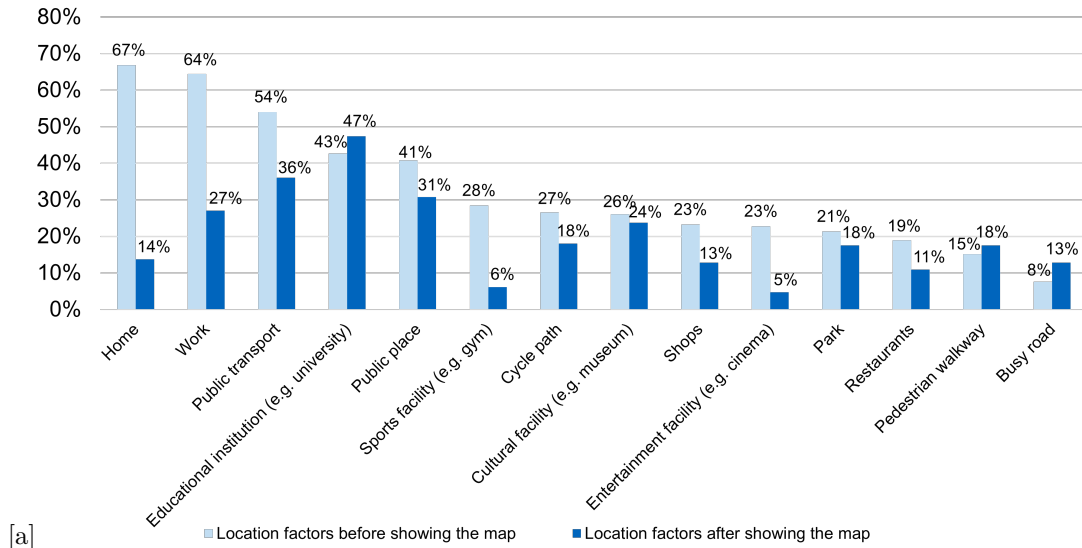


Figure 5.8: Survey results for "Location factors": a) Preferences for location factors before and after showing the map; b) Heatmap of selected locations for a MH (middle) and municipal scale (bottom right)

Source: Own depiction, data based on Geofabrik Download Server. Projection: QGIS

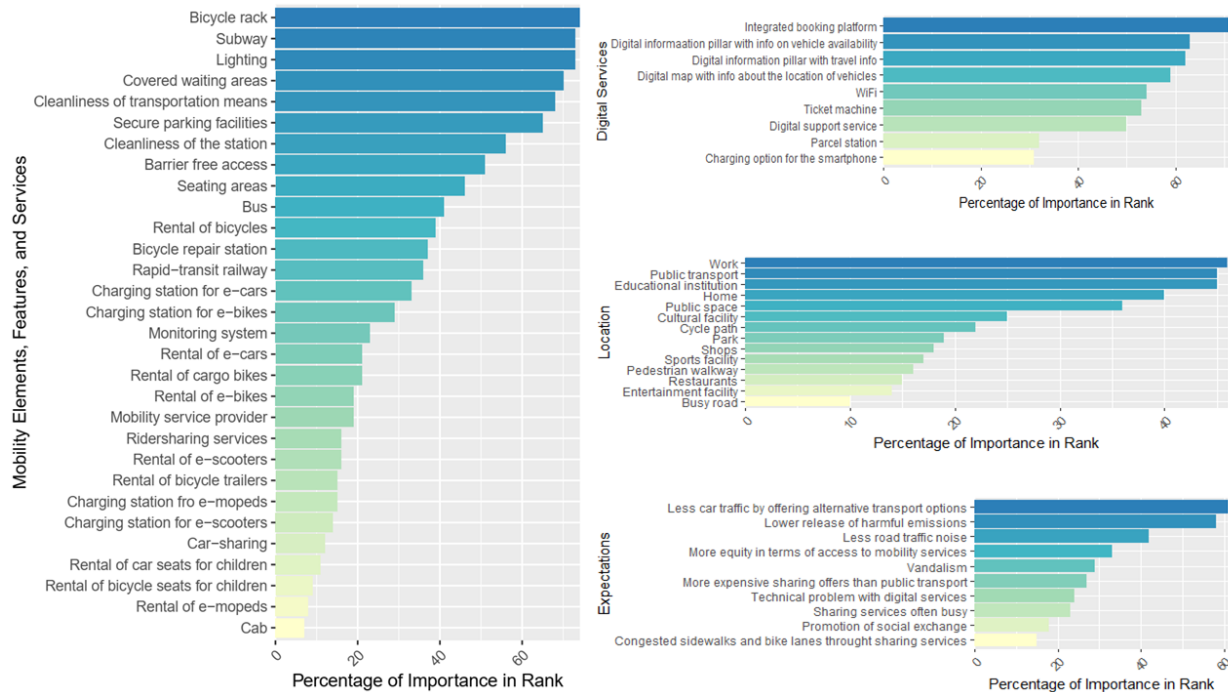


Figure 5.9: Ranking of importance for services, location and expectations

stations to become widespread in Munich. However, few respondents express concerns about a MH in the city, while suggesting a regional focus instead of an urban one. Furthermore, some argue that the architecture of the mobility station is not attractively designed.

It is worth considering that there is evidence that MHs alone may not lead to significant reductions in car traffic or a shift towards sustainable transport modes as expected from respondents' wishes. For MHs to be effective, they need to be paired with "push measures", such as reducing the availability of parking spaces and increasing parking tariffs, as stated by [Hachette and L'hostis \(2023\)](#). The latter emphasises that MHs need to be integrated within a broader urban mobility strategy to discourage car use effectively³⁷. Without these complementary policies, the potential benefits of MHs —such as reducing car dependency and encouraging modal shifts— may not be fully realised. This approach ensures that MHs do not merely serve as additional transport options but actively contribute to reducing car usage and promoting sustainable urban mobility.

The last block on "general attitude towards a MH" shows that 58% of respondents fully agree with the development of a MH in Munich, and 35% of respondents believe that a MH is likely to be useful in the city of Munich. It can therefore be concluded that more than three-quarters of all respondents consider a MH in Munich to be useful. An overview of the results is given in the following graphs in Figure 5.9, where the mobility elements, features and services, digital services, location and expectations are ranked by importance.

³⁷<https://www.uantwerpen.be/en/research-groups/research-group-for-urban-development/research/infrastructure-mobilities/mobility-hubs/>

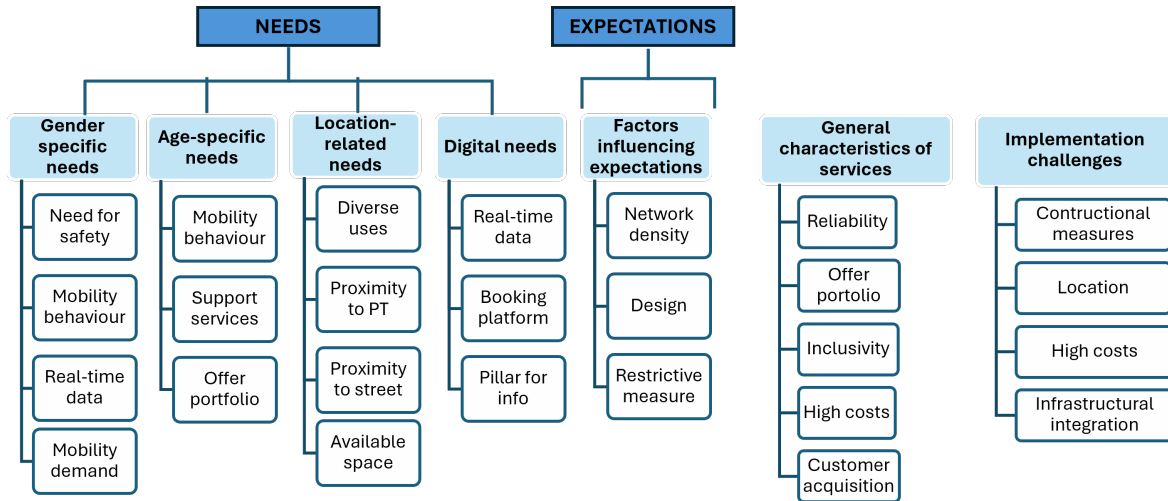


Figure 5.10: Coding taxonomy of interview data

5.5.2 Interview results

The results of the interviews constitute the qualitative phase and are evaluated alongside an analysis of quantitative results derived from all thematic blocks. These findings are then organised into categories and subcategories to facilitate comparison between the survey and interview data during the analysis process (Figure 5.10). Six people were interviewed (half from the administrative context and half from the entrepreneurial context). The composition of the interviewees was as follows: two persons from the mobility department of the city of Munich, responsible for the planning of mobility stations in Munich; the third person was responsible for transport planning and mobility management in the neighbouring city of Fürstentfeldbruck and he had previously conducted research on mobility stations in the city of Munich. On the company side, an employee from "Tier Mobility", an e-scooter and bicycle rental company, was involved because the interviewee was responsible for partnerships with PT companies in Munich. In addition, we involved the managing director of a planning office for urban and transport planning in Munich, in charge of planning and designing a large mobility station in Munich. Thirdly, a person from the Munich Transport and Tariff Association responsible for sharing systems and networked mobility was approached using the snowball principle.

In the next paragraphs, we report the main findings regarding the needs discussed within the interviews. Gender discrepancies were discussed with interviewees concerning primary elements of PT features options at MHs, categorising them under the main category "gender-specific needs" (figure 5.10). The interview participants justify gender-specific needs for PT features with a different 'need for safety' and 'mobility behaviour' of men and women. 'Real-time data' represents the resulting needs of women and can counteract this discrepancy. We provide an example of an answer regarding gender-specific needs of women for real-time information, describing the need to accurately plan and assess whether services are available at a location at specific times of the day and night:

"For example, at night, when it's already dark and I feel unsafe. And if I know, "okay my bus or the subway is coming in 10 minutes," then I can go to a café where I might also feel better."

Moreover, under the same categorisation, 'mobility demand' and 'reliability' can also be included since they change among genders, especially regarding the transport of children. These differences are crucial for the attractiveness of shared services.

Secondary mobility elements mainly highlight "age-specific needs". In this context, several interviewees believe that e-scooters should still be present in every mobility station because, in the long term, they can also lead to a change in thinking and mobility behaviour among the elderly. The results on secondary mobility elements as part of the transportation opportunities at a MH indicate that a more diverse offer portfolio of sharing options can be helpful due to age-related differences in mobility behaviour. In addition, there was broad consensus among interviewees that support services, such as training or events, can counteract the barriers older people face when it comes to e-scooters. Indeed, one of the participants was convinced that:

"If you want to make [e-scooters] more attractive and get older people to use them, you have to create mobility opportunities to test them beforehand in a safe environment, for example in a parking lot or during an event."

Moving the discussion to the category "digital needs", the main findings from the interviews regard the smart elements as 'real-time data', 'integrated booking platform' and 'information pillar', intended also as subcategories. Some interviewers refer to 'inclusivity', 'offer portfolio' and 'reliability' as "general characteristics of services" and not specific needs. Additionally, to the already mentioned, the other two conflicting subcategories of the "general characteristic of services" are individuated from the interviewers in 'high costs', for example, providing Wi-Fi and 'customer acquisition', increased by digital services. About the 'high costs' of digital services and the choice to provide only some of them, one of the participants argues that:

"The moment you would need light and Wi-Fi, only one of them works, and then you have to prioritise."

The last category of needs is "location-related needs", which the interview participants explain through the following subcategories that influenced the selection of the location by the survey participants: 'concentration of diverse uses', 'proximity to public transport', 'proximity to street' and 'available space'. In summary, the reasons behind the site selection are the same for both the interview participants and the survey participants. Indeed, a high concentration of diverse uses and proximity to PT play a key role in both perspectives, as demonstrated in the following quotes:

"Well, we have residential buildings, we have a lot of leisure activities that are located there, but also the university. That means we already have so many interests that come together there."

"At the point on Theresienstraße, there is also the subway station, so I think these are more typical destinations and traffic originating".

According to the interview partners, proximity to the street plays a major role in the site selection of the survey participants, but they also based their choice of location for a MH strongly on the available space. The discussion on "expectations" regards the survey findings as realistic, albeit achievable only when complemented by a comprehensive network of mobility stations in Munich. According to the interviewers, the survey expectations were influenced by three main factors, intended as subcategories: 'network density', which means that mobility stations need to be integrated with the public transport system; 'design', which promotes a change of mindset; 'restrictive measures' that have to accompany mobility stations' expansion to occur traffic relief and reduce car attractiveness, as stated in the following quote.

"It needs restrictive measures in the street space, as long as I can still park that doesn't cost me much, I always find the parking space quickly, I don't need these offers."

5.6 Discussion

In this section, we discuss the key findings of our study, emphasising both strengths and the specific limitations encountered. The survey results have revealed that the respondents generally have a diverse range of needs and preferences regarding the features of a MH, some of which are weighted very differently by the respondents depending on their socio-demographic characteristics. Concerning the participants' socio-demographics, attention was paid to age or gender respectively for each question. Although the mixed-methods approach employed in this study generally corroborates the survey findings, leading to a robust validation of most topics, it is essential to acknowledge that the conclusions drawn are context-dependent and may not be universally applicable.

One of the main issues identified is that the respondents' expectations of MHs might be overly optimistic or unrealistic if not accompanied by complementary policy measures. For example, while participants expressed high expectations regarding the potential for MHs to reduce private car usage and emissions, these outcomes are contingent upon the implementation of additional "push" measures, such as reducing parking availability or increasing parking costs, as emphasised by recent studies. In particular, [Nijland et al. \(2015\)](#) and [Claasen \(2020\)](#) investigate the effects of the carsharing introduction in Dutch cities on car ownership as well as the reduced need for private cars when a MH exists around. These studies suggest that MHs alone are unlikely to drive significant behavioural changes without a broader policy framework that actively discourages car use. To support the expectations regarding the potential reduction of harmful emissions, it is possible to consult the Mobi-Mix project ([Hachette and L'hostis, 2023](#)), which gives an in-depth insight into how MHs contribute to having a more sustainable environment.

Moreover, while the study adds a novel perspective by highlighting gender-specific safety concerns, particularly among women, it is important to consider that these findings, while consistent with existing literature ([Elmashhara et al., 2022](#); [Bell, 2019](#)), may reflect the particular socio-cultural context of the study area. The preferences for shared services also reveal generational differences, with older individuals showing less interest in these options. This finding aligns partially with the literature but also suggests that life stage and broader societal factors, such as digital literacy and familiarity with shared services, play a significant role ([Reck and Axhausen, 2021](#); [Wang et al., 2021](#)). The experts point out that this should be considered when designing a MH to ensure inclusivity.

The location of MHs emerged as a critical factor in our study, with both quantitative and qualitative data underscoring the need for proximity to public transport to maximise their effectiveness and to reach as many target groups as possible. This aspect is also stated by [Anderson et al. \(2017\)](#) and [McQueen et al. \(2021\)](#), which emphasise the importance of the proximity of MHs to public transport stops to integrate the services offered in a MH into the route of potential users. However, the purpose of an individual's trip can vary over time, making it challenging to accommodate these temporal fluctuations in planning. While our findings are well-supported by the literature [Ambroz et al. \(2016\)](#); [Aono \(2018\)](#); [Blad \(2021\)](#); [Miramontes Villarreal \(2018\)](#);

[Monzon-de Caceres and Di Ciommo \(2016\)](#), it is important to recognize the challenges in translating these insights into practice, particularly in dense urban areas where space is limited. The practicality of developing a dense network of MHs, as suggested by experts, must be balanced against these spatial constraints and meet all potential mobility needs to enable long-term modal shift.

Concerning expectations, they play an important role when it comes to creating incentives for the use of services at a MH. It could be useful to show users the effects of MHs utilisation. In this way, the benefits of using services at a mobility station become tangible, and the expectations of potential users towards the means of transport can be positively influenced. Given these results, we propose some recommendations derived from the interviewers and directed to mobility planners responsible for MHs implementation. The "implementation challenges" category represents these results, with corresponding subcategories as main factors for planners: 'construction measures', 'location', 'high costs' and 'infrastructural integration'. Recommendations are based on strong preferences for transportation opportunities, digital and non-digital services and the location of MHs of Munich's citizens and mobility experts.

To optimise the accessibility and convenience of MH, it is recommended to strategically locate them adjacent to subway, bus, and tram stops, thus enhancing transport opportunities. Efforts should be directed towards securing available space near these nodes to facilitate the integration of all services, minimising walking distances between various transport modes to a maximum of five minutes, as it is revealed by the survey where 83% of respondents would spend a maximum of five minutes in transferring. However, challenges may arise in finding suitable space near public transport stops due to the limited availability of space, as well as defining clear wayfinding.

To enhance user experience and safety, it is advisable to ensure that MHs have well-lit and covered waiting areas consistently available, although balancing gender-specific preferences in these features may pose challenges. Prioritising shared transportation services, including rental bicycles, electric cars, e-scooters and cargo bikes, is recommended to cater to a broad spectrum of users, which means facing overcoming barriers to adoption, especially among older population groups. Similarly, emphasising bicycle-related services based on user preferences and addressing gender-specific differences in mobility-related services, such as the transport of children, are crucial recommendations. Implementing integrated booking platforms and digital information systems with real-time data at MHs can further enhance user experience and convenience, despite challenges related to high construction costs and digital literacy among users. Finally, prioritising locations for MHs proximate to workplaces, residential areas, and public transport networks, even if a high concentration of different uses means also less available space. Addressing these recommendations and challenges is crucial to realising the potential of MH in reducing negative environmental impacts associated with car usage, noise and emissions as emerged from the expectations of citizens and experts. The main policy recommendations are summarised in the following figure 5.11.

Regarding the main limitations of our study, a more diverse group should be involved, including people who are not PT users, to facilitate their transition from private motorized transport. Other disadvantages of the online survey are the exclusion of people who are not digitally literate or those who do not have online access and the lack of information about who completed the survey and whether the survey was completed by participants, for example, with assistive devices ([Döring and Bortz, 2016](#)).

An additional limitation of this study is related to the use of a non-probability sampling method, which led to a higher proportion of students being included in the sample. The sample used in this study is a "convenience sample." Using an online survey, not everyone in the population had the same opportunity to participate: Only those with internet access and who encountered the survey were able to participate ([Döring](#)

	Recommendations	Challenges
Transport opportunities	MH should be located directly adjacent to subway, bus, and tram stations or within a short walking distance of major public transport hubs, ensuring seamless connectivity and easy access for passengers.	Identifying and securing sufficient available space near public transport offers to accommodate the full range of services offered by MH. Navigating urban density constraints, competing land use priorities, and the need for proximity to public transport, especially in densely populated areas like Maxvorstadt in Munich.
Maximum distance of the different transport modes	At best, a maximum of 5 minutes walking time between the various offers.	Identifying a suitable location that can accommodate all services in one central space and is conveniently accessible via public transport, particularly in densely populated areas like Maxvorstadt in Munich.
Features of public transport	Lighting and covered waiting areas should always be available; features should generally enhance a sense of safety and comfort.	Addressing gender-specific differences in needs and preferences related to public transport features such as lighting and waiting areas. Consider factors like lighting, coverage, and the design of waiting areas to accommodate these differing needs.
Shared services	Focus should be on rental of bicycles, electric cars and cargo bikes; broad offer necessary for older population groups.	Tailoring the availability of shared services, such as e-scooters, to age-specific preferences based on the location.
Mobility-related services	Strong preference for all services related to the bicycle.	Tailoring services to gender-specific needs while avoiding the reinforcement of gender disparities in the services such as offering child seats for bicycles more prominently on routes that are more frequently used by women.
Digital services	Integrated booking platforms and digital information pillar with real-time data should always be in place; contributes to feeling of safety and acquisition of customers	Covering high construction costs as electricity is not always available at the desired location for the MH; Ensuring the accessibility of digital services requires accommodating varying levels of digital literacy among users.
Location factors	Proximity to work or home is desired if no location is specified; if area is specified, proximity to educational institution, public transport and public place is preferred.	Finding a location where there is a high concentration of different uses, proximity to public transport and available space.
Expectations	Impact of MH should reduce negative effects of car such as traffic, noise and emissions.	Offering a comprehensive and area-wide network of MH required to achieve desired effects.

Figure 5.11: Recommendations for policy makers

and Bortz, 2016). It is unclear what the selection probability was for the individual elements in the sample and how the sample can be distorted compared to the target population (Döring and Bortz, 2016). This method was chosen because it allows for quick subject identification and is cost-effective (Higginbottom, 2004). Since this study used a convenience sample and not a simple random sample, it is impossible to calculate the probability that a Munich citizen would be included in the sample, as not all residents had the same or a known chance of inclusion (Döring and Bortz, 2016). While this introduces potential biases, particularly in terms of generalizability to the broader population, the study's validity is supported by the use of appropriate statistical methods, such as cross-tables, which help mitigate the impact of this limitation.

The empirical component of this study is based on a single-case analysis, which inherently limits the generalizability of the findings (Flick, 2021). Consequently, it remains uncertain how the needs and expectations toward a MH might differ in other contexts, such as rural areas or different cities. However, the insights gathered provide a valuable foundation for informing similar urban environments, particularly those comparable to Munich.

Since the insights gathered in this study were collected but not directly incorporated into the design of an MH, they align with the 'Consultation' level of participation on Arnstein's Ladder (as discussed in 5.4), which correspond to early stages. However, while it does not constitute a fully participatory design framework, it is indispensable to fulfil the goals of the co-design approach, which is to reach the 'Citizen Power' level, as outlined by Arnstein (1969). Given the scope of the project, the timeframe and the need for an initial structured exploration of needs and expectations, consultation was a pragmatic choice that maintains alignment with the principles of co-design while guaranteeing feasibility. Higher levels of participation foster more robust partnerships between citizens and traditional decision-makers, granting citizens meaningful decision-making power (Arnstein, 1969).

The distance between the steps of co-design is greater the higher one climbs the ladder, and the application of the last steps, which refer to citizen control, requires a distinctly high and constant expenditure of effort and collaboration between the various actors, aimed directly at the application of results. This apparent limitation reflects the progressive nature of co-design, as stated by Sanders and Stappers (2008), where initial consultations can evolve into deeper collaborative processes as projects develop.

5.7 Conclusion and Future Research

This study contributes to the recent literature on the involvement of key stakeholders, especially citizens, in the design and planning processes of MHs by understanding their specific needs and expectations. The mixed-methods approach helped us to generalise citizens' needs and expectations based on the survey and the interview results. The latter helped us to understand more deeply and give relevance to the information collected from the survey phase, confirming that a one-size-fits-all approach is inadequate.

Employing a mixed-methods approach allowed us to avoid any hierarchy of methods and mix qualitative and quantitative approaches, usually considered incompatible (Kamargianni and Melinda, 2018), while converging to the advantage of the phenomenon being analysed (Lee, 2019). The goal of the mixed-methods approach is not to position itself as a replacement for purely qualitative or quantitative approaches. Instead,

it seeks to leverage the strengths of each while mitigating their limitations ([Johnson and Onwuegbuzie, 2004](#)). By integrating the broad generalizability and statistical rigour of quantitative methods with the depth and contextual understanding provided by qualitative methods, the mixed-methods approach enables a more comprehensive exploration of complex urban mobility planning. This approach acknowledges that some questions are best addressed by combining numerical data and rich narrative insights, offering a more holistic perspective than either method alone.

In interdisciplinary studies like this one, where expertise from social sciences, economics and transport engineering must converge, the mixed-methods approach proves particularly valuable in addressing complex, multifaceted issues ([Morse, 2016](#)). This methodology facilitates a functional integration of different disciplinary perspectives, allowing researchers to navigate and synthesise different analytical frameworks and priorities. Specifically, in our case, it helps bridge potential gaps between data collection from users and the practical feasibility considerations and professional insights of experts and policymakers. By doing so, this approach ensures that stakeholder voices are meaningfully incorporated into decision-making processes, leading to more robust outcomes ([Hurmerinta-Peltomäki and Nummela, 2006](#)).

By employing a mixed-methods approach, this study was able to collect and analyse diverse data, revealing nuanced expectations across socio-demographic groups. These differences are particularly pronounced in areas such as security and digital services, which significantly influence the attractiveness, acceptance, and trustworthiness of MHs. The integration of quantitative survey data with qualitative insights allowed us to identify not only the general preferences of different groups but also the underlying reasons for these preferences, providing a richer understanding of their specific needs.

This understanding is critical from a practical perspective. The findings suggest that mobility planners must carefully consider the location, design and services offered at MHs to attract and accommodate different user groups. For example, while digital services like smartphone charging and Wi-Fi emerged as key drivers for attracting users, qualitative insights highlighted the equal importance of non-digital services, such as adequate lighting and sheltered waiting areas, especially for older adults and women. The mixed-methods approach ensures these insights are both data-driven and deeply contextual, enabling planners to design MHs that are user-centric while addressing logistical challenges, such as space constraints near public transport nodes.

While this study offers valuable insights into the needs and expectations of citizens regarding MHs, it is important to acknowledge certain limitations that may affect the generalisability and representativeness of the findings.

Firstly, the study employed a convenience sampling method, chosen due to its cost-effectiveness and the ability to quickly recruit participants, aligning with similar research methodologies as noted by [Higginbottom \(2004\)](#). A non-probability sampling strategy could reflect more the population's diversity or distribution, as not all residents had an equal or known chance of inclusion ([Döring and Bortz, 2016](#)). This choice introduced a bias in the sample composition, resulting in an overrepresentation of specific groups, such as students, while underrepresenting others, particularly older adults. This skewed demographic profile limits the extent to which the findings can be generalised to the broader population of Munich residents. According to this, further research should focus on a larger sample in a citywide approach and include a broader population with more diverse socio-demographic characteristics. As this work is a case study set in a specific location, future research should also aim to specifically interview the target groups present in the given environment.

Additionally, the reliance on an online survey further narrowed the participant pool to individuals with Internet access and those who encountered the survey. As [Döring and Bortz \(2016\)](#) highlights, such methods

exclude segments of the population without equal access to or familiarity with digital tools, potentially overlooking barriers to adoption faced by less digitally literate groups, such as older adults. This exclusion is significant, as these groups may have distinct needs and expectations regarding MHs, particularly regarding accessibility and security.

Despite these limitations, the study’s validity is bolstered by the use of robust statistical methods, such as cross-tabulation, which effectively contextualise and analyse the data by revealing patterns and relationships between socio-demographic factors and user expectations. Cross-tabulation enables a detailed examination of how specific variables, such as age or gender, correlate with preferences for security and digital services, providing nuanced insights into diverse user needs. Additionally, the integration of qualitative data further complements these statistical analyses by offering explanatory depth, enabling the interpretation of observed patterns within their real-world context. This combination of methods helps mitigate potential biases arising from the sampling approach chosen, ensuring that the study’s findings remain grounded, relevant, and actionable for diverse stakeholders.

To conclude, this study clearly reveals the role of a MH in the transport network as well as reflected in the services offered there. Future research on MHs should therefore aim to collect data following a design that is suitable for the specific environment and target group. This information would be useful for the large-scale implementation of MHs in different locations. Further recommended actions based on new case studies should also be formulated in order to build a solid database for mobility planners and policymakers.

This work has shown the importance of digital components in a MH. Therefore, further research should focus on how to successfully design digital services so that they can be easily used by all population groups. Digital components should simplify the use process and not be perceived as a barrier.

From our findings, it is valuable that waiting areas are consistently well-lit and covered to significantly enhance comfort and security. This aspect is directly connected with the complexities of balancing gender-specific preferences. Additionally, expanding access to a diverse range of shared transport options—such as rental bicycles, electric vehicles, e-scooters, and cargo bikes—will address the needs of various user groups, including older population segments who may face adoption challenges. Tailoring bicycle-related services and addressing gender-specific mobility needs, such as those related to child transport, will further improve service effectiveness.

Finally, once the planned MHs are implemented in alignment with the identified needs and expectations of the community, it will be essential to conduct a comprehensive follow-up evaluation. This evaluation should focus not only on the functional effectiveness of the hubs but also on measuring levels of acceptance and trust among users, as these factors are critical to ensuring the long-term success and integration of the MHs into the community.

Part IV

A POLICY PERSPECTIVE FOR INTEGRATED MOBILITY: AN EXTENSION TO POTENTIAL URBAN CONTEXT

Chapter 6

Policy Evaluation and Future Framework for Mobility Hubs

6.1 Motivation of the Study

With the intention of being a policy evaluation and the conclusion of the thesis, this chapter is designed to synthesise the previous chapters' findings and to provide recommendations to policymakers. The aim is not only to consolidate the research but also to translate key insights into practical policy guidelines that can be applied in diverse urban contexts, expanding beyond the case studies evaluated in earlier sections.

The inclusion of a policy perspective at the end of this thesis is crucial for two reasons. First, it reflects the applied nature of the research, recognising that the true value of academic work lies in its potential to inform real-world decision-making. As emphasised in the introduction, we believe that research in the field of urban mobility should be solution-oriented, focusing on the practical needs of local governments and stakeholders. Therefore, this chapter aims to bridge the gap between academic knowledge and concrete policy implementation.

Second, the growing challenges in urban mobility—such as congestion, pollution, and inefficiency—demand that innovative solutions be not only identified but also tailored to different urban environments. As urban areas vary in size, structure, and transport needs, it is vital to propose adaptive and scalable policies. This chapter provides a framework for replicating the lessons learned in cities of different sizes, from small and medium-sized cities to large metropolitan areas, and under varying conditions, such as monocentric or polycentric urban forms.

The motivation behind this chapter is also to include in this thesis the research activities of the author carried out during the PhD in the field of mobility policy. Indeed, this part lists the key outcomes and finds some application outside the case studies already discussed. One of these occasions had to do with the direct involvement of stakeholders from the city of Porto (Portugal), as well as other mobility administrators from European cities, which have enriched the thesis' outcomes with additional qualitative results within an international project. The author has also experienced a rich involvement in the city where was based (Rimini, Italy) through the internship with the local mobility administration. The part of the chapter corresponding to this period represents an early approach with a current Bus Rapid Transit (BRT) project, Metromare, but it does not represent a complete study on this topic because of the restricted time and research available.

The Rimini study primarily relies on observational data, such as the status quo of the already existing directions, as well as the in-progress ones. These are grouped by the author into some reports that were useful for the administration to orient and implement the multimodality along the Metromare line. This collaboration constitutes the basis for defining sustainable mobility strategies that are both replicable and efficient. By offering context-specific recommendations, this policy evaluation underscores the importance of integrating academic findings into practical, real-world mobility improvements.

6.2 Introduction

In this chapter, we aim to summarise the key findings from the previous sections of the thesis, particularly focusing on implementing MHs, and useful to propose some policy priorities that must be considered by decision-makers. Our research offers innovative contributions that deal with the resilience of transport networks and the role of MHs in urban development. The insights gained from these areas offer a robust basis

for evaluating current transport policies and proposing a new framework that could be adapted to different urban contexts.

Multiple factors shape transport behaviour and choices of transport modes, evolving over time and influencing major shifts in lifestyles, work patterns, and demographics (Lucas et al., 2016). These changes profoundly affect mobility behaviour, leading to new mobility needs and requirements. In turn, this evolution drives the demand for inclusive and accessible policies that ensure equal mobility opportunities for all citizens (Van Wee and Geurs, 2011).

Bearing in mind that urban transport demand is growing, the proposed framework holds significant potential for future applications, supporting decision-makers in small, medium, or large cities, whether monocentric or polycentric. By ensuring the integration of different transportation modes and enhancing urban resilience, this framework can guide cities in addressing the increasing complexity of urban mobility.

In the following subsections, we also consider a specific urban setting, such as Rimini (Italy), where part of this thesis was developed in conjunction with *Patrimonio per la Mobilità di Rimini (PMR)*, which is a private company, participated by local institutions, which owns and maintains the local PT infrastructure in the province of Rimini. This case study exemplifies the real-world applicability of the research, demonstrating how local insights can inform broader policy recommendations. In particular, the study of *Metromare*, still in development, can inform policymakers about its current and future integration into a wider mobility system.

The research presented in the previous chapter also serves as a bridge between this research and other ongoing or completed mobility projects, allowing us to step back from the specific focus on MHs and explore broader themes in sustainable urban mobility. To broaden the perspective on urban development, this chapter provides insights into the concepts of the communities of practice and urban sprawl, integrating MHs within a comprehensive framework for sustainable urban mobility.

Moreover, we want to emphasize the importance of policy evaluation grounded in academic research, ensuring that insights from this thesis are translatable into practical strategies, but also to foster a wider interest for future interdisciplinary research that can extend these findings, offering pathways for future exploration of sustainable urban mobility solutions across various urban contexts.

6.3 Key Outcomes and Transferability

Parts I and II have been developed around the concept of MHs and how they can be integrated with the urban transport network when considering resilience. We note that a broad body of literature exists on MH definitions and components, but the effects of their presence in the transport network have not been sufficiently researched.

So, after a scouting phase on resilience indicators, we assessed the resilience of transport networks including MHs. Their role is fundamental for enhancing the integration between different transport modes and thus mitigating network failures in case of problems.

This research highlights which elements contribute to transport network resilience, which are essentially the following:

- Redundancy in routes and services, allowing for alternative paths during disruptions and switching

between modes (Xu et al., 2015). It refers to the supply of alternative effective routes available for travellers between a specific OD pair (Berdica, 2002);

- Flexibility, because of the dedicated and permanent location of MHs, where public and shared mobility options are available and integrated, allowing users to combine different means of transport during a single trip (Jones et al., 2000).

The results are a more integrated urban transport network that can better respond to possible disruptions or satisfy passengers' demand for PT or shared modes.

In other words, MHs enhance multi-modal integration, making travel more efficient and user-friendly. Additionally, multimodal networks, built around MHs, can accommodate a substantially increased demand for transport (Xu et al., 2015). By doing so, they play a crucial role in reducing the reliance on private vehicles by providing seamless connectivity. This integration not only enhances the efficiency of the transport system but also promotes environmentally sustainable travel behaviour.

Some studies (Ritchie and Roser, 2020; Geipel et al., 2024) affirm that cities with already existing MHs show increased PT ridership, reduced carbon emissions, and improved sustainable mobility practices. According to the European Commission (Innovation-Union, 2014), multimodality relies on convenience, speed, cost, reliability and predictability of different transport modes to provide more efficient solutions for moving people and goods. The Commission also mentions how the COVID-19 pandemic has highlighted the importance of multimodality in enhancing the resilience of our transport systems, and demonstrated public readiness to adopt sustainable alternatives.

The EU mission aims to support the conditions necessary for greater adoption of safe, competitive and affordable sustainable modes. Individuals are increasingly willing to shift to sustainable transport options, especially for daily commutes, when the alternatives provided are affordable, accessible and efficient.

Regarding this inclination, it is necessary to mention that digital solutions should be considered as well, when planning MHs. Within the broader concept of MaaS, they bring diverse transport services into on-demand platforms. Lu et al. (2018) showed how the socio-demographic characteristics of passengers and their travel options have an impact on the value of waiting and the time on-board. The better users are informed through ITS about the different modes of travel available, the shorter the waiting time is perceived.

These elements are further developed in the following section, which represents a zoom-in analysis of the locations and components of MHs, defined through stakeholder participation. The main findings are summarised as follows:

- MHs should be established at fixed locations near PT services, offering at least two different options (e.g., one PT mode and one shared mode) (Geurs et al., 2024).
- Optimally located MHs improve transport network resilience by enhancing connectivity and accessibility.
- To support decision-making in mobility projects such as MHs implementation, MCA can be used to incorporate different stakeholder perspectives (Macharis et al., 2009). This approach enables the selection of the best alternatives, influenced by stakeholder evaluations of the alternatives and criteria.
- Stakeholder involvement is a cornerstone of the co-creation approach, promoting effective mobility solutions and bridging the gap between policymakers, researchers, and communities (Keseru et al., 2024). Different levels of engagement correlate with varying degrees of project acceptance and feasibility.

- MHs should be designed to meet user needs, with special consideration for the requirements of disadvantaged groups, including women, the elderly, children and people with physical impairments (Martinez et al., 2024).

Given these findings, we used the study of resilience to stress the importance of MH positioning. Our analysis and in-depth review of prior studies on optimising transport services and local government plans revealed that often, these regard network nodes in terms of resilience. Instead, they tend to prioritise other criteria, which can seldom be traced in policy documents.

The key findings of this thesis on the optimal locations for implementing MHs highlight that, according to the experts consulted, resilience is a highly relevant criterion when introducing new transport services, such as bike-sharing stations. Specifically, placing shared mobility stations at strategic locations like PT stops can be seen as the first step in creating MHs, in order to have well-defined areas where multimodal options are readily available and easily combined to support seamless travel (Geurs et al., 2024).

The model proposed in Chapter 4 is scalable and adaptable for cities of various size which have available where there is an existing database for the selected criteria such as air pollution, population density and socio-economic data. Our MCA can also be modified to align with the priorities of decision-makers who may wish to emphasise different criteria. However, we strongly recommend that criteria be selected from across all urban dimensions—demography, environment, equity, points of interest (POIs) and network-based metrics—to ensure a comprehensive approach.

Once the location of MHs is established, the next crucial step is to engage a broad spectrum of stakeholders to capture their needs and expectations, and align these with policy priorities. The outcomes gathered from stakeholder involvement are particularly valuable, as they bridge the gap between research and real-world application, bringing the perspectives of end-users and policy-makers into the applied world (Bosetti et al., 2014). These findings enable a more user-centred, practical approach, extending beyond theoretical models, to validate solutions through the real-world experiences and requirements of diverse groups.

This focus on stakeholder engagement, particularly through co-creation, builds on the authors' involvement in similar projects where collaborative input was foundational. By actively involving stakeholders in this way, we not only validate our results but also create a scalable model adaptable to different contexts. Successful replication in other cities will require a commitment to inclusivity, accessible data collection, and flexibility in integrating feedback into policy design. This approach ensures that the proposed solutions are robust, widely accepted, and responsive to the unique challenges and needs of each urban environment.

To resume the key outcomes, and to reflect on and compare the objectives set at the beginning of the thesis, a flowchart is proposed to synthesise the overall research (Figure 6.1). It also anticipates the limitations and further research direction that will be discussed in Section 6.7.

**Key Findings and Transferability Outcomes of Mobility Hubs and
Integrate Sustainable Mobility
RESEARCH OUTCOMES**

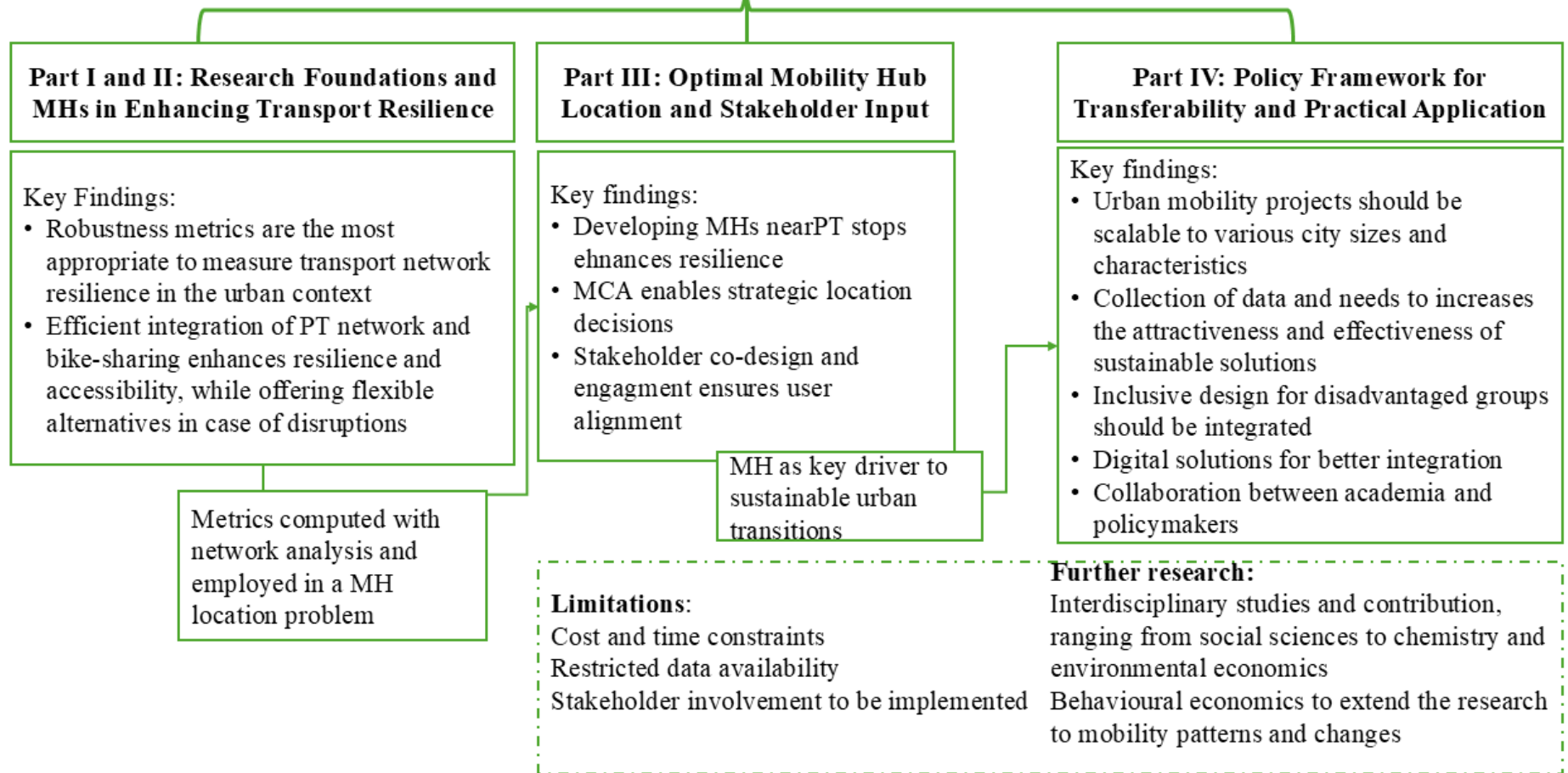


Figure 6.1: Thesis outcomes flowchart

6.4 Strategies to Foster Mobility Hubs and Sustainable Mobility

The implementation of MHs is one of many initiatives encompassed within the broader framework of sustainable mobility. Today, driven by the National Recovery and Resilience Plan (NRRP) as part of the €750 billion NextGenerationEU (NGEU) programme, most European cities are actively transitioning toward sustainability across various sectors. Given that the transport sector is responsible for 40% of total CO₂ emissions (Bosetti et al., 2014), there is growing interest from both academia and government to develop and implement effective solutions.

Applying the concept of MHs in cities that currently lack such infrastructure presents unique challenges. For these cities, the successful introduction of MHs often requires foundational resources that may not be readily available, such as reliable and comprehensive data on current mobility patterns, user needs, and transit gaps. These cities often lack detailed, recent data and (digitally-)integrated transport systems that are essential to the planning and optimisation of MHs. Furthermore, without open data or sharing frameworks and collaboration between city departments and private mobility providers, the process of implementing MHs can be significantly hindered. To overcome these barriers, cities need access to robust data, technical expertise, and coordinated urban planning strategies that can support the seamless integration of MHs into the existing mobility system.

Building on the outcomes discussed in the previous section, this one presents policy recommendations derived from our study to inform and guide future mobility planning. In addition to reinforcing the existing foundations of Sustainable Urban Mobility Plans (SUMP), we propose new pillars—or expand upon existing ones—that should form the core of urban mobility planning. These pillars are partially influenced by the findings proposed by EIT Urban Mobility, an initiative of the European Institute of Innovation and Technology (EIT). We emphasise resilience, accessibility and inclusivity in urban transport systems, addressing emerging challenges such as climate resilience, equitable access, stakeholder participation and technological integration. By introducing these additional elements, we aim to support more comprehensive and forward-looking mobility strategies that can respond dynamically to evolving urban needs and contribute to sustainable and livable cities.

Many cities aim to mitigate congestion and pollution caused by excessive private car use, but they often lack effective transport network planning that addresses structural, environmental and social factors. Efficient mobility goes beyond merely transporting people and goods. It must also ensure user safety and reliability.³⁸ Residents need assurance that they can reach their jobs, schools or homes on time, even in the face of disruptions, technical failures or extreme conditions.

While cars have traditionally been viewed as the safest mode of transport, current policies should strive to shift this perspective by implementing specific measures that enhance the attractiveness of public transportation and shared mobility options while disincentivising private vehicle use. The successful adoption of shared mobility services, which are central to MHs, requires thoughtful design and targeted incentives to encourage usage. Physical, economic and social barriers must be addressed and minimised to promote greater adoption of these alternatives.

Lastly, for mobility measures to be effectively implemented, they must gain public acceptance, which is often challenging. Engaging citizens, policymakers, associations and transport operators can facilitate this process. By incorporating different perspectives through consultations and community involvement, mobility plans can inherently promote justice and safety, ensuring that they reflect the needs and values of

³⁸<https://europa.eu/eurobarometer/surveys/detail/2226>

the communities they serve.

The following Table 6.1 summarises these aforementioned aspects, without claiming to be exhaustive.

Table 6.1: Thematic categories and policy measure to suggest MHs implementing strategies

Thematic categories	Basic policy measures	Up-scaling
Public transport efficiency	Resilient transport network; capacity to handle extreme events and failures	Position MHs at high-demand, strategic locations to ensure connectivity during disruptions and enhance multimodal access
Public transport attractiveness	Enhance accessibility; reduce travel and waiting times	Optimise PT services at MHs; improve access to PT and shared modes through wayfinding and integrated ticketing
Reducing private car usage	Regulation (LTZ zones, parking pricing); allocate space for pedestrians and cyclists; dedicated PT routes	Expand PT and shared services; increase MHs in both urban and rural areas to better serve diverse districts
Boosting public and shared transport use	Improve integration across modes	Strategically locate MHs to facilitate seamless modal switches; facilitate first/last mile by shared transport; safe infrastructure for parking and ride facilities
Stakeholder engagement	Inclusive and accessible design	Enable co-creation through workshops, meetings and projects involving a range of stakeholders, such as Community of Practice initiatives
Justice and safety	Plan for PT access in underserved areas, especially for marginalized and low-income populations; consider diverse needs (e.g., elderly, children, women)	Gather user needs directly; ensure fair service distribution and incentives for those with fewer resources; increase policy communication and community-level capacity building

Given the complexity and unique characteristics of each urban and regional context, mobility planning must be grounded in field-oriented studies that reflect specific local needs and challenges. Rather than relying on broad generalisations, effective planning should employ a structured categorisation of methods and indicators tailored to diverse settings. This approach allows for a more nuanced understanding of mobility patterns, environmental impacts and socio-economic factors unique to each area. Categorisations enable planners to apply adaptable frameworks that can be fine-tuned for different city size, population demographics and infrastructure levels, ultimately enhancing the feasibility and relevance of mobility solutions.

By grounding mobility plans in context-specific data and insights, planners can create sustainable and resilient transport systems that respond to local realities while maintaining flexibility to adapt over time.

In the next subsections, we explore one of the issues which have been extensively addressed in this thesis, by providing insights also from other scientific collaborations conducted over the years.

6.4.1 From Quantitative to Qualitative Research: Policy Evaluation with Stakeholder Involvement

This thesis can be described as a mix of qualitative and quantitative methods, the results of the latter occupied the first part of the manuscript, assessing the resilience of the transport network and the optimal positioning of MHs. This chapter shifts attention to the crucial next step, already introduced in Chapters 5 and (partially) 4: incorporating qualitative insights through stakeholder engagement. Although quantitative methods offer valuable metrics and models, they often lack the nuanced perspectives that emerge from direct interaction with those interested and involved in mobility planning. A stakeholder-inclusive policy evaluation adds depth to our analysis, allowing us to understand the implications of proposed changes and ensuring that solutions meet the diverse needs of the community. This chapter aims to link technical findings with practical, user-centred policy recommendations by combining quantitative evaluation with qualitative feedback.

Top-down strategies in mobility are often seen as conservative and less effective. Today, many mobility projects incorporate bottom-up approaches to better address the complexities of urban mobility and its impacts (outstanding examples are SmartHubs, CIVITAS, PLUS Change Project, I-CHANGE, cambiaMO, and DREAMS). Although a significant gap remains between scientific research and practical application, there is a growing commitment at the European, national and local levels—particularly among EU countries—to implement policies informed by these findings.

One of the key elements of this innovative approach is the involvement of stakeholders from the beginning of the project to its implementation and scalability. They represent individuals, groups or organisations, private or public, which are impacted by or has the ability to influence a proposed project and its implementation (Bosetti et al., 2014).

The research presented in Chapter 5 is an example of preliminary stakeholder engagement, involving citizens as well as experts, for suggesting components and claiming their needs regarding MHs, but it is not followed by a practical realisation, and it remains at an exploratory study level. Although the co-creation and co-design approaches require a broader involvement also in the further steps of the research, other means are available to initiate the active engagement process.

Within the Knowledge Brokerage Programme on Sustainable Transitions (2023-2024), organized by the Social Sciences and Humanities for Climate, Energy and Transport Research Excellence (SSH CENTRE), we focus on defining the characteristics of stakeholders potentially involved in mobility projects, through the building phase of a Community of Practice (CoP) for Mobility³⁹. According to the European Commission's 'Science4Policy' Competence Framework⁴⁰, CoPs are essential to increase the impact of science in policy-making, helping in understanding and achieving key policy priorities because of the continuous interaction among stakeholders and consequently enhanced capabilities.

A CoP can be defined as a collaborative network where various stakeholders share their interests and knowledge over a specific topic (Wenger et al., 2002), with the scope of regularly participating in the decision-

³⁹The full report "Towards Sustainable Mobility: A Roadmap For Establishing A Community Of Practice In Porto" will be available at <https://sshcentre.eu/city-hub-porto-knowledge-brokerage/>

⁴⁰https://knowledge4policy.ec.europa.eu/visualisation/competence-framework-'science-policy'-researchers_en

making process. It is also useful to facilitate and promote the acceptance of sustainable mobility practices across diverse groups (Di Ciommo et al., 2023), from citizens and administrators to people with disabilities and the elderly. Engaging directly with these key stakeholders empowers collaborative development and implementation of sustainable solutions tailored to their needs.

As a primary step, we invited local authorities, PT operators, researchers and associations to a workshop of two days in Porto, Portugal, during which we also propose to define which stakeholders need to be engaged when considering urban mobility and, eventually, the creation of a CoP for it. The results are shown in the stakeholder matrix:

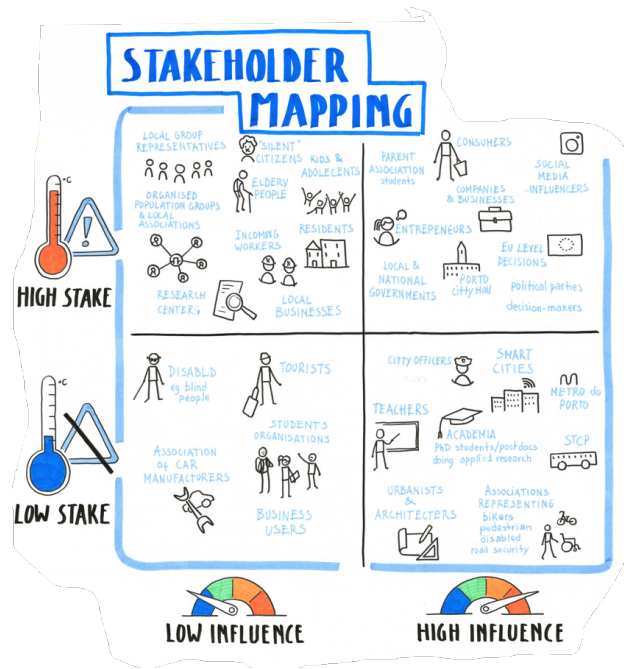


Figure 6.2: Stakeholder mapping resulted from the workshop in Porto in April 2024

Source: Luisa G. Costa

This matrix reveals which are the different weights always associated with stakeholders. The most usually listened ones have both high stake and influence, for instance, consumers, political parties, companies, while the ones with low stake and influence are often excluded from the public debate and scarcely considered, they are disabled individuals, student organisations. In between there are stakeholders with low influence but high stake, which can strengthen to be listened to and included in the decision-making process, as well as those with high influence but low stake, which are fundamental to push the change, such as associations, transport operators and researchers. This produces an imbalance of powers and interests that is difficult to equilibrate.

For this reason, the collaboration between stakeholders, their full engagement and the government's commitment allows the support of integrated and human-centred urban mobility policies and measures. Furthermore, this method deals with capacity building, political advocacy, monitoring and the evaluation process, which is a combined responsibility of the stakeholders involved. In this view, it ends in a long-term

vision that can push a sustainable transition.

Precisely because of its characteristics, a CoP requires a particularly long timeframe and a comprehensive involvement of stakeholders as well as facilitators, in this case researchers. For this reason, it was not possible to engage in this discourse the stakeholders involved in the research presented in Chapter 5, as the author of this thesis was involved in the research that had already been started by TUM and the work was concentrated in a well-defined period of time, not enough to stimulate the creation of a CoP. By the way, other parallel research of the team in Munich approaches CoP building quite closely, so that our research would have been an unplanned repetition.

6.5 Follow-up of Ongoing Projects: Bus Rapid Transit as a Tool towards Integrated Mobility in the City of Rimini

6.5.1 Background of the Research

The aforementioned challenges regarding the transition towards sustainability, in particular in urban mobility, have also been addressed by Italian cities, which are not the core of this thesis but were inevitably a subject of study because of the author's geographical context. For this reason, it was decided to include a part dedicated to the city of Rimini (Italy) and the Metromare project, reporting on a short-period collaboration with local and regional administrators, and with the prospect of a continuing interaction with the University of Bologna (Rimini Campus) in the future.

This collaboration has primarily translated into a six-month internship, preceded by previous exchanges and updates about the urban mobility system, led by the engineer responsible for Metromare and its expansion, Roberto d'Andrea. This experience involved an in-depth analysis of planning documents and feasibility studies for integrating the new system with existing PT services. Field inspections were conducted at existing and planned stops to assess their potential for intermodal connectivity and accessibility improvements.

This practical engagement enabled a hands-on evaluation of sustainable mobility solutions, directly linking the Rimini case study to the thesis's broader discussion of transport planning methodologies. Although the analysis in this section is primarily based on observation and reports drawn up by the author, it also reflects insights gathered through direct exchange with policymakers and transport planners, in line with the thesis's objective of assessing the feasibility of sustainable mobility interventions in different urban contexts.

The analyses extracted from the detailed reports submitted to PMR were used internally to support decision-making processes. Despite attempts to apply the same methodologies developed in the thesis, such as MCA and network-based indicators, the availability of accurate data was a significant challenge. Passenger data and GTFS feeds are owned by AMR (Agenzia Mobilità Romagna), which limits full access to these datasets, complicating their integration into the analysis. This limitation highlights the difficulties in conducting data-driven planning when access to key mobility datasets is constrained.

Nevertheless, Rimini remains an ideal case study to test and refine these methodologies, given the ongoing transformation of urban mobility. The next steps would be to explore how these tools could be applied in this context, identifying the existing conditions, the main opportunities for integration and the areas that

could benefit the most in terms of accessibility.

Therefore, a research project involving PMR and the Rimini Campus is currently being approved for the next three years, in which these analyses can certainly be extended with the support of this exploratory study. Community engagement activities, where it might be possible to develop a CoP as described in the previous section, are also envisaged during this long period.

6.5.2 Setting the Context: Rimini and The Influences of Urban Form on Mobility Supply

Rimini is one of the main cities of the Emilia-Romagna region (Italy), accounting for a population of about 150,000 inhabitants and an area of 136 km². Most of the population is concentrated in the city centre and in the northern part of the city. The average population density is 4,828 inhabitants/km², including tourists, which accounts for 16% of the overall population. It is known as an economic and industrial core in the Romagna territory, proven also by the 50% employment rate over the total active population, higher if compared to the national rate. Among all the sectors, the tertiary is the most consistent (77% of the GDP), to which tourism is one of the most recognised.⁴¹

The city of Rimini assumes an intense role in shaping the new form of urban transition and proposes pioneering ways to live in a more sustainable context. One of the biggest challenges is to convince citizens to switch from their private cars and PT options, which are usually considered less efficient and unpredictable. At a municipal level, the local administration must encourage these changes and be the protagonist of the environmental transition.

Rimini is located in a strategic position because it is a crossing point between the Adriatic coast and the hinterland, connecting several cities and their respective businesses, including the Republic of San Marino. Within the region, it represents the promoter of local tourism because of the notable seaside and the many cultural and exhibition events organised throughout the year. For these reasons, the city must deal daily with mobility issues for citizens and tourists.

The city spreads longitudinally and is divided into two main parts by the railway line ("Ferrovia" in Figure 6.3) and is delimited by the sea in the east and the main state road to the west (N16). The city can be divided into three main zones: zone A (East), which experiences a seasonality related to tourism, in particular in subzone A3; zones B and C (West), which show typical residential and business patterns, with a slight drop in summer activity, where congestion problems are spread throughout the day.

This specific urban form influences the use of PT services as well as micromobility. Understanding the factors affecting ridership in urban areas with physical constraints as Rimini is crucial to designing suitable transport systems (Tsepenta et al., 2021). In addition, cities, such as Rimini, may have to deal with urban sprawl, which draws a new concept of the city, with no delimited borders. It consists of a process of urban change in opposition to a compact city (Couch et al., 2007), where the boundaries are easier to identify, and which affects transit-oriented development.

As also supported by the study of Pan et al. (2009), urban form influences travel mode choice for non-work travel, which also means, on the other hand, that the spread of urban land use into suburban areas tends to encourage greater reliance on private cars (Susilo and Maat, 2007) if not accompanied by high access to PT services. This phenomenon often results in a reduction in PT use, as well as a decline in walking and cycling (Cervero and Landis, 1992), with drastic effects on congestion. In such a context, urban planners

⁴¹<https://statistica.comune.rimini.it/>

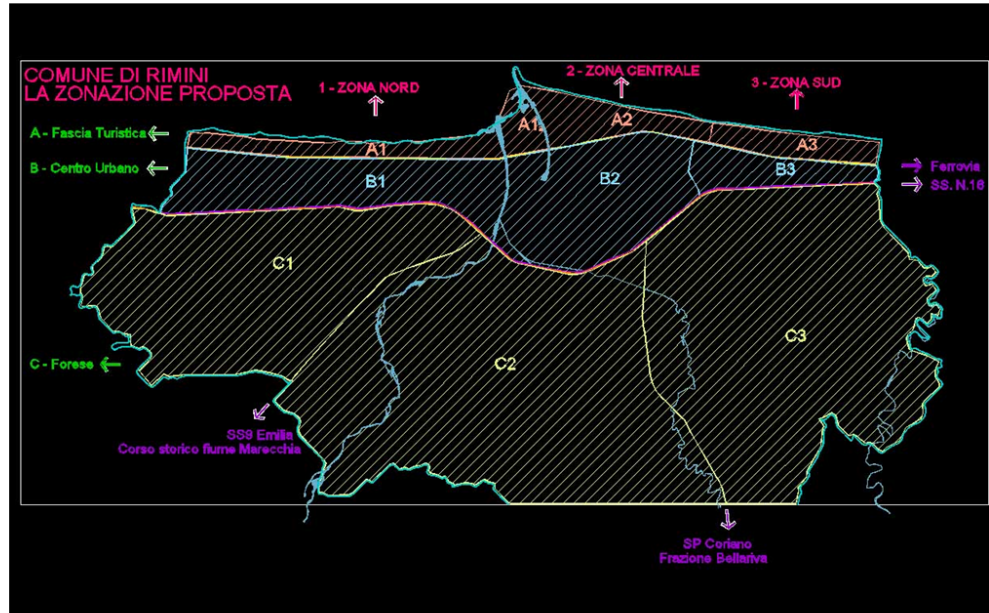


Figure 6.3: Rimini zones

Source: P.M.R. s.r.l.

have to incorporate in mobility projects not only analyses derived from the influence of urban form and travel accessibility, but also individual abilities and family or job environment, in other words, socio-economic factors (Susilo and Maat, 2007).

Rimini, like other cities extended along the seaside, is affected by this phenomenon and needs specific measures to contrast this risk. Adequate network and infrastructure planning for longitudinal connections is required, and becomes a key a widespread active and shared mobility (Ignaccolo et al., 2022). Polycentric networks, instead of monocentric, combined with an adequate supply of PT services and the spatial spread of activities, offer a convenient environment for commuting, without the need to use private vehicles.

Papastavrinidis et al. (2021) states that the adoption of sustainable mobility fitted with the urban area has not only environmental benefits, but also economic, social and financial ones, because it creates ideal conditions to move and increase the quality of life. Policies have to gradually force these changes by following network planning principles, derived from the EU initiative for active modes⁴². Among these principles, the most relevant for this thesis are:

- affordability and inclusiveness;
- attractiveness and efficiency of infrastructure;
- multimodal connectivity;
- data collection and availability.

⁴²https://transport.ec.europa.eu/news-events/news/commission-proposes-list-principles-boost-cycling-across-europe-2023-10-04_en

As highlighted by [Ignaccolo et al. \(2022\)](#), in line with EU guidelines, accessibility analysis between origins and destinations should be integrated not only as a post-design computational evaluation, but also in the initial planning phase. Incorporating accessibility early on enables passenger flow data to inform the design of new routes, bicycle lanes and other infrastructure, ensuring that these elements meet real mobility demands. To enhance this accessibility, connection nodes, such as MHs, play a crucial role in providing efficient travel times and manageable distances for users. Additionally, safety and security are critical factors influencing behavioural shifts in mobility choices, as discussed in Chapter 5. In this regard, policies aimed at reducing vehicle speed limits and improving public lighting networks can significantly contribute to creating a safer and more user-friendly environment, thereby encouraging greater adoption of sustainable transport modes.

6.5.3 Promotion of Sustainable Mobility with Metromare and Suggestions from Data

The main project developed in terms of environmental, economic and social views is Metromare. It represents a BRT, electric and with a dedicated road which runs parallel to the traditional Adriatic railway line, at the moment between the central stations of Rimini and Riccione.

The local administrations and, formally, AMR have received many inputs for the realisation of this project, as well as economic incentives through state, regional and municipal funds. The complex system around this infrastructure has attracted many studies, including this research that was conducted over six months, in the autumn and winter of 2023/2024 at PMR.

Metromare meets the ambitious objective of identifying strategic guidelines for maintaining and improving the mobility and accessibility conditions of the territory. The ancestor of Metromare is the trolleybus line from downtown Rimini to downtown Riccione, active since the summer of 1939. The trolleybus line was the backbone of public transport in the main touristic areas during the economic boom and the great expansion of the Rimini area. Thus, Metromare has replaced it and responded to the need to renew the PT network offered along the coastal route, representing a solution to guarantee regularity and safety of transport, through a system capable of offering users a high-quality and sustainable service.

According to the PMR reports, Rimini is facing CO₂ emissions, congestion and traffic noise derived by vehicles, which cost 494 million euros. As a matter of fact, to reduce these external costs and simultaneously promote more sustainable transport modes, the presence of cycleways is consistent within the urban area (about 22% of total roads).⁴³ According to the last update, the total of kilometres dedicated to bicycle infrastructure is 135, and the main urban and extra-urban cycle paths are four: “Pista ciclabile ad anello” – 12 km, “Rimini-Riccione mare e collina” – 32 km, “San Giuliano a mare: fiera-Lungomare Tintoni” - 5 km, “Rimini- Novafeltria” – 12 km.

The idea behind Metromare is to follow the sustainable mobility principles (mentioned in Subsection 6.5.2) and combine different PT and shared or active modes to promote overall sustainable mobility. Connected to the Metromare project, it is fair to mention the Bike Park, a physical hub located in front of the main rail station and the first Metromare stop, where it is possible to leave a private bike as well as rent one. It serves as an intermodal hub because it allows one to reach the train station by cycling and to catch any PT mode from one of the closeby stops. Intermodality is also promoted through discounts for those who benefit from it. This service is fully available during the week and offers 12 types of bicycles, between traditional and electric ones, including cargo bikes. At the Bike Park, there is also a bike workshop, equipped with mechanical and

⁴³<https://www.comune.rimini.it/novita/tutte-le-proposte-scoprire-rimini-e-dintorni-bicicletta>

informational assistance, electric bike charging, an accessories store, luggage storage and a refreshment area.

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The entire route of Metromare is located on the upstream side of the Bologna–Ancona railway line, for 9.8 km. This proximity allows for direct interconnections with three railway stations (Rimini station, Rimini Miramare and Riccione station), and 15 intermediate stops in between.

From the technical viewpoint, the main attributes of Metromare are: full electric traction, with corresponding zero emissions in all driving conditions; IMC (in motion charging) allows to recharge of the vehicles; assisted driving and autonomous driving.

From the operational viewpoint, travel time from Rimini to Riccione accounts for 22 minutes. Rides are offered from 05.00 a.m. to 01.00 a.m. during wintertime, and from 06.00 a.m. to 02.00 a.m. during the summer months. The frequency of service is 15 minutes in winter and 10 minutes in the summer period, at a speed of 23.5 km/h. The service can potentially supply 900 passengers/h per direction of travel.

The introduction of Metromare represents a potential improvement in connectivity due to its role of stimulating the development of fully operational MHs, which transform conventional PT stops into multi-functional nodes of connectivity. The elimination of the railway underscores its role in overcoming longstanding infrastructural barriers, making movement across the territory smoother and more seamless.

Building on this foundation, the next chapter explores how Metromare’s advanced technical and operational features—such as zero-emission electric traction, high-frequency service, barrier-free boarding, and dedicated space to active mobility—encourage the development of robust MHs. These hubs, strategically located along the route, aim to address geographic imbalances in transport availability and enhance connections between the North-South interland axis and emerging East-West flows. By introducing dedicated mobility services like bike-sharing and pedestrian infrastructure at stops, Metromare catalyses equitable access to sustainable transport solutions, while serving as a model for integrated urban mobility systems.

Through this lens, Metromare would evolve from a transport corridor into a transformative backbone for the region’s mobility network, directly contributing to the equitable development of MHs and fostering greater intermodal connectivity.

6.5.4 Insights Into the Latest Project Steps: Strengths and Weaknesses for Integrated Mobility

This section aims to give some insights into the Metromare project and its future development towards Rimini Fiera. We evaluate the next steps, focusing on the evolution of Metromare stop design into fully-launched MHs, the compensation of North-South interland directionality with East-West flows, and the introduction of dedicated mobility services at Metromare stops. These latter aspects highlight the strategic value of Metromare in connecting Rimini’s urban core with peripheral areas. This design mitigates geographic imbalances in transport availability, ensuring more equitable access to mobility services.

These advancements are aligned with core principles of integrated mobility: enhancing attractiveness, promoting intermodality, and avoiding discontinuity (Ignaccolo et al., 2022). To fully understand these aspects, we analyse in more depth some of the main existing and planned stops and their potential limits and strengths.

The Rimini F.S. and Principe Amedeo stops, respectively from the already existing and the new planned route, stand out together as one of the most important hubs due to their proximity to the Rimini Central

⁴⁴www.bikeparkrimini.it

A more compelling aspect lies in examining the potential of the new stations (Figure 6.5), particularly those assessed during an on-site inspection conducted with the project’s lead engineer. Among these, the Rivabella stop stands out as an example of both opportunity and challenge, as it currently lacks integration with the PT network.



Figure 6.5: In process Metromare line

Source: P.M.R s.r.l.

This new stop is to be developed just beyond the left bank of the Marecchia River. However, this location does not naturally function as a central hub for connectivity, as it lies between areas of relatively low-density activity. While residential settlements exist both upstream and downstream toward the sea, they predominantly cater to tourist or seasonal use, limiting the everyday PT.

The planned infrastructure includes a new bridge over the Marecchia River, positioned alongside the railway bridge. This bridge will feature not only a dedicated Metromare lane but also bicycle and pedestrian paths, which will enable residents from the right bank to access the Rivabella stop. Currently, the two embankments at this location are entirely disconnected, and the availability of PT within the surrounding residential areas is sparse. Moreover, there is no direct connection between the two banks, which further hinders accessibility and intermodal integration.

Due to these characteristics, these stops present both strengths and challenges: the new bridge and integrated bike/pedestrian paths have the potential to enhance accessibility, providing a crucial link for residents and promoting more sustainable mobility options. The challenges deal with the low density and seasonal nature of nearby residential settlements, which may limit the immediate utility of the stop, while

the current lack of PT services in the area calls for additional investments to create a comprehensive and connected transport network.



Figure 6.6: The location for Rivabella future stop

Another key objective of the new Metromare development is to boost ridership and enhance the overall attractiveness of PT services. A decisive strategy in achieving this is the careful placement of Metromare stops in strategic locations, particularly in areas characterised by high car traffic and significant commuter activity, largely driven by nearby residential zones. These locations are vital for capturing potential PT users and encouraging a shift away from private vehicle use.

The Popilia stop (Figure 6.7) fills an area of almost complete inefficiency. It is planned in a low-density zone but high industrial concentration, which means hundreds of workers travelling by private car or private services to their workplaces. It is an area devoid of tourist flows except on the days of trade fairs, due to its proximity to the eastern entrance of the fair center. At present, the small urban agglomeration in via Popilia is served exclusively by line 91, while the area close to Emilia and Adriatic state roads is served by lines 9 and 91. The bus stops are at a great distance from each other, which disincentivises their use by those who can use their private vehicles. Businesses and residential buildings beyond N16 state road are also to be included in the radius of the Metromare stop.

The Popilia stop, despite its peculiarities, has a high potential for the possible daily users that would benefit from it, i.e. all those who work in one of the companies adjacent to the stop. In particular, SCM Group S.p.a (world leader in material processing technologies) provides a private shuttle service from the Rimini station to transport its employees coming from the province of Pesaro. This service is exposed to traffic variations and does not guarantee complete hourly coverage, but only in certain predetermined time

slots. Replacing the shuttle with the Metromare service would not only reduce the environmental impact of these journeys but would also guarantee greater efficiency in terms of frequency, reliability, as well as a reduction in costs for the company and the users. With a view to the development of this stop, it is appropriate to consider a broader design that also covers a series of additional services such as bars, local shops, sharing services, suitable pedestrian routes, parking spaces and street lighting. In fact, the area would be more exploitable if urban planning changes could be considered. The existing bicycle path should be integrated with the future Metromare stop, as should the bus routes that run along the main road, providing a preferential route for them and defining a junction route between the various modes of transport.



Figure 6.7: The location for Popilia future stop

*Source: P.M.R. s.r.l.

Combining strategic localization with intermodal functionality ensures that these stops become true hubs of connectivity, maximizing their potential to support sustainable urban mobility. In order to underscore the characteristics of Metromare stops and emphasize their potential use as MH, we discuss them under the perspectives of land use, multimodality integration at the moment and future development. Table 6.2 serves as a diagnostic tool for identifying the strengths and weaknesses of each stop in terms of connectivity and intermodality.

The stops are divided into two sections: Rimini F.S - Riccione F.S. corridor (already in place) and Rimini F.S. - Rimini Fiera corridor (under development). We identify different land use patterns based on the differentiation proposed by Dondi et al. (2011) and PMR reports.⁴⁵ They refer to the city centre when the area is characterized by high population density, business activity, and public services; residential zones are predominantly residential neighbourhoods with housing and not many other facilities; touristic zones are heavily oriented towards tourism activities, seasonal activities because of the seaside, including hotels

⁴⁵<https://drive.pmrimini.it/files/>

and resorts; in service areas, facilities like airports, industries, schools or offices are concentrated; public parks/green areas refer to stops adjacent to green spaces or parks.

Stop	Land Use	Multimodality Integration Status Quo		Potential for Multimodal and Integrated Development	
		High	Low	High	Low
Rimini F.S.-Riccione F.s.					
Rimini F.S.	City Centre	x		x	
Kennedy	Touristic zone	x		x	
Pascoli	Residential zone	x			x
Lagomaggio	Residential zone		x		x
Toscanini	Residential zone	x		x	
Bellariva	Touristic zone		x		x
Marebello	Touristic zone		x	x	
Rivazzurra	Residential zone	x		x	
Fiabilandia	Entertainment area		x	x	
Miramare Station	Services area	x			x
Miramare Aeroporto	Services area		x	x	
Marano	Residential zone		x		x
D'Annunzio Nord	Residential zone		x		x
Alba	Residential zone		x		x
Dante	Residential zone	x		x	
Riccione Porto	Touristic zone		x	x	
Ceccarini-Riccione F.S.	Touristic zone	x		x	
Rimini F.S.- Rimini Fiera					
Principe Amedeo	City Centre	x		x	
San Giuliano	Residential zone	x		x	
Rivabella	Touristic zone		x		x
Sacramore – Celle	Public park/green area	x		x	
Popilia	Services area		x	x	
Fiera Est - Teodorico	Residential zone		x	x	
Rimini Fiera	Entertainment area	x		x	

Table 6.2: Characteristics of Metromare stops: land use, multimodality integration and potential development

The "Land use" of these areas reflects the impact of urban sprawl, which has expanded the city's boundaries and transformed some neighbourhoods into predominantly residential zones with minimal or no services. These areas are compelled to rely on other parts of the city for essential amenities, creating a pressing need for frequent and efficient transport connections to bridge the gap.

Additionally, stops located in areas with a strong tourist vocation face unique challenges. These stops experience intense passenger flows during the summer months, driven by seasonal demand, but remain largely underutilised and isolated for the rest of the year. This seasonal imbalance underscores the need for tailored strategies to address fluctuations in demand and improve year-round accessibility.

With "Multimodality integration (status quo)", we indicate with 'high' those stops that offer at least two different transport modes, one PT option and one active mode in terms of the integrated road network. Indeed, half of the stops have a bicycle lane passing close by and allowing for an easy switch between BRT and biking. At the moment, BSSs are not available at any stop, except for the train station. Indeed, Rimini employs a free-floating bike and scooter system, which allows users to leave the vehicles anywhere, but also causes problems in handling them.

'Low' multimodal integration refers to those stops that are at a walkable distance of more than 5 minutes from another PT option, or not visible from the Metromare stop, which reduces the accessibility and the movement of users between them.

Some stops provide (or will provide) parking spaces around them to accommodate users coming from the hinterland by private car and those who have no other means of reaching the stop. This is the case of Toscanini, Rivazzurra and Sacramora-Celle (Figure 6.8), where the design plan foresees that, at this intersection, the branch line towards the Viserba school and residential area adjacent to the Viserba railway station will be extended. Furthermore, the stop Sacramore close to the Celle neighbourhood, within the perimeter between N16 state road, the Marecchia River and the Via Emilia, is lacking any PT service. This often results in travel to the city centre only by private means. The Via Emilia, in the stretch from the state road towards the San Giuliano neighbourhood, has a high concentration of car traffic throughout the day.



Figure 6.8: The location of Sacramore future stop

Source: P.M.R. s.r.l.

The column "Potential for multimodal and integrated development" indicates the potential for enhancing multimodality and intermodality at each stop. Stops marked under 'high' have strong opportunities for improvement, while those under 'low' face challenges due to infrastructure, demand or geographic constraints. Some potential improvements, discussed with PMR, regard stops in residential zones that should benefit from park-and-ride facilities, sometimes not feasible due to physical barriers. Instead, stops in tourist zones may require facilities for temporary parking, luggage storage, and bicycle/scooter rentals. This requires an effort and long-term vision from the local administration, which can transform these stops into effective MHs able to improve the supply of sustainable mobility.

6.5.5 Lessons Learned and Next Potential Application

In summary, this investigation serves as a valuable tool for identifying gaps and prioritising targeted actions in areas planned for the expansion of the Metromare network. By analysing current land use, multimodal integration, and potential for further development at each stop, planners can address deficiencies in connectivity and accessibility. This approach not only supports the strategic improvement of the PT system, but also ensures that investments are directed toward areas with the greatest potential to enhance mobility and intermodality.

Although these descriptive analyses are novel and have never been conducted before on this case study, the study lacks the quantitative application of the methods developed in the thesis for other contexts. A potential development is outlined in this section, taking into account the limitations encountered along the way and already mentioned in Section 6.5.1.

Regarding the inaccurate GTFS data, it would be possible to manually correct the errors and integrate the Metromare route into the dataset. This integration could allow for scenario-based simulations and enable a quantitative assessment of: betweenness centrality measures, in order to verify if the strategic stops we have qualitatively identified correspond to the most critical ones; connectivity measures and potential increase with the Metromare new line service; definition of travel time isochrones (see [Malandri et al. \(2025\)](#)) to evaluate how Metromare alters access to key urban areas.

From an MCA perspective, we are laying the groundwork for prioritising investments and infrastructure improvements along the Metromare stops. We have been discussing these aspects only with the experts from PMR and the municipal administration, but the aim is to extend this analysis to the rest of the population to collect needs and expectations towards this project. We could not directly apply an MCA because we lacked time and resources, but also permissions from the responsible office, with whom we collaborated. The interviews already collected by AMR on existing PT lines were not sufficiently representative of the entire population, and did not answer our questions regarding connectivity with the bicycle system, but were nevertheless useful to guide the report produced for PMR on customer satisfaction (not included in this thesis).

As already mentioned, the participatory planning remains underdeveloped in the Rimini study and is restricted to the experts from PMR. For reasons of synthesis and coherence of the thesis, we do not report on the entire process of expert involvement and discussion; other stakeholders, such as residents, tourists, and businesses, could be included in the next steps, where surveys to gather perceptions on accessibility gaps, workshops and pilot studies could be planned.

Our current qualitative findings can guide the integration of complementary services, such as bike sharing or pedestrian infrastructure, as well as identify underserved areas, but the evaluation of Metromare's impact on connectivity is necessary to quantify the changes induced by this infrastructure investment, reduce barriers and implement integration between the different transport modes, thereby fostering a seamless and sustainable transport ecosystem in the metropolitan city.

6.6 Final Remarks

This chapter aims to outline the current and potential development towards MHs and their practical implications for sustainable urban mobility. The proposed policy suggestions are a combination of theoretical findings and results from projects in which the authors participated. This section serves as a recap of the path drawn until December 2024, while fast and effective innovations are introduced day by day.

It also partially presents the outcomes and reflections resulting from the exchange with policymakers, from both Porto and Rimini. This aspect aims to add value to the thesis and to discuss the feasibility of sustainable mobility measures in different contexts.

The investigation conducted together with PMR in Rimini has been fundamental to visualise concrete change in urban mobility due to the introduction of the Metromare line, a BRT able to facilitate the connection in the whole metropolitan area, bridging the North-South gap and (in the future) the one between the seaside and the hinterland. Its stops represent a potential stage to create effective MHs and integrated mobility. In this framework, we highlighted the Metromare aspects related to the progressive development of multimodality.

Metromare fits perfectly into the goals set out in the Environmental Action Programme⁴⁶ for a sustainable future in several respects. In fact, consistently with the aforementioned plan, Metromare implies the construction of infrastructure for bicycle, pedestrian and electric mobility, as well as the development of intermodality. In addition, these energy-efficient transport systems allow the reduction of climate-changing emissions in a consistent manner, which is the most challenging objective among those proposed by the EU. These challenges are among the priorities of local policymakers who, in order to cope with the new demographic and mobility demand dynamics, have chosen to undertake a significant change in local PT towards sustainable and shared forms of mobility.

Sustainable mobility, as described in this section, can be understood as a valid alternative to private transport means, uniting the various urban and peri-urban contexts, taking into account urban development and green areas, as well as paying special attention to the historic city centre. Efforts in this regard are considerable, but necessary to put climate change actions into practice.

As emphasised in the individual analysis of the Metromare stops, most of them have a multimodal potential in terms of integration, which at the moment remains only at the planning stage. New infrastructure, if not integrated and designed to meet a growing demand for efficient and accessible mobility services, might remain unused and represent a waste of resources. Metromare is intended to be a demonstration that designing a multimodal and integrated service from the outset is possible.

6.7 Final Conclusions, Limitations and Further Research Directions

Sustainable urban mobility offers a multi-dimensional set of benefits that extend beyond environmental improvements to encompass economic, social and financial gains. As noted by Papastavrinidis et al. (2021),

⁴⁶https://environment.ec.europa.eu/strategy/environment-action-programme-2030_en

these advantages stem from fostering ideal conditions for movement, which, in turn, enhance the overall quality of life. However, achieving such outcomes requires gradual policy interventions that encourage sustainable behaviour and prioritise long-term changes.

Within this perspective, the conclusion of this thesis underscores the innovative focus on integrating network resilience metrics as a critical factor in urban mobility research. While MHs have now been extensively studied, much of the existing research emphasises their typologies, components and characteristics. However, insufficient attention has been given to their potential role as contributors to the resilience of transport networks.

This thesis addressed this gap by analysing how MHs can strengthen the resilience of urban areas, particularly through their strategic placement and integration into the transport system. Unlike traditional approaches, this research highlights the importance of optimising the location of MHs to enhance the robustness of the entire network, especially in response to disruptions or failures.

Furthermore, this thesis emphasised the necessity of stakeholder participation in MH planning and design. Engaging a diverse set of stakeholders early in the planning process ensures that MHs are not only technically viable but also socially inclusive and aligned with the needs of the community. By bridging the gap between theoretical frameworks and practical implementation, this research contributes to advancing both the academic understanding and real-world application of resilient and sustainable urban mobility systems.

A significant potential extension of this research lies in deepening the understanding of the socio-demographic characteristics of passengers. In particular, it could be worthwhile to establish if a resilient transport network, where MHs can integrate PT and shared modes, is accessible for all, including more vulnerable people such as the elderly, migrants and kids.

Moreover, users have different perceptions of efficient mobility. Indeed [Lu et al. \(2018\)](#) emphasises that users perceive waiting- and on-board time differently depending on their demographic attributes. Recognising these variations underscores the need for mobility plans that are sensitive to the population's diverse needs. For local governments, at the planning phase, employing "personas" or prototypes representing various user profiles could serve as an invaluable tool. Innovative approaches are essential to creating a more robust framework for socially responsible planning ([Vallet et al., 2020](#)). These methods should aim to untangle and clearly articulate the multifaceted social impacts of future mobility scenarios, ensuring that decision-makers can address societal needs, equity and well-being more effectively. For instance, these prototypes would enable policymakers to test mobility strategies effectively, capturing and addressing the specific needs of different user groups before full implementation. By integrating these approaches, planning processes can become more inclusive and responsive, fostering solutions that balance social, environmental and economic priorities.

Linked to the previous issue, this research deals with stakeholder engagement and participation in MH planning, but does not pretend to be complete and satisfactory. Stakeholders play a critical role as catalysts for a successful transition to sustainable mobility solutions. In this research, they were involved during the preliminary stages, where their input was essential for defining criteria for implementing new MHs and prioritising user needs. However, to sustain long-term engagement and ensure the adoption of sustainable solutions, fostering Communities of Practice (CoPs) could prove transformative.

CoPs offer a dynamic space where individuals and organisations collaborate to exchange practical knowledge, share experiences, and co-create innovative solutions. As highlighted by [Di Ciommo et al. \(2023\)](#), these communities enable participants to gain insights through peer-to-peer learning and external perspectives. Such collaborative environments empower stakeholders to devise tailored solutions that address specific challenges, creating a robust foundation for scalable and context-sensitive mobility interventions.

While early stakeholder engagement does not entirely mitigate potential conflicts, it significantly contributes to smoother implementation processes and should be considered a prerequisite for proposing new policies. This research's early stakeholder involvement serves as a foundation for future participatory approaches, demonstrating the importance of inclusive collaboration in achieving sustainable mobility goals.

Despite its contributions, this research has encountered several limitations, which nonetheless could serve as focal points for future investigations.

The most impactful one is the data limit. Access to mobility data posed a significant challenge, particularly within the Italian context. The reliance on simulations due to the unavailability of real data on public transit passenger flows or shared transport usage limited the precision of the analysis. Future research should prioritise collaborations with transport operators and service providers to access real-time data, ensuring a more accurate and reliable foundation for evaluating mobility trends and interventions.

Data constraints are followed by time and resource constraints. The time allocated to research does not always correspond to what is needed, and does not foresee any problems that may affect the research process. Such delimited time and funds led to the reshaping of the scope of the study. Expanding the research to track real-time changes in mobility patterns and assess the impact of new policy interventions, such as pilot MHs—could provide richer insights. Additionally, extending the analysis to multiple cities of varying size would enhance the generalisability of findings, offering broader and more diverse policy recommendations.

As already mentioned, engaging with stakeholders requires both time and effort, which do not systematically produce fruitful results. While stakeholder involvement is an integral part of this research, more comprehensive engagement, such as conducting detailed interviews and focus groups with users, urban planners and policymakers, during and after project implementation, could provide qualitative insights to complement quantitative findings. This would ensure that proposed solutions are not only data-driven but also aligned with community needs and expectations.

As posed in the motivation of this thesis, this research also aims to reduce the gap between academia and the actual implementation of sustainable and concrete solutions. To do so, interdisciplinary collaboration is required to shape adaptable and achievable outcomes. Integrating expertise from fields such as chemistry, environmental science, and public health could add substantial value. For instance, quantifying environmental impacts, such as reductions in emissions and improvements in air quality, could provide compelling evidence for the broader benefits of MHs. Similarly, evaluating public health outcomes, such as reduced respiratory illnesses or the beneficial effects of increased physical activity due to the use of sharing and active modes, would add a critical dimension to the sustainability assessment of integrated mobility solutions.

Among the unexplored opportunities, of particular interest are the ones in the fields of environmental economics, behavioural economics, and broader economic modelling. These areas can offer deeper insights into the economic implications and incentives driving the adoption of resilient mobility systems. Exploring economic benefits through the evaluation of cost savings for users and the economic impact of more efficient transport systems could be a desirable extension of this research in the near future. Moreover, a Cost-Benefit Analysis could be included to assess the long-term environmental and economic benefits of MH implementation. Additionally, the decision-making processes of city residents when choosing between sustainable and non-sustainable transport options are crucial to promote behavioural change. This could be combined with dynamic pricing, incentives, or congestion charges when MHs are integrated into urban transport networks. Such studies could help design pricing mechanisms that optimise network efficiency while maximising user satisfaction.

Public-private partnership is becoming an increasingly central issue in the implementation of sustainable

transition projects, so it could be profitable to investigate how to maintain MHs and attract public and private investments.

In conclusion, this thesis has highlighted the transformative potential of MHs as a central component of integrated and sustainable urban mobility systems. By addressing the above limitations and exploring related topics, future research can build on the foundations to which this thesis contributed to provide a more comprehensive understanding of how MHs and integrated transport networks contribute to sustainable cities. As cities face increasing pressures from climate change and urbanisation, the adoption of such integrated and participatory approaches represents a promising strategy for fostering sustainable urban futures, while calling for policy commitment to transform mobility systems for the better.

Part V

Appendix

Annex 1: Overview of Resilience Studies in Transport Systems

Table 6.3: Review papers on transport network resilience.

Authors	Year	Title	Issue/Description of the paper
Faturechi & Miller-Hooks	2014	Measuring the Performance of Transportation Infrastructure Systems in Disasters: A Comprehensive Review	Comprehensive overview of transport infrastructure performance during disasters; categorizes literature by qualitative or quantitative assessments.
Reggiani, Nijkamp, Lanzi	2015	Transport resilience and vulnerability: The role of connectivity	Distinction between engineering and ecological resilience, emphasizing the relationship between resilience and connectivity in transport networks.
Mattsson, Jenelius	2015	Vulnerability and resilience of transport systems – A discussion of recent research	Summarizes transport system vulnerability and resilience, assessing performance based on previous studies and defining key authors in the field.
Calvert, Snelder	2018	A methodology for road traffic resilience analysis and review of related concepts	Overview of performance concepts, focusing on resilience indicators in traffic flow and determinants of specific attributes.
Zhou, Wang, Yang	2019	The resilience of Transportation Systems: Concepts and Comprehensive Review	Synthesizes recent literature on resilient transportation, focusing on metrics and models for measuring resilience in systems.
Bešinović	2020	Resilience in railway transport systems: a literature review and research agenda	Defines key concepts and classifies papers by metrics and approaches, explaining various methods.
Goncalves, Ribeiro	2020	Resilience of urban transportation systems: Concept, characteristics, and methods	Discusses resilience definitions and characteristics, evaluating mobility subsystem resilience to develop an assessment tool.

Authors	Year	Title	Issue/Description of the paper
Pan, Yan, He, He	2021	Vulnerability and resilience of transportation systems: A recent literature review	Provides specific definitions of vulnerability and resilience, analyzing metrics and methods from both qualitative and quantitative perspectives.

Table 6.4: Papers selected for the review.

Authors	Title	Year	Resilience Typology	Category	Application
Li D. Liu Y. Song Y. Ye Z. Liu D.	A Framework for Assessing Resilience in Urban Mobility: Incorporating Impact of Ridesharing	2022	static	topological	Urban
Karagulian F. Valenti G. Liberto C. Corazza M.	A Methodology to Estimate Functional Vulnerability Using Floating Car Data	2023	dynamic	topological	Urban
Gao Y. Wang J.W.	A resilience assessment framework for urban transportation systems	2021	static	topological	Urban
Beheshtian A. Don- aghy K.P. Rouhani O.M. Geddes R.	Adaptation planning for climate-resilient urban infrastructures	2019	static	optimization	applicable to urban
da Mata Martins, M. C., da Silva, A. N. R., & Pinto, N.	An indicator-based methodology for assessing resilience in urban mobility	2022	static	topological	Urban
Rahimi- Golkhandan A. Garvin M.J. Wang Q.	Assessing the Impact of Transportation Diversity on Post-disaster Intraurban Mobility	2021	static	topological	Urban

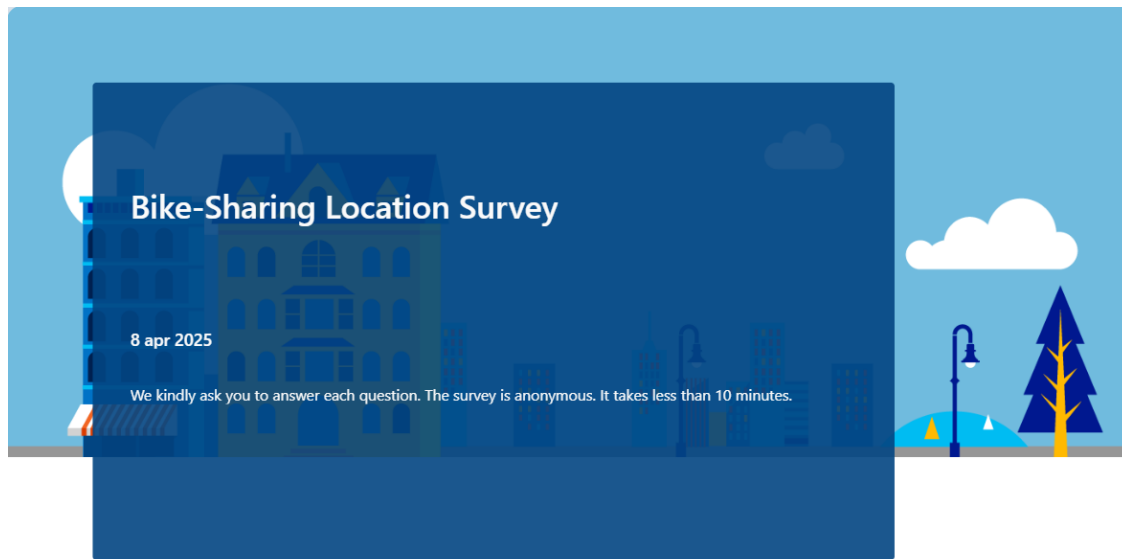
Authors	Title	Year	Resilience Typology	Category	Application
Ge Y. Du L. Ye H.	Co-optimization approach to post-storm recovery for inter-dependent power and transportation systems	2019	dynamic	optimization	applicable to urban
Carmona H.A. De Noronha A.W.T. Moreira A.A. Araújo N.A.M. Andrade J.S. Jr.	Cracking urban mobility	2020	dynamic	topological + simulation	Urban
Koc E. Cetiner B. Rose A. Soibelman L. Tacioglu E. Wei D.	CRAFT: Comprehensive Resilience Assessment Framework for Transportation Systems in Urban Areas	2020	dynamic	topological + others	Urban
Ilbeigi M. Meimand M.E.	Empirical analysis of impacts of post-disaster human mobility patterns on the resilience of transportation networks	2020	dynamic	topological	Urban
Tang J. Wan L. Nohta T. Schooling J. Yang T.	Exploring resilient observability in traffic-monitoring sensor networks: A study of spatial-temporal vehicle patterns	2020	dynamic	data-driven	Urban
Azolin L.G. Rodrigues da Silva A.N. Pinto N.	Incorporating public transport in a methodology for assessing resilience in urban mobility	2020	dynamic	topological	Urban
Khaghani F. Jazizadeh F.	mD-Resilience: A multi-dimensional approach for resilience-based performance assessment in urban transportation	2020	dynamic	data-driven	Urban
Cordero D. Rodriguez G.	Merger of Network Graph Indicators to Estimate Resilience in Latin American Cities	2022	static	topological	Urban

Authors	Title	Year	Resilience Typology	Category	Application
Wang X. et al.	Multi-criteria robustness analysis of metro networks	2017	dynamic	topological	Urban
Bucar R.C.B. Hayeri Y.M.	Quantitative assessment of the impacts of disruptive precipitation on surface transportation	2020	static	topological + simulation	Urban
Östh J. Reg- giani A. Ni- jkamp P.	Resilience and accessibility of Swedish and Dutch municipalities	2018	static	topological + economic variables	applicable to urban
Santos T. Silva M.A. Fernandes V.A. Mars- den G.	Resilience and vulnerability of public transportation fare systems: The case of the city of Rio De Janeiro Brazil	2020	static	fuzzy logic	Urban
Yabe T. Rao P.S.C. Ukkusuri S.V.	Resilience of Interdependent Urban Socio-Physical Systems using Large-Scale Mobility Data: Modeling Recovery Dynamics	2021	dynamic	data-driven	Urban
Yao K. Chen S.	Resilience-Based Adaptive Traffic Signal Strategy against Disruption at Single Intersection	2022	dynamic	optimization	Urban
De La Mota I.F. Huerta- Barrientos A.	Simulation-optimization of the Mexico City public transportation network: A complex network analysis framework	2017	static	topological + simulation	Urban
Ilbeigi M.	Statistical process control for analyzing resilience of transportation networks	2019	dynamic	topological	Urban
Koc E. Bar- baros Cetiner M. Lee J. Nutakki A. Soibel- man L.F. Tacioglu E.	System-based resilience assessment of networked transportation systems in metropolitan areas: Case of greater Los Angeles	2019	dynamic	topological	Urban

Authors	Title	Year	Resilience Typology	Category	Application
Mirzaee S. Wang Q.	Urban mobility and resilience: exploring Boston's urban mobility network through twitter data	2020	static	topological	Urban
Khaghani F. Rahimi-Golkhandan A. Jazizadeh F. Garvin M.J.	Urban transportation system resilience and diversity coupling using large-scale taxicab GPS data	2019	dynamic	data-driven	Urban
Zhang Y. Ng S.T.	A hypothesis-driven framework for resilience analysis of public transport network under compound failure scenarios	2021	dynamic	topological + simulation	Urban
Guo J. Du Q. He Z.	A method to improve the resilience of multimodal transport network: Location selection strategy of emergency rescue facilities	2021	dynamic	topological + optimization	applicable to urban
Bevrani B. Burdett R. Bhaskar A. Yarlagadda P.K.D.V.	A multi-criteria multi-commodity flow model for analysing transportation networks	2020	static	optimization	applicable to urban
Chopra S.S. Dillon T. Bilec M.M. Khanna V.	A network-based framework for assessing infrastructure resilience: A case study of the London metro system	2016	static	topological	Urban
Verschuur J. Pant R. Koks E. Hall J.	A systemic risk framework to improve the resilience of port and supply-chain networks to natural hazards	2022	dynamic	topological	General
Das R.	Approach for measuring transportation network resiliency: A case study on Dhaka Bangladesh	2020	dynamic	topological	Urban

Authors	Title	Year	Resilience Typology	Category	Application
Henry E. Furno A. El Faouzi N.-E.	Approach to quantify the impact of disruptions on traffic conditions using dynamic weighted resilience metrics of transport networks	2021	dynamic	topological	Urban
Martín B. Ortega E. Cuevas- Wizner R. Ledda A. De Montis A.	Assessing road network resilience: An accessibility comparative analysis	2021	static	data-driven + simulation	Urban
Aparicio J.T. Arsenio E. Henriques R.	Assessing robustness in multi-modal transportation systems: a case study in Lisbon	2022	static	topological + simulation	Urban
Wang Z. Xu X.	Assessing route redundancy of freeway networks in Mega-city regions	2022	static	topological + data-driven	Urban
Sohouenou P.Y.R. Neves L.A.C.	Assessing the effects of link-repair sequences on road network resilience	2021	dynamic	topological + simulation	Urban
Nogal M. Honfi D.	Assessment of road traffic resilience assuming stochastic user behaviour	2019	dynamic	optimization	applicable to urban
Nouasse H. Doniec A. Lozenguez G. Duviella E. Chiron P. Archimède B. Chuquet K.	Constraint satisfaction problem based on flow graph to study the resilience of inland navigation networks in a climate change context	2016	static	optimization + simulation	General
Argyroudis S.A. Na- siopoulos G. Mantadakis N. Mitoulis S.A.	Cost-based resilience assessment of bridges subjected to earthquakes	2021			
Liu H. Lin J. Zhang M.	Disaster resilience of transport infrastructure in urban areas: An overview of measures	2021	dynamic	optimization + data- driven	Urban

Annex 2: Bike Sharing Location Survey (example questions)



Bike-Sharing Location Survey

* Obligatoria

Instructions and Goal

Our aim is to construct a ranking of locations in which to implement a bike-sharing station, by means of Multi-Criteria Analysis (MCA), where:

- the alternatives are the **urban public transport stops**, which currently do not include a bike-sharing station;
- the criteria are nine. They cover proximity to places of interest-amenities, socio-demographic and environmental indicators, and metrics analysing the resilience of the urban public transport network.

For the sake of clarity, the key concepts of the criteria are defined below:

- Green areas** = open-space areas reserved for parks and other "green spaces"
- Sports/entertainment centers** = gyms, swimming pools, movie, theaters, etc.
- Tourism areas** = monuments, archaeological sites, etc. (excluded green areas)
- Schools** = educational buildings (including kindergartens)
- High-density areas** = areas with high rate of population per square kilometer
- High-employment areas** = areas with high number of locations of companies
- High-polluted areas** = areas with high air pollution values
- Low income areas** = areas with low income values
- Critical PT stations** = stations that have a high centrality in the network, measured by centrality metrics (e.g. betweenness). These are the stops whose non-availability (during a disruption) causes extensive damage to network connectivity.

For each pair of criteria, choose which one is the most important for you, and assign a value from 1 (slightly more important) to 8 (extremely more important), according to the AHP method (Saaty, 2008).

The results of the questionnaire will be used to construct the set of weights to be used in the MCA.

In Choosing Where to Place a Bike-Sharing Station:

1. Which is **more** important between **Proximity to green areas** and **Proximity to sport/entertainment centers**? *

Seleziona la risposta



2. How much **more** important is from 1 to 8? *

1	2	3	4	5	6	7	8
---	---	---	---	---	---	---	---

3. Which is **more** important between **Proximity to green areas** and **Proximity to tourism areas**? *

Seleziona la risposta



4. How much **more** important is from 1 to 8? *

1	2	3	4	5	6	7	8
---	---	---	---	---	---	---	---

Sezione 2

**Personal Information**

73. Professional Background *

- ☐ Urban Planner
- ☐ Decision-maker
- ☐ Transport Engineer
- ☐ Academic/Researcher
- ☐ Other

74. Gender *

- ☐ Female
- ☐ Man
- ☐ Prefer not to say

75. Age *

Inserisci la risposta

Sezione 3

...

Thank you

Thank you for providing your input on the relative importance of these criteria. Your responses will be used to determine the best location for Mobility Hubs in our case studies.

Annex 3: AHP template and results

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 15.09.2018

Free web based AHP software on:

<http://bpmsg.com>**Only input data in the light green fields and worksheets!**

n= 9 Number of criteria (2 to 10) Scale: 1 **AHP 1-9**

N= 17 Number of Participants (1 to 20) α : 0,1 Consensus: 47,5%

p= 0 selected Participant (0=consol.) 2 7 **Consolidated**

Objective

Author

Date

Thresh: 1E-08

Iterations: 4

EVM check: 2,1E-10

Table	Criterion	Comment	Weights	+/-
1	PGA		9,3%	1,8%
2	PSR		6,5%	1,3%
3	PTA		9,2%	1,2%
4	PS		8,7%	1,4%
5	HDA		16,9%	1,8%
6	HEA		12,4%	1,9%
7	HPA		8,7%	1,2%
8	CPT		18,8%	2,8%
9	LIA		9,5%	0,9%
#		for 9&10 unprotect the input sheets and expand the question section ("+" in row 66)	0,0%	0,0%

Result

Eigenvalue

Lambda: 9,092

MRE: 15,2%

Consistency Ratio

0,37

GCI: 0,03

Psi: #RIF!

CR: 0,8%

Matrix

normalized
principal
Eigenvector

	PGA	PSR	PTA	PS	HDA	HEA	HPA	CPT	LIA	0
PGA	1	2	5/6	11/4	1/2	2/3	1	1/2	1	-
PSR	1/2	1	2/3	1	2/5	4/9	6/7	2/5	3/5	-
PTA	12/9	11/2	1	11/8	1/2	3/5	1	5/9	1	-
PS	4/5	1	8/9	1	5/9	4/5	11/3	1/2	1	-
HDA	2	24/9	2	14/5	1	12/3	13/4	4/5	17/8	-
HEA	11/2	21/4	12/3	11/4	3/5	1	12/5	1/2	13/7	-
HPA	1	11/6	11/9	3/4	4/7	5/7	1	1/2	5/6	-
CPT	2	22/5	14/5	2	11/4	2	2	1	21/3	-
LIA	1	15/8	11/9	1	1/2	5/7	11/5	3/7	1	-
0	-	-	-	-	-	-	-	-	-	1

9,32%

6,50%

9,15%

8,75%

16,87%

12,41%

8,67%

18,82%

9,50%

0,00%

Calculation of Consensus Indicator based on RGGM results

		1	2	3	4	5	6	7	8	9	10	1,2742	β
RGGM results	1	21%	9%	11%	5%	7%	7%	27%	4%	9%	-		
	2	25%	7%	9%	4%	17%	6%	11%	4%	17%	-		
	3	25%	6%	9%	4%	16%	6%	11%	4%	18%	-		
	4	6%	17%	2%	24%	4%	5%	30%	6%	6%	-		
	5	3%	6%	2%	2%	25%	21%	8%	28%	4%	-		
	6	3%	5%	17%	12%	14%	13%	6%	16%	14%	-		
	7	23%	13%	22%	17%	4%	4%	4%	4%	9%	-		
	8	1%	28%	2%	16%	5%	8%	5%	30%	3%	-		
	9	2%	3%	19%	8%	23%	10%	4%	17%	15%	-		
	10	4%	3%	18%	2%	20%	21%	1%	24%	8%	-		
	11	2%	3%	5%	26%	27%	8%	14%	13%	2%	-		
	12	16%	2%	2%	15%	13%	15%	2%	33%	3%	-		
	13	15%	3%	16%	1%	16%	13%	1%	20%	15%	-		
	14	3%	4%	2%	3%	12%	13%	10%	39%	12%	-		
	15	9%	2%	2%	11%	13%	12%	11%	40%	2%	-		
	16	4%	1%	13%	14%	11%	2%	17%	23%	14%	-		
	17	20%	5%	13%	2%	22%	22%	2%	11%	4%	-		
	18	-	-	-	-	-	-	-	-	-	-		
	19	-	-	-	-	-	-	-	-	-	-		
	20	-	-	-	-	-	-	-	-	-	-		
p-avg		0,108	0,069	0,097	0,097	0,146	0,109	0,098	0,186	0,091	0	6,783	α
Shannon Entropy	1	0,33	0,219	0,24	0,142	0,182	0,182	0,354	0,134	0,219	-	2,00263	7,4
	2	0,347	0,178	0,221	0,131	0,299	0,175	0,244	0,134	0,299	-	2,02648	7,6
	3	0,346	0,177	0,219	0,13	0,297	0,173	0,243	0,126	0,307	-	2,01928	7,5
	4	0,164	0,302	0,077	0,34	0,136	0,153	0,361	0,17	0,172	-	1,87518	6,5
	5	0,094	0,169	0,09	0,086	0,347	0,327	0,205	0,358	0,134	-	1,80837	6,1
	6	0,099	0,158	0,3	0,253	0,275	0,263	0,173	0,29	0,279	-	2,0913	8,1
	7	0,339	0,261	0,331	0,299	0,135	0,135	0,135	0,135	0,214	-	1,98435	7,3
	8	0,059	0,357	0,089	0,296	0,15	0,202	0,156	0,362	0,11	-	1,78052	5,9
	9	0,084	0,096	0,313	0,195	0,339	0,23	0,126	0,303	0,282	-	1,9678	7,2
	10	0,123	0,101	0,307	0,071	0,322	0,327	0,057	0,341	0,199	-	1,84937	6,4
	11	0,086	0,096	0,153	0,35	0,353	0,196	0,28	0,267	0,078	-	1,85889	6,4
	12	0,291	0,075	0,075	0,285	0,267	0,285	0,071	0,365	0,098	-	1,81353	6,1
	13	0,288	0,106	0,291	0,06	0,291	0,262	0,059	0,319	0,284	-	1,96117	7,1
	14	0,114	0,136	0,092	0,108	0,255	0,266	0,233	0,367	0,254	-	1,82424	6,2
	15	0,218	0,068	0,079	0,239	0,26	0,252	0,239	0,367	0,075	-	1,79663	6,0
	16	0,132	0,062	0,264	0,276	0,245	0,084	0,304	0,337	0,274	-	1,97842	7,2
	17	0,323	0,142	0,269	0,066	0,331	0,331	0,068	0,248	0,13	-	1,90697	6,7
	18	-	-	-	-	-	-	-	-	-	-	0	1,0
	19	-	-	-	-	-	-	-	-	-	-	0	1,0
	20	-	-	-	-	-	-	-	-	-	-	0	1,0
p-avg*ln(p-avg)		0,24	0,184	0,226	0,226	0,281	0,242	0,227	0,313	0,218	0	8,6426	γ

Annex 4: Rank of 72 alternatives (PT stops) for r=5 minutes.

Criteria measurements for 72 alternatives, corresponding normalized score and rank											
Stop name	PGA	PTA	PS	PSR	CPT	HPA	LIA	HDA	HEA	score	rank
Laim	2	1	7	4	384467	9.96	4215	10756	6.5	0.6279422	1
Pündterplat	4	118	10	1	1264	10.21	4464	15723	3.9	0.3466531	2
Scheidplatz	1	2	16	0	106504	10.21	4464	15723	3.9	0.2778657	3
Bonner Platz	6	29	12	0	57564	10.21	4464	15723	3.9	0.2395073	4
Hohenzoller	2	0	18	41	60761	10.21	4464	15723	3.9	0.2319383	5
Klopstockstr	6	0	81	9	2195	10.21	4464	15723	3.9	0.2226388	6
Barlachstraf	5	1	67	17	1211	10.21	4464	15723	3.9	0.2089731	7
Candidplatz	4	2	8	41	65005	10.07	2544	6711	5.3	0.1978446	8
Petuelring	1	21	1	0	35680	10.21	4464	15723	3.9	0.1953116	9
Herzogstraß	6	0	19	36	4549	10.21	4464	15723	3.9	0.1909524	10
Infanteriestr	5	5	43	9	5242	10.21	4464	15723	3.9	0.1887469	11
Rümannstra	3	1	51	3	4808	10.21	4464	15723	3.9	0.1884607	12
Angererstraf	6	3	22	26	1253	10.21	4464	15723	3.9	0.1845565	13
Ackermannst	7	0	28	9	1066	10.21	4464	15723	3.9	0.1822395	14
Heckschersst	9	0	0	0	1593	10.21	4464	15723	3.9	0.1814507	15
Georg-Birk-S	7	0	28	0	1070	10.21	4464	15723	3.9	0.1808178	16
Karl-Theodo	7	1	15	19	609	10.21	4464	15723	3.9	0.1806358	17
Nordbad	3	1	8	28	13853	10.21	4464	15723	3.9	0.1788356	18
Mildred-Sch	5	0	33	0	580	10.21	4464	15723	3.9	0.1769902	19
Barbarastraf	6	0	16	2	5603	10.21	4464	15723	3.9	0.1735372	20
Clemensstr	6	8	0	8	26	10.21	4464	15723	3.9	0.1726770	21
Stegener We	3	0	72	0	4967	9.96	4215	10756	6.5	0.1703193	22
Ackermanns	4	2	10	6	8091	10.21	4464	15723	3.9	0.1680376	23
Elisabethpla	4	1	15	1	2260	10.21	4464	15723	3.9	0.1663772	24
Scheidplatz	3	1	16	7	4162	10.21	4464	15723	3.9	0.1663438	25
Kurfürstenpl	2	5	15	1	7117	10.21	4464	15723	3.9	0.1663211	26
Winzererstr	3	2	5	13	708	10.21	4464	15723	3.9	0.1645470	27
Kölner Platz	3	0	10	0	1889	10.21	4464	15723	3.9	0.1624677	28
Gartenstraß	2	2	0	0	4707	10.21	4464	15723	3.9	0.1610096	29
Claude-Lorr	8	6	1	42	2962	10.07	2544	6711	5.3	0.1573669	30
Pronnerplat	5	0	6	47	4836	9.96	4215	10756	6.5	0.1525540	31
Säulingstraß	10	0	26	0	6276	9.96	4215	10756	6.5	0.1521517	32
Ammersees	5	1	48	0	13841	9.96	4215	10756	6.5	0.1478234	33
St.-Quirin-Pl	7	5	34	0	18603	10.07	2544	6711	5.3	0.1436211	34
Mangfallplat	9	0	14	1	8157	10.07	2544	6711	5.3	0.1358888	35
Fürstenriede	6	7	11	3	28612	9.96	4215	10756	6.5	0.1356872	36
Jakob-Gelb-l	4	4	0	38	343	10.07	2544	6711	5.3	0.1321131	37
Friedenheir	8	0	8	0	11996	9.96	4215	10756	6.5	0.1312458	38
Pörschache	8	0	0	8	2784	9.96	4215	10756	6.5	0.1277092	39
Laimer Platz	4	0	4	12	26653	9.96	4215	10756	6.5	0.1222702	40
Mangfallplat	7	1	11	0	12525	10.07	2544	6711	5.3	0.1220432	41
Gerhardstra	3	2	29	9	16877	10.07	2544	6711	5.3	0.1204829	42
Westendstr	2	1	1	12	27937	9.96	4215	10756	6.5	0.1181454	43
Menaristraß	5	0	19	0	5804	9.96	4215	10756	6.5	0.1145881	44
Kurzstraße	3	0	28	6	10918	10.07	2544	6711	5.3	0.1139458	45
Agnes-Bernz	5	5	1	10	8605	9.96	4215	10756	6.5	0.1134061	46

Säbener Str	6	2	13	0	6046 10.07	2544	6711 5.3	0.1133717	47
Siglststraße	6	0	8	0	1112 9.96	4215	10756 6.5	0.1133003	48
Agnes-Bern	6	1	3	0	1657 9.96	4215	10756 6.5	0.1124792	49
Tiroler Platz	5	1	20	2	6698 10.07	2544	6711 5.3	0.1120380	50
Hans-Thona	5	1	7	0	2044 9.96	4215	10756 6.5	0.1076082	51
Winterstraße	5	9	0	2	875 10.07	2544	6711 5.3	0.1068814	52
Schäufelein	5	0	0	0	0 9.96	4215	10756 6.5	0.1057835	53
Aindorferstr	1	1	0	0	19609 9.96	4215	10756 6.5	0.1046483	54
Guido-Schn	4	1	0	0	7869 9.96	4215	10756 6.5	0.1035705	55
Hönigschmi	4	0	6	0	3806 9.96	4215	10756 6.5	0.1027528	56
Südtiroler St	2	0	1	15	8808 10.07	2544	6711 5.3	0.1000288	57
Authariplatz	3	0	16	0	4587 10.07	2544	6711 5.3	0.0995302	58
Stroblstraße	2	0	1	9	2434 9.96	4215	10756 6.5	0.0979606	59
Lebscheestr	2	1	16	0	4268 10.07	2544	6711 5.3	0.0972375	60
Lautensacks	2	0	1	1	4376 9.96	4215	10756 6.5	0.0959802	61
Ludmillastr	3	0	8	0	6396 10.07	2544	6711 5.3	0.0959193	62
Hauzenberg	2	0	0	1	1262 9.96	4215	10756 6.5	0.0950695	63
Elsenheimer	1	2	0	3	545 9.96	4215	10756 6.5	0.0947870	64
Am Lokschu	1	0	1	1	77 9.96	4215	10756 6.5	0.0939953	65
Griechenstr	3	0	0	1	3936 10.07	2544	6711 5.3	0.0933938	66
Autharistraß	3	0	0	0	1826 10.07	2544	6711 5.3	0.0927525	67
Wilhelm-Kul	2	1	0	8	2136 10.07	2544	6711 5.3	0.0926916	68
Theodolinde	1	0	11	0	96 10.07	2544	6711 5.3	0.0920192	69
Tierpark (Ale	2	0	0	5	0 10.07	2544	6711 5.3	0.0907920	70
Theodolinde	2	1	0	0	2488 10.07	2544	6711 5.3	0.0905672	71
Klinikum Ha	1	0	0	0	432 10.07	2544	6711 5.3	0.0889870	72

Annex 5: Online Survey "Need and expectations towards a smart mobility hub"

Needs and expectations towards a smart mobility hub

Dear participant, thank you very much for your willingness to participate in this survey!

In the coming years, the city of Munich would like to realise many mobility projects that aim at a networked, environmentally friendly and space-saving mobility. Smart mobility hub are part of this as well.

The research team at the Technical University of Munich would therefore like to conduct a survey. This is to record the needs and expectations of Munich's citizens for a smart mobility station. In the course of the survey, it will also be investigated where smart mobility stations should best be placed. The results will flow into the EU-funded research project "SmartHubs", which focuses on the development of smart mobility stations.

Let's go! Let's shape the development of smart mobility stations together! 😊

There are 29 questions in this survey.

Next

General mobility behaviour

***On average, I am currently on the move on this many days in a week:**

🔵 Choose one of the following answers

- ☐ less than 1 day
- ☐ 1 day
- ☐ 2 days
- ☐ 3 days
- ☐ 4 days
- ☐ 5 days
- ☐ 6 days
- ☐ every day
- ☐ never

***Please indicate how often you currently use the following means of transport in general:**

	daily or almost daily	1-3 days per week	1-3 days per month	less often than monthly	never or almost never
Ways by foot	☐	☐	☐	☐	☐
Bicycle	☐	☐	☐	☐	☐
Motorbike	☐	☐	☐	☐	☐
Own passenger car	☐	☐	☐	☐	☐
Passenger car as a rider	☐	☐	☐	☐	☐
Car sharing vehicle	☐	☐	☐	☐	☐
Public transport	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐
E-moped	☐	☐	☐	☐	☐

***Do you use mobile devices such as smartphones or tablets for the following?**

☒ Check all that apply

- ☐ Yes, for timetable or delay information
- ☐ Yes, for the purchase of tickets
- ☐ Yes, for route planning or road navigation
- ☐ No

Primary mobility elements

What is a smart mobility station?

What actually is a smart mobility station? A smart mobility station is a physical, highly visible location that serves as a hub for mobility. In a smart mobility station, there can be a variety of rental services (shared mobility), such as the rental of bicycles or e-scooters. A smart mobility station is also integrated within walking distance of public transport systems such as the underground or bus, as well as the infrastructure of pedestrians and cyclists. The Münchner Freiheit is an example of a mobility station.

The component "smart" in the term "smart mobility station" describes digital services that are available to the user of the mobility station. An example of "smart" services can be the option to book tickets with the smartphone. Another example is the display of travel data on a digital information pillar.

In a smart mobility station, non-mobility related services and elements can also be present, such as cafés or shops.

***In a smart mobility station, the following public transport modes (subway, bus, etc.) would be important to me for daily mobility:**

	very important	rather important	rather unimportant	irrelevant	no answer
Bus	☐	☐	☐	☐	☐
Tram	☐	☐	☐	☐	☐
Subway	☐	☐	☐	☐	☐
Rapid-transit railway	☐	☐	☐	☐	☐
Mobility service provider (Uber)	☐	☐	☐	☐	☐
Cab	☐	☒ very important	☐	☐	☐

***The following features would be important to me in public transportation (subway, bus, etc.) in a smart mobility station:**

	very important	rather important	rather unimportant	irrelevant	no answer
Barrier free access	☐	☐	☐	☐	☐
Monitoring system	☐	☐	☐	☐	☐
Covered waiting areas	☐	☐	☐	☐	☐
Seating areas	☐	☐	☐	☐	☐
Lighting	☐	☐	☐	☐	☐
Cleanliness of transportation means	☐	☐	☐	☐	☐
Cleanliness of the station	☐	☐	☐	☐	☐

Please take a moment and think about what else you would find important in a smart mobility station for public transport (subway, bus, etc.):

Secondary mobility elements

***In a smart mobility station, the following sharing offers (bike rental, car sharing, etc.) would be important to me for daily mobility:**

	very important	rather important	rather unimportant	irrelevant	no answer
Rental of cargo bikes	☐	☐	☐	☐	☐
Rental of bikes	☐	☐	☐	☐	☐
Rental of e-bikes	☐	☐	☐	☐	☐
Rental of e-scooters	☐	☐	☐	☐	☐
Rental of e-mopeds	☐	☐	☐	☐	☐
Car-sharing	☐	☐	☐	☐	☐
Rental of e-cars	☐	☐	☐	☐	☐
Ridesharing services	☐	☐	☐	☐	☐

Please take a moment to think about what else you would find important about a smart mobility station in terms of sharing services (bike rentals, car sharing, etc.):

Mobility-related services

***In a smart mobility station, the following mobility-related services (charging stations, bike racks, etc.) would be important to me for daily mobility:**

	very important	rather important	rather unimportant	irrelevant	No answer
Charging station for e-cars	☐	☐	☐	☐	☐
Charging station for e-mopeds	☐	☐	☐	☐	☐
Charging station for e-scooters	☐	☐	☐	☐	☐
Charging station for e-bikes	☐	☐	☐	☐	☐
Bicycle rack	☐	☐	☐	☐	☐
Secure parking facilities for private bicycles	☐	☐	☐	☐	☐
Bicycle repair station	☐	☐	☐	☐	☐
Rental of car seats for children	☐	☐	☐	☐	☐
Rental of bicycle seats for children	☐	☐	☐	☐	☐
Rental of bicycle trailers	☐	☐	☐	☐	☐

Please take a moment to think about what else you would find important about a smart mobility station in terms of mobility-related services (charging stations, bike racks, etc.):

Digital Services

***In a smart mobility station, the following digital services (booking platform, WiFi, etc.) would be important to me:**

	very important	rather important	rather unimportant	irrelevant	no answer
Digital support service	☐	☐	☐	☐	☐
Ticket machine	☐	☐	☐	☐	☐
Charging option for the smartphone	☐	☐	☐	☐	☐
WiFi	☐	☐	☐	☐	☐
Digital information pillar with travel information	☐	☐	☐	☐	☐
Digital map with information about the location of the vehicles	☐	☐	☐	☐	☐
Digital information pillar with information on vehicle availability	☐	☐	☐	☐	☐
Parcel station	☐	☐	☐	☐	☐
Integrated booking platform	☐	☐	☐	☐	☐

Please take a moment to think about what else you would find important about a smart mobility station in terms of digital services (booking platform, WiFi, etc.):

General mobility behaviour

***On average, I am currently on the move on this many days in a week:**

④ Choose one of the following answers

- ☐ less than 1 day
- ☐ 1 day
- ☐ 2 days
- ☐ 3 days
- ☐ 4 days
- ☐ 5 days
- ☐ 6 days
- ☐ every day
- ☐ never

General services

*The following services and offers should definitely be available at a smart mobility station:

	very important	rather important	rather unimportant	irrelevant	no answer
Kiosk	☐	☐	☐	☐	☐
Café	☐	☐	☐	☐	☐
Drugstore	☐	☐	☐	☐	☐
Toilet	☐	☐	☐	☐	☐
Lockers	☐	☐	☐	☐	☐
Grocery shop	☐	☐	☐	☐	☐
Clothing shop	☐	☐	☐	☐	☐
On-site support service	☐	☐	☐	☐	☐
Information board about points of interest in the surrounding area	☐	☐	☐	☐	☐

Please take a moment to think about what else you would find important in terms of services and offerings at a smart mobility station:

Location

*It is important to me that the smart mobility station is close to these places:

☐ Check all that apply

- ☐ Work
- ☐ Home
- ☐ Shops
- ☐ Restaurants
- ☐ Public place
- ☐ Park
- ☐ Pedestrian walkway
- ☐ Cycle path
- ☐ Busy road
- ☐ Public transport
- ☐ Cultural facility (e.g. museum)
- ☐ Entertainment facility (e.g. cinema)
- ☐ Educational institution (e.g. university)
- ☐ Sports facility (e.g. gym)

Map Maxvorstadt

***Please do not use the zoom function of the map. Please do not change the section of the map, only move the red pin.**

Below is a map of Munich showing the Maxvorstadt district and the main campus of the Technical University. Please click on the red pin on the map and drag the pin to the location on the map that you find most suitable for building a smart mobility station. Then press "Next" at the bottom right.

48.1494729 11.5676822



Kurzbeispiel Kartendaten © 2022 COWI, Geobasis-DE/BKG (©2009), Google Nutzungsbedingungen Fehler bei Google Maps melden
 Drag and drop the pin to the desired location. You may also right click on the map to move the pin.

❗ If the map does not open, select the internet address (URL) and press the enter key.

Factors Maxvorstadt

Half time! You have already completed half of the survey 😊

★What factors did you consider when selecting the location for the smart mobility station in the previous question? Proximity to...

📘 Check all that apply

- ☐ Work
- ☐ Shops
- ☐ Restaurants
- ☐ Educational institution (e.g. university)
- ☐ Sports facility (e.g. gym)
- ☐ Entertainment facility (e.g. cinema)
- ☐ Cultural facility (e.g. museum)
- ☐ Park
- ☐ Public place
- ☐ Home
- ☐ Pedestrian walkway
- ☐ Cycle path
- ☐ Busy road
- ☐ Public Transport
- ☐ Other:

Design and Transfer

***The following design features would be important to me in a smart mobility station:**

📌 Check all that apply

- ☐ Greenery
- ☐ Enlarged pavements
- ☐ Parklets (street furniture to linger)
- ☐ Pedestrian lighting
- ☐ Protected waiting areas
- ☐ General cleanliness
- ☐ Blue infrastructure such as fountains
- ☐ Good visibility of the smart mobility station in public space
- ☐ Artistically designed infrastructure (e.g. colourful painting of pedestrian walkways)

***For switching from one mobility option to another (for example, from the subway to the e-scooter), I would spend a maximum of that much time:**

📌 Choose one of the following answers

- ☐ 1 minute walk
- ☐ 2 minutes walk
- ☐ 3 minutes walk
- ☐ 4 minutes walk
- ☐ 5 minutes walk
- ☐ 6 minutes walk
- ☐ 7 minutes walk
- ☐ 8 minutes walk
- ☐ 9 minutes walk
- ☐ 10 minutes walk
- ☐ more than 10 minutes on foot
- ☐ I do not want to transfer

Expectations

Only a few questions left! Thank you for your support! 🙌

•What impact(s) do you expect from sharing services (bike rentals, car sharing, etc.) offered at a smart mobility station?

🔗 Check all that apply

- ☐ Lower release of harmful emissions
- ☐ Less road traffic noise
- ☐ Promotion of social exchange
- ☐ Congested sidewalks and bike lanes through sharing services
- ☐ Less car traffic by offering alternative transportation options
- ☐ More equity in terms of access to mobility services
- ☐ Technical problems with digital services
- ☐ That sharing services are often occupied/busy
- ☐ Vandalism
- ☐ That the sharing offers are more expensive than public transportation
- ☐ Other:

Spending time at a SMH

	fully agree	agree	disagree	do not agree at all
I think a smart mobility station is good, which not only provides mobility services, but also offers opportunities to spend time.	☐	☐	☐	☐

General Attitude

★

	Yes, definitely	Yes, probably	No, probably not	No, definitely not	I can't say
Do you think that a smart mobility station in the city of Munich would make sense in principle?	☐	☐	☐	☐	☐

What would you like to see in a smart mobility station in Munich that has not yet been covered by this survey?

What are your general expectations for a smart mobility station in Munich?

Socio-demographic questions

Almost there! Only your personal details are missing 🍌

★How old are you?

📌 Choose one of the following answers

- ☐ below 18 years old
- ☐ 18 to 24 years old
- ☐ 25 to 34 years old
- ☐ 35 to 50 years old
- ☐ 51 to 65 years old
- ☐ above 65 years old

★I am:

📌 Choose one of the following answers

- ☐ female
- ☐ male
- ☐ diverse

***What is your highest educational qualification?**

Choose one of the following answers

- ☐ Still a pupil/(still) without a degree
- ☐ Elementary or lower secondary school leaving certificate
- ☐ Secondary school leaving certificate or comprehensive school leaving certificate
- ☐ Higher education entrance qualification, high school diploma or professional training with high school diploma
- ☐ Bachelor degree
- ☐ Master/Diploma degree
- ☐ PhD
- ☐ No degree
- ☐ Other:

***What is your current profession?**

Choose one of the following answers

- ☐ Full time
- ☐ Part time
- ☐ Apprentice
- ☐ Pupil
- ☐ Student
- ☐ Homemaker
- ☐ Pensioner / Retiree
- ☐ Currently unemployed
- ☐ Other:

***Please enter your postal code:**

Only numbers may be entered in this field.

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