Integrating Nano-hubs into Brussels: Toward Sustainable Cycle Logistics and Last-Mile Delivery

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"A vida da gente é feita de momentos!"
À minha mãe, Marineusa Braga da Silva.

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1. Introduction

The rise of e-commerce, accelerated by the COVID-19 pandemic, has reshaped the logistics landscape dynamics and placed increasing pressure on urban delivery systems (Schorung et al., 2023a, 2023b; Cauwelier et al., 2024). The shift to online shopping has intensified the demand for space dedicated to freight activities within cities, reinforcing the relevance of "proximity logistics"—the integration of logistics infrastructure within dense and mixed-use urban environments (Buldeo Rai et al., 2022; Sakai et al., 2023). At the same time, new environmental regulations in high-density areas are driving the need for more adaptable freight transport modes and a reconfiguration of the urban fabric (Mohamed et al., 2023) as governments accelerate efforts to promote sustainable mobility and reduce environmental footprints in response to climate concerns. Together, these pressures have made the integration of logistics with sustainability goals a critical policy concern, placing increasing demands on authorities to align goods movement with broader urban planning strategies (Comi et al., 2024).

In this evolving context, cycle logistics has emerged as a promising solution. By relying on cargo bikes, which are either electric or non-motorized vehicles, these models offer a cleaner and more space-efficient alternative to traditional van-based deliveries (Lebeau et al., 2023; Kuzia, 2024). Conventional freight approaches, often car-oriented, contribute to congestion, encourage continued investment in motorized infrastructure, and undermine efforts toward more pedestrian-friendly, proximity-based urbanism and livable cities (Bibri et al., 2020; Gehl, 2010; Rodrigue et al., 2017).

Cargo bikes are now more widely available in Europe (Schorung et al., 2023b) and are particularly well-suited for navigating narrow streets, pedestrianized zones, and other areas where motorized vehicles face access restrictions (Paudel & Yap, 2024). However, cargo bikes have limited capacity and range, which can make them less effective without a supporting network of urban logistics hubs, such as micro- and nano-hubs (ITF, 2024a). These hubs support bridging the gap between larger transport networks and localized transference, reducing van travel and supporting mode shifts (Kania et al., 2022). Consolidating freight at smaller hubs located closer to consumers can improve the efficiency of last-mile deliveries (Lebeau et al., 2023), particularly when combined with the environmental and social benefits of cargo bikes (Cowie & Fisken, 2023).

Nano-hubs are small-scale facilities located near consumers that enable efficient last-mile deliveries via cargo bikes. Their size and potential for mobility and shared use make them especially adaptable to evolving urban conditions. Additionally, they can promote horizontal collaboration among logistics stakeholders, increasing efficiency and flexibility (Hribernik et al., 2020).

Despite their advantages, identifying suitable locations for logistics hubs remains a challenge, as urban areas grow denser and competition for space intensifies. While these hubs can contribute to a more efficient use of urban space by optimizing the movement of goods (Andruetto et al., 2024), their successful implementation and long-term sustainability depend on balancing economic, environmental, and social factors, especially in the context of cycle logistics (Breen et al., 2023).

In Brussels, the integration of cycle logistics with a network of nano-hubs is underway, marking a significant step toward sustainable urban freight solutions. Yet, this transition brings its own set of challenges. **One of the most pressing issues is the use of public space for business purposes**, raising concerns about fairness and impacts on livability. Another key difficulty lies in the **absence of a clear framework to get local support and inform stakeholders to get these small hubs installed**. Moreover, **ensuring consistent utilization of these facilities is essential to justifying the space they occupy in city centers**. Addressing these concerns requires a holistic planning approach that goes beyond logistical efficiency to incorporate societal and environmental impacts of shifting to more sustainable modes of transport (Assmann et al., 2019; Cowie & Fisken, 2023). According to Bjørgen and collaborators, there is a gap in the literature and practice where most studies prioritize the technical and economic aspects of urban logistics while overlooking the environmental and societal impacts on urban fabric, public space, and local communities (Bjørgen et al., 2019).

To address tensions between implementing freight infrastructure and the use of public space, the concept of **Sleeping Assets** becomes particularly relevant. These are underused or inactive infrastructure or urban elements that can be repurposed to host sustainable logistics solutions (Schachenhofer et al., 2023). In this context, **sleeping assets offer a less intrusive alternative for integrating nano-hubs into the urban fabric and can help align sustainable logistics goals with broader urban livability strategies**.

Building on these perspectives and grounded in the reality of Brussels, this research intends to advance the understanding of how small hubs, when aligned with cargo bikes, can support balancing efficiency for last-mile delivery with environmental and societal goals of logistics, focusing on public space usage and the integration of nano-hubs in dense urban areas, ultimately supporting the transition to more livable and sustainable cities. The relevance of this research lies in its potential to address challenges in urban logistics created by e-commerce growth and increasing delivery demands. It also aims to promote a shift toward more sustainable transportation modes by accelerating the adoption of cargo bikes. The findings can support the development of local policies by informing strategies that respond to social concerns, emerging environmental regulations, and the evolving dynamics of a city like Brussels that is in constant adaptation.

The hypothesis is that nano-hubs can offer a sustainable and adaptable solution to the challenges of last-mile logistics. In doing so, they have the potential to support urban planning goals while positively influencing the environmental and social dynamics of the city they serve.

This first chapter (**Chapter 1 – Introduction**) presents the research problem, focusing on the role of small-scale logistics hubs in supporting sustainable last-mile deliveries. It outlines the growing relevance of cycle logistics in response to e-commerce-driven delivery demands, environmental regulations, and urban space constraints, and highlights the potential of nano-hubs as an adaptable solution that can help reconcile efficiency goals with broader societal and environmental objectives.

In light of these developments, this master's thesis addresses the following main question: **How can nano-hubs be integrated into Brussels' cycle logistics system to balance space demands with the goals of sustainable last-mile delivery?**

This main question is explored through three analytical dimensions:

- **Context and Barriers:** What challenges and opportunities influence the integration of nano-hubs into Brussels' dense urban fabric, particularly regarding competing space uses, planning, and regulations?
- **Spatial Suitability:** Which locations in Brussels are most suitable for nano-hubs, considering the policy context, ongoing initiatives, and the need to balance operational efficiency with urban livability?
- **Strategic Implementation:** What strategies can support the integration of nano-hubs in Brussels to ensure they are context-sensitive and aligned with long-term, sustainable urban logistics goals?

To answer the research question and subquestions, the study is structured as follows:

Chapter 2 – Theoretical Foundation: Review of relevant literature on city logistics, last-mile delivery, and the emerging role of micro- and nano-hubs in supporting sustainable urban logistics. It also discusses cargo bike potential, spatial constraints, and emerging infrastructure needs.

Chapter 3 – Framing the Context: Case Study Brussels-Capital Region (BCR): Contextualizes the research within the Brussels-Capital Region. It explores the goals of the Good Move plan, the Shifting Economy strategy, and other ongoing initiatives shaping the evolution of cycle logistics in Brussels.

Chapter 4 – Research Design: It presents the mixed-methods approach combining qualitative data from literature, stakeholder interviews, and policy documents with spatial data processed through a context-sensitive GIS-based Multi-Criteria Decision Analysis (MCDA) framework.

Chapter 5 – Results and Analysis on Integrating Nano-hubs into Brussels: Presents how qualitative insights informed the spatial criteria and reports the outputs from each GIS-MCDA stage.

Chapter 6 – Discussion: Interprets spatial analysis findings for sustainable nano-hub integration in Brussels, discusses implications and limitations, and outlines future research.

Chapter 7 – Conclusion: Highlights the adaptable GIS-MCDA framework, key strategies for nano-hub integration in Brussels, and the broader role of nano-hubs in advancing sustainable, livable cities.

2. Theoretical Foundation

2.1. City logistics and the last mile

City logistics refers to strategies for managing the movement of goods in urban areas to improve efficiency and minimize negative impacts such as congestion and emissions (Özbekler & Karaman Akgül, 2020; Comi et al., 2024). Nevertheless, the rapid growth of urban logistics, driven by rising delivery demands, is intensifying these challenges. Although freight transport represents only 10–15% of vehicle kilometers in cities, it accounts for 25% of CO_2 emissions, 30% of NOx, 50% of fine particulate matter, and 40% of noise pollution (Lebeau & Macharis, 2016). In Belgium, this expansion is evident: postal and parcel deliveries have increased fivefold in the last decade, reaching 365 million shipments in 2021 (BCLF, 2023).

Urban planning is increasingly moving away from car dependency toward more livable, pedestrian-friendly environments (Gehl, 2010). In city centers, this shift supports compact, high-density design with mixed uses and improved accessibility by walking, cycling, and public transport (Rodrigue et al., 2017; Bibri et al., 2020; Moreno, 2024).

However, logistics systems have not kept pace with these transformations. They remain largely aligned with car-oriented infrastructure, operating in a competitive market shaped by rising e-commerce and delivery volumes (Assmann et al., 2019). Yet logistics, like cities, are not static. It constantly demands adjustments and flexible responses, matching the transition towards green deliveries and shifting to solutions more compatible with the contemporary urban model (Comi et al., 2024). A key challenge, however, is managing growing freight demand while preserving urban quality of life (Maes, 2017).

The use of cargo bikes holds significant potential in Belgian cities. Up to 25% of urban goods transport and 50% of service-related trips could be shifted to bicycles (Wrighton & Reiter, 2016). When considering professional transport as a whole (freight, delivery, services, and business trips), at least 33% of motorized trips could be shifted to carrier cycles. This figure could be even higher, as it only accounts for goods under 200 kg and trips of 7 km or less (BCLF, 2023). According to Macharis (2023), cargo bikes could handle up to 50% of goods delivered to cities.

Realizing this potential requires supportive conditions. Advances in cargo bike and container design, consolidation strategies to shorten delivery distances, and enabling regulations could significantly accelerate the shift toward cycle logistics (BCLF, 2023). More specifically, in the Brussels-Capital Region, freight transport covers an estimated distance of 1.6 million kilometers per week, driven primarily by small retail (26%), followed by warehouses and transportation (20%), wholesale trade (19%), and crafts and services (16%) (urbike SC, 2023).

The growing need for cycle logistics is further reinforced by changes triggered by the COVID-19 pandemic. Changes in consumer behavior, public policy, and commercial activity have accelerated the push to bring supply chains closer to end consumers (Buldeo Rai et al., 2022). As a result, there is an increasing need for last-mile logistics solutions that are better aligned with urban conditions, including compact storage facilities dedicated to supporting these last-mile operations (BNP Paribas Real Estate, 2022). The rise of these specialized facilities reflects the operational and spatial demands of online shopping, which has intensified pressure on urban logistics infrastructure (Rodrigue, 2020). Their location, size, delivery radius, and staffing requirements vary depending on factors such as urban form, e-commerce penetration, and delivery strategies adopted by service providers (Schorung et al., 2023b).

Within this evolving landscape, cargo bikes have emerged as a key component of last-mile solutions, particularly when combined with new infrastructure typologies suited to dense city environments. A recent trend in urban delivery is the increasing use of cycles alongside the implementation of small-scale facilities (Mohamed et al., 2023). These cycles can take the form of a bi-, tri-, or quadricycle. According to European standards (CEN/TC 333/WG 9), the term "carrier cycles" is used as a generic classification. In this master's thesis, however, the term "cargo bike" will be used instead, as it is more widely recognized and commonly understood (BCLF, 2023).

Cargo bikes (Figure 1) are bicycles equipped with containers for transporting freight (Assmann, Müller, et al., 2020). They can transport loads ranging from 40 to 250 kilograms, including both goods and passengers, and can operate legally as bicycles if they comply with weight and size regulations (Macharis, 2023). Most are limited to a motor power of 250 watts, with electronic assistance that disengages above 25 km/h, ensuring the safety of both riders and pedestrians (Assmann, Müller, et al., 2020; Macharis, 2023).

As cities face increasing pressures from climate change and urbanization, the need for sustainable transport solutions in urban logistics is becoming more urgent. Cargo bikes offer a viable alternative for last-mile deliveries, particularly when integrated with transshipment hubs (Assmann, Lang, et al., 2020). This shift reflects a growing emphasis on sustainability and livability[1] in city logistics strategies.

Traditional last-mile methods—that typically involve van-based deliveries, car-oriented infrastructure, and centralized distribution centers—are becoming incompatible with contemporary urban planning goals. These approaches contribute to congestion, pollution, and inefficient land use. In contrast, cycle logistics shifts to cargo bikes, smaller logistics facilities, and decentralized

[1] Livability is the degree to which a place is suitable or good for living in (Cambridge Dictionary, 2025).

distribution points to enable more flexible, low-impact freight systems tailored to dense urban environments (Schrader et al., 2024).

Cargo Bike: 2 wheels	
Long John Payload: max. 130kg Volume: 65x60x80cm Width: approx. 60cm	
Rear loader Payload: max. 300kg Volume: 150x100x120cm Width: approx. 100cm	

Figure 1. Examples of current cargo bike models being used in Brussels by BCLF partners.
Source: Photos by the author and written content based on Assmann, Müller, et al., 2020.

The potential of cargo bikes to reduce greenhouse gas (GHG) emissions makes them a compelling alternative to traditional delivery vans. However, their effectiveness depends on the presence of appropriate infrastructure, particularly strategically located hubs (Andruetto et al., 2024). Despite their growing relevance, there remains a lack of clear guidelines for the planning and siting of such facilities, which limits the integration of cargo bikes into urban logistics systems (Assmann, Lang, et al., 2020).

To maximize the adaptability and sustainability of cycle logistics, a supporting network of small hubs is essential. Lebeau et al. (2023) highlight that both the environmental performance of cargo bikes and the benefits of freight consolidation can be maximized through the development of well-placed, high-quality infrastructure. To achieve this potential, further research is needed to guide municipalities in planning these hubs and building the logistics ecosystems required to scale cycle-based deliveries.

2.2. Reframing urban logistics for sustainability

The future success of markets will increasingly depend on how well companies and entire value chains balance profitability with growing environmental and social responsibilities. This shift requires embracing the concept of the **Triple Bottom Line** (Elkington, 1997), which advocates that operations should aim to be increasingly conscious of their responsibility and contribution to economic, environmental, and social aspects. As Mommens and Macharis (2023) explain, sustainability extends beyond climate change mitigation and includes the planet (the physical/natural environment), people (social well-being), and profit (economic viability).

In the context of urban logistics, Cowie and Fisken (2023) argue that the full adoption of the Triple Bottom Line and a strong commitment to providing a more environmentally sustainable solution for the last mile are key factors for its successful establishment and operation (Cowie & Fisken, 2023).

A practical starting point for advancing sustainability in the last mile is raising awareness about the external costs of transport, a way of placing a monetary value on the cost of transport to society (Macharis, 2023). These externalities, such as air pollution, noise, and road congestion, represent the gap between private costs (incurred by users) and social costs (borne by society as a whole). Since market mechanisms do not naturally encourage individuals to consider these broader effects, transport decisions often fail to account for the full societal impact, leading to inefficiencies and negative consequences (Schroten & de Bruyn, 2019).

A 2017 study by Jochen Maes quantified these externalities in Belgium by comparing the costs of cycling and light commercial vehicles (LCVs) per vehicle-kilometer in urban freight transport. The results demonstrate that cargo bikes are significantly more sustainable, with nearly zero external costs in most categories: congestion, emissions, climate change, noise, and infrastructure wear. In contrast, LCVs impose significant costs in all of these categories, with total externalities amounting to approximately 1.45 EURct per vehicle-kilometer, compared to just 0.09 EURct for cargo bikes. The only cost category where cycling presents higher external costs than LCVs is in accidents (0.09 vs.

0.003 EURct/vkm), likely due to the greater vulnerability of cyclists (Maes, 2017). Regarding these results and according to the cAIRgo bike project in Brussels, Maes's research revealed that every kilometer traveled by LCVs imposes 94% higher costs on civil society and public agencies than the same distance covered by cargo bikes (urbike SC, 2023).

The lower external costs of cargo bike deliveries not only show their environmental and economic advantages but also reflect the growing relevance of cycle-based freight systems in cities. This brings attention to the broader concept of **cycle logistics**, which is increasingly recognized as a sustainable alternative to conventional motorized transport (Cowie & Fisken, 2023).

The European Cycling Federation (ECF) defines cycle logistics as the transportation of any kind of goods between locations using bicycles, helping decrease the number of unnecessary motor vehicles on the roads (ECF, 2016). This includes logistics companies offering delivery services, as well as retailers, service providers, and manufacturers that rely on bicycles for transporting goods. The European Cycle Logistics Federation (ECLF) expands this definition to include municipal services using bicycles, for example, in street cleaning or park maintenance (BCLF, 2023).

In Belgium, a definition according to BCLF includes "*all activities and services associated with the processing of goods flows with cycles. Intuitively, it majority includes transportation and distribution of goods in a private or professional context*" (BCLF, 2023, p. 11). According to the BCLF, cycle logistics offers significant environmental, social, and economic advantages. Environmentally, it reduces greenhouse gas emissions, fine particulate pollution, and noise. Socially, it promotes fair and secure working conditions for couriers, improves job quality, and supports a more equitable labor market. Economically, it stimulates local employment, supports small businesses, and reduces public costs related to congestion, accidents, and health impacts (BCLF, 2024b).

To fully realize these benefits, cycle logistics infrastructure must be designed and located with a strong focus on livability. Adopting a more people-oriented perspective in logistics can help align financial objectives with environmental and social goals, thereby ensuring long-term sustainability and effectiveness (Cowie & Fisken, 2023).

Assman and collaborators (2019) argue for the need for a holistic planning approach that connects urban logistics with urban planning to integrate cargo bikes into the urban fabric. Their research identifies a gap in the literature regarding planning applied to transshipment in the last mile. According to the authors, most of the literature available does not consider the social aspects of urban quality, livability, and effects on public space. To address this, the authors emphasize incorporating the perspectives of both citizens and infrastructure users during the planning phase. This approach can enhance the usability and social acceptance of logistics hubs, supporting a stronger connection between these facilities and their urban surroundings. They propose reimagining hubs not only as functional logistics points but also as social spaces (Assmann et al., 2019). For the authors, key planning elements include:

(i) design strategies with a communication-friendly approach, incorporating features like an open building design with an area serving as a stopover for cargo bikes; and

(ii) enhanced functionalities, expanding functions to include new services such as parcel counter services, cargo bike garages, cafes, or rental stations for cargo bikes.

Yet, as Buldeo Rai (2024) notes, little research has explored how citizen participation intersects with urban logistics or which practices could improve public understanding of the sector, its functioning, and possible alternatives. Reframing urban logistics as an essential urban service, rather than an industrial activity that threatens livability, is important to ensuring it is supported and developed to serve city life in the best possible way (Buldeo Rai, 2024).

Complementing this spatial and social perspective, Cowie and Fisken (2023) present a comparative analysis of diesel vans, electric vans, and cargo bikes in terms of their social and environmental sustainability (Table 1), using a scale from negative (-) to neutral (0) and positive (+). The results emphasize the advantages of cargo bikes, which outperform the other modes across all indicators. Diesel vans consistently score negatively due to their significant contributions to traffic congestion, greenhouse gas emissions, and noise pollution. Electric vans show environmental improvements, particularly in reducing pollutants, CO_2, and noise, but remain neutral in social areas such as vehicle and accident reduction[2], livability, and public space use. This suggests that while electrification is a step forward, it is not a comprehensive solution for urban logistics. In contrast, cargo bikes receive positive scores across all categories. Their benefits to social and environmental goals highlight cargo bikes' transformative potential in creating more sustainable and resilient freight systems (Cowie & Fisken, 2023).

Table 1. Sustainability impact vs. mode of transport. Source: Adapted from Cowie & Fisken (2023).

Sustainability impact / mode of transport	Social sustainability goals				Environmental sustainability goals			
	Reduction of accidents	Reduction of vehicles	Livability	Use of public space	Reduction of pollutants	Reductions of CO_2 emissions	Reduction of noise	Conservation of energy
Diesel vans	-	-	-	-	-	-	-	-
Electric vans	0	0	0	0	+	+	+	-
Cargo bikes	+	+	+	+	+	+	+	+

[2] For the author of this master's thesis, electric vans do indeed have negative impacts on public space and the livability of cities, as they occupy a considerable portion of public space that could otherwise be used to improve walkability and cycling and create a more people-centered urban environment. The reduction in the number of motorized vehicles in circulation would allow increasing green areas for the configuration of social spaces (for social interaction/meetings) or the development of street/local commerce, among many other possible uses.

While cargo bikes demonstrate strong sustainability benefits, their implementation still faces important technical and operational challenges. A key barrier is the shortage of suitable urban space and the difficulty of visually integrating hubs into the existing urban landscape, which can complicate large-scale implementation (Kania et al., 2022). Cowie and Fisken (2023) point out two additional constraints: payload limitations and the need for well-placed logistical hubs. Although heavier loads can be transported, exceeding optimal weight reduces maneuverability and speed, limiting the bike's efficiency for certain deliveries, like hill starts on challenging surfaces (e.g., cobblestones), making them particularly difficult. To address the limited range of cargo bikes, the authors emphasize the importance of small hubs, located near final delivery points, to allow shorter delivery distances and improve efficiency (Cowie & Fisken, 2023). This is particularly relevant for the last mile, which remains the most costly and resource-intensive segment of urban logistics (Janinhoff et al., 2024).

2.3. Nano-hubs for last-mile delivery

Small-scale logistics hubs are increasingly recognized as key components of sustainable logistics strategies (Kania et al., 2022). Rather than replacing large distribution centers, their role is to refine and support a multi-scale logistics system, following a continuum approach that enhances the structure of urban freight operations (Schorung et al., 2023a). Strategically positioned closer to end-consumers, these hubs support the transfer of goods from conventional carrier vehicles, such as trucks and light commercial vehicles (LCVs), to more sustainable transport options like cargo bikes (Andruetto et al., 2024). By reducing the presence of commercial vehicle movements, small-scale hubs also have the potential to minimize traffic congestion and improve the efficiency of last-mile distribution (Hribernik et al., 2020).

The literature refers to small-scale logistics facilities using a variety of terms, reflecting the diversity of models and functions they encompass. These include *microhubs* (Hribernik et al., 2020; Katsela et al., 2022; Schrader et al., 2024), *micro-distribution hubs* (Locus, 2024), *micro-fulfillment centers* (Karaoulanis, 2024), *micro-consolidation centers* (MCC) (Assmann, Müller, et al., 2020), *cycle courier transshipment hubs* (Brussels Mobility, 2024b), or *nano-hubs* (Kania et al., 2022). In this study, the term "nano-hub" is used to emphasize the smaller scale and the specific function of the logistics spaces under analysis. While "microhub" is often used to describe a broad range of urban transshipment facilities, the concept of the nano-hub highlights more compact infrastructures dedicated to cargo bike logistics. Moreover, this terminology aligns with the nomenclature adopted in the Brussels case study. Ultimately, the purpose of these small-scale hubs remains consistent: to improve the efficiency of last-mile delivery services with cargo bikes, reduce urban congestion, and contribute to more sustainable freight transport systems.

Typically, nano-hubs consist of a compact facility and a designated loading area adapted for cargo-bike swap bodies, with spatial requirements varying depending on the number of operators and local conditions (depending on the number of hubs, 1-3 parking spaces) (Kania et al., 2022). Importantly, these nano-hubs can be shared. Mohamed and collaborators (2023) emphasize the value of shared logistic facilities, which can avoid complex cost-sharing mechanisms. Shared nano-hubs can also be a tool to facilitate multiple operators to collaborate (ITF, 2024b), as they can be used by one or more businesses, allowing for stakeholder cooperation and shared resources among different users. One practical model is the implementation of a two-stage delivery system, where nano-hubs act as centralized transfer points within the city. In this setup, multiple carriers work together, pooling their resources and efforts to achieve shared logistics and transportation goals. This collaboration includes the physical transfer of shipments between partners and the joint use of both tangible and intangible resources, such as logistics facilities, vehicles, information systems, and strategies for planning and optimization (Hribernik et al., 2020).

Certain nano-hubs are fully operational and permanent projects, while others are either short-term experiments or temporary (a hub that addresses short-term logistical needs in local areas, such as construction projects that require the establishment of a temporary consolidation hub for materials and supplies during the construction period, or specific events that require temporary logistical support) (Anciaes & Jones, 2023; Patier & Abdelhai, 2023).

Requiring fewer investments in infrastructure, nano-hubs can operate from a building or be based on a mobile infrastructure (Patier & Abdelhai, 2023). Their compact physical footprint makes them particularly well-suited to dense urban environments where space is limited. Cowie and Fisken (2023) describe them as central nodes for efficient sorting and distribution in the parcel's last mile (Cowie & Fisken, 2023). At these transfer points, goods are moved from larger freight vehicles to smaller, low-emission modes such as cargo bikes, enabling cleaner and more efficient last-mile delivery within dense urban areas (see Figure 2).

Building on this understanding, this master's thesis adopts the term **nano-hub** to describe small-scale facilities located closer to final delivery destinations—one to five kilometers away (Locus, 2024). These hubs are typically mobile pilots that can be flexibly installed or relocated within dense urban areas and are designed to occupy approximately one to three parking spaces. Functioning as local delivery points, the **last-mile deliveries from the nano-hub to the final destination are made by cargo bike, while parcels arrive at the nano-hub by truck or van**. In the Brussels Capital Region, these nano-hubs act as intermediary nodes connecting regional hubs or larger company warehouses to final delivery zones (Sarrazin, 2024). They are also planned to be shared hubs, based on the principle of horizontal collaboration between logistics operators to promote more efficient and sustainable distribution practices (see Figure 3).

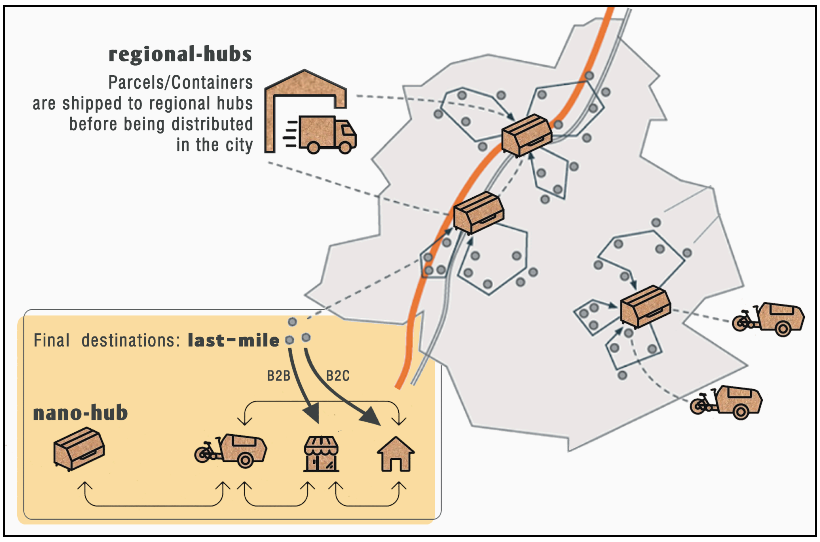


Figure 2. From regional hubs to nano-hub distribution and final destinations.
Source: adapted by the author based on Sarrazin, 2024; OVO, 2025.

Figure 3. Type of nano-hub being implemented in Brussels.
Source: Sarrazin, 2024.

To help integrate nano-hubs into the city without adding pressure on public space, this thesis draws on the concept of **sleeping assets—underused urban infrastructures that hold potential for alternative functions**. As highlighted by de Schachenhofer and collaborators (2023), reactivating these spaces offers an opportunity to overcome key implementation barriers for infrastructure in sustainable last-mile logistics by making use of existing assets rather than claiming new public space. In this context, sleeping assets provide a less intrusive and more adaptive strategy for integrating nano-hubs in dense urban areas, aligning with the need for flexibility and public acceptance in early-stage logistics initiatives.

2.4. Reactivating underused infrastructure for sustainable delivery systems

To enhance sustainability in last-mile logistics, Schachenhofer and collaborators (2023) introduce the concept of sleeping assets, underused urban infrastructures that hold potential for alternative uses. This concept responds to the growing need for innovative and resource-efficient solutions in increasingly congested and space-constrained urban environments. By identifying and reactivating these assets, cities can help reduce pressure on public space usage while supporting more sustainable logistics operations. Table 2 presents an overview of sleeping asset categories, detailing their characteristics, examples, possible benefits for urban logistics, and the challenges associated with their implementation. Schachenhofer et al. (2023) recommend that municipalities consider these underused resources when developing logistics strategies.

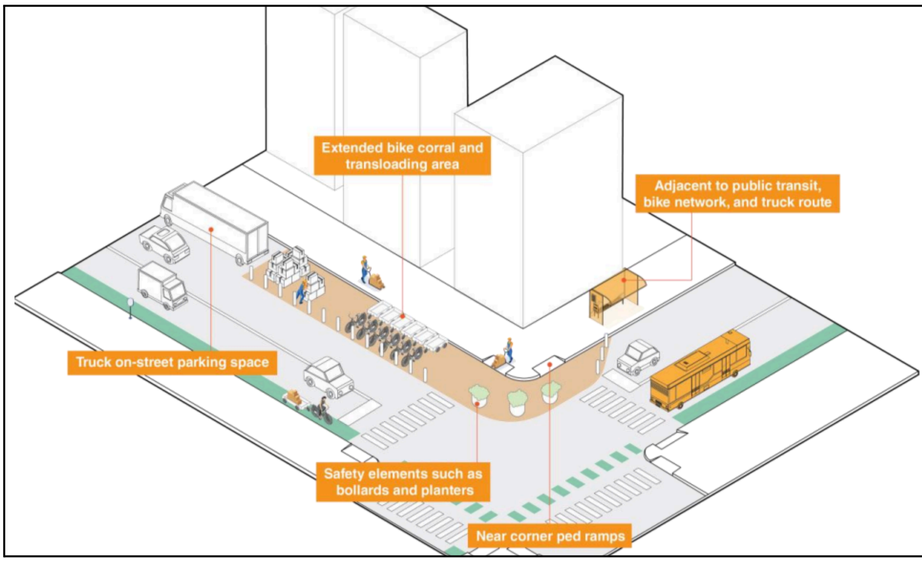
Table 2. Description of the three main categories of sleeping assets.
Source: Adapted from Schachenhofer et al., 2023.

Category	Description	Examples	Potential Benefit	Implementation Challenges
Neglected routes	Existing paths, tracks, and lanes that are currently underused	- Underutilized waterways (rivers, canals) - Railways and tram tracks - Bus lanes	- Reduced traffic congestion - Decreased air pollution - Supplemented transport capacities - Potential GHG emission reduction	- Infrastructural barriers - Higher initial costs (e.g., for electric boats) - Need for integration with last-mile solutions
Idle real estate	Urban spaces and buildings that are vacant or not fully utilized	- Empty or partially occupied buildings - Underused parking garages and areas - Residual area in cities	- Addresses logistics sprawl - Enables small-scale logistics facilities closer to customers - Reduces travel distances for freight vehicles	- High urban real estate prices - Challenges in finding suitable spaces - Potential conflicts with existing urban planning
Underused resources	Transportation vehicles and infrastructure with excess capacity	- Passenger vehicles with empty seats - Freight vehicles with unused cargo space - Transportation infrastructure during off-peak hours	- Improved efficiency of existing resources - Reduced need for additional vehicles - Potential for innovative last-mile solutions	- Coordination between different users - Technological integration challenges - Potential regulatory barriers

In this master's thesis, the focus is on one specific category: *idle real estate*, also referred to as *residual areas*[3]. This includes vacant buildings, underused spaces within occupied structures, parking zones, and areas with temporal availability—such as those unused during specific times of the day or week. Repurposing such spaces for nano-hubs not only meets the spatial needs of cargo bike operations but also creates opportunities to support urban livability through multifunctional, community-integrated logistics infrastructure.

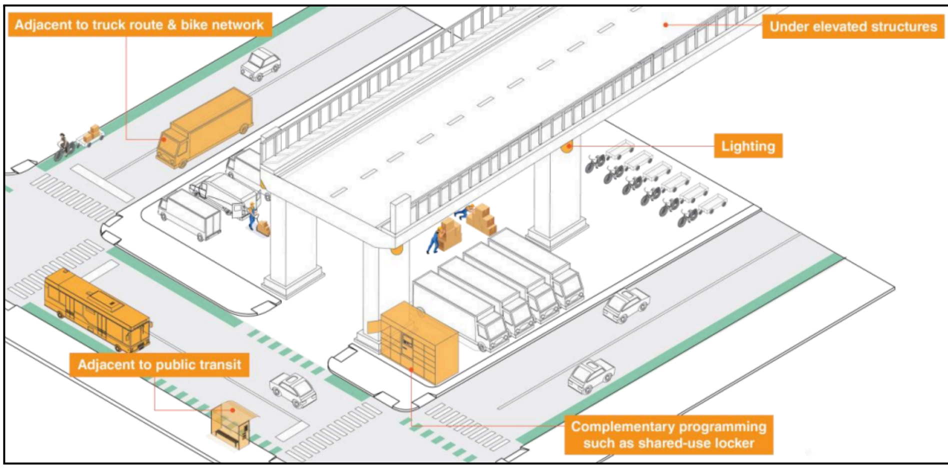
[3] Refers to urban spaces and buildings that are vacant or not fully utilized. An example of a residual area can be seen in Figure 5.

In New York City, the Department of Transportation (NYC DOT) has launched a three-year pilot program repurposing *sleeping assets* into microhubs to address growing urban freight demands. This initiative is part of a broader strategy to reduce reliance on large delivery trucks by shifting to smaller, electric-powered vehicles and cargo bikes (NYC DOT, 2024d). The program features two hub typologies: **on-street microhubs**, compact curbside zones with transloading areas and safety barriers (Figure 4); and **off-street microhubs**, larger facilities located under elevated structures (Figure 5). On-street microhubs are approximately 24–30 meters in length and include regulatory signage and markings to support efficient transloading operations. Off-street hubs, located on city-owned land, vary in size and may include additional facilities such as storage, vehicle maintenance, charging stations, and weather protection (NYC DOT, 2024d).



On-Street Hub Features:
- 80-100 feet in length
- Regulatory signage and/or other markings designating it as a microhub
- Transloading space for package sorting and transfer to electric vehicles, bikes, and walkers
- (Cargo) bike corrals
- Upgraded safety barriers (flexible delineators, bollards, armadillos, planters, etc.)

Figure 4. New York City on-street microhub zones.
Source: NYC DOT, 2023.



Off-Street Hub Features:
- Variation in size based on site location
- Vehicle and goods storage
- Vehicle repair/maintenance
- Transloading space for package sorting and transfer to electric vehicles, bikes, and walkers
- Weather protection and lighting
- Opportunities for additional amenities and programming

Figure 5. New York City off-street microhub zones.
Source: NYC DOT, 2023.

This initiative responds to the surge in e-commerce and the corresponding increase in residential deliveries, up from 40% to 80% since the COVID-19 pandemic. By concentrating truck deliveries at these microhubs, the city aims to minimize the circulation of large trucks on local streets, reducing congestion and the incidence of double-parking, which often obstructs bike lanes and poses hazards to cyclists and pedestrians. Additionally, these microhubs target contributing to the city's sustainability goals by lowering greenhouse gas emissions and improving air quality (Brendlen, 2024).

To guide implementation, the pilot program initially focused on studying critical aspects such as siting criteria, infrastructure, safety measures, utilization patterns, and enforceability (Figure 6). Engaging with stakeholders is emphasized to refine locations, design equitable outcomes, and foster the adoption of sustainable and safe logistics practices (NYC DOT, 2023).

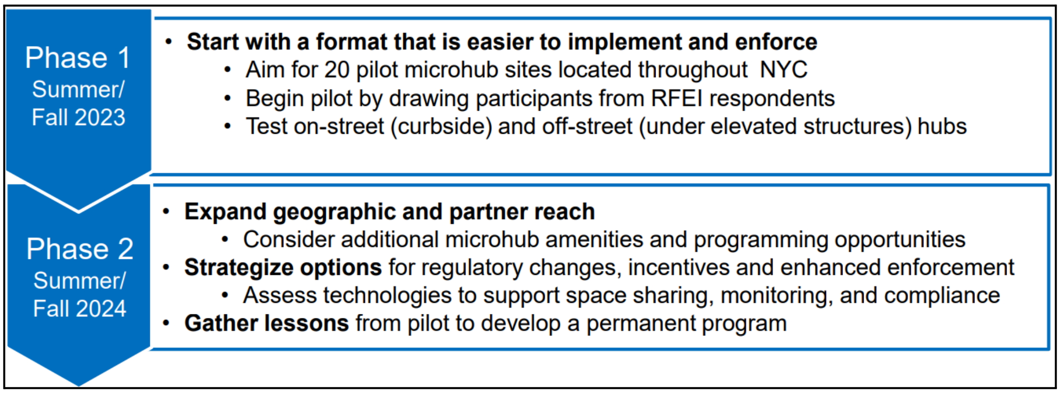


Figure 6. NYC DOT Pilot Framework and Phasing.
Source: NYC DOT, 2023.

Participating companies, selected through a Request for Expressions of Interest (RFEI), act as **microhub operators** and are managed by a license agreement. They are responsible for being in charge of last-mile transfers from commercial vehicles to sustainable modes, such as cargo bikes or electric carts. Operators must obtain annual permits from NYC DOT, maintain clean and safe microhub zones, and provide usage data and feedback to support program evaluation. Non-compliance may result in permit suspension or revocation, ensuring accountability and performance throughout the pilot (NYC DOT, 2024d).

Site selection for the pilot was informed by geographic analysis, land-use patterns, and stakeholder input. Criteria prioritized locations with high-density, mixed-use environments, particularly areas where commercial or manufacturing uses intersect with residential neighborhoods. Additional factors included proximity to truck routes, transit connections, and bike lane infrastructure, as well as alignment with *Priority Investment Areas* identified in the NYC Streets Plan.

These locations were required to accommodate truck parking, safe transloading zones, and infrastructure that supports efficient and secure operations (NYC DOT, 2023).

As part of the operating agreements, participating companies are required to use sustainable transport modes and comply with safety and data-sharing protocols. NYC DOT collects data from each microhub regularly to monitor performance and assess the pilot's success. Key indicators include the type of sustainable vehicles used, average daily and weekly usage rates, and the number of deliveries completed from each hub, disaggregated by type of transport mode (NYC DOT, 2023).

The pilot launched with up to 20 proposed sites across the city, combining both on-street and off-street typologies. Initial locations included the Upper West Side in Manhattan (on-street), Greenpoint in Brooklyn (off-street), and Clinton Hill in Brooklyn (off-street) (Figures 7, 8, and 9). By the end of 2024, these sites will be under review and open to feedback from local stakeholders and community groups to ensure that implementation responds to neighborhood needs and concerns.

Figure 7. Upper West Side location for on-street microhub.
Source: NYC DOT, 2024a.

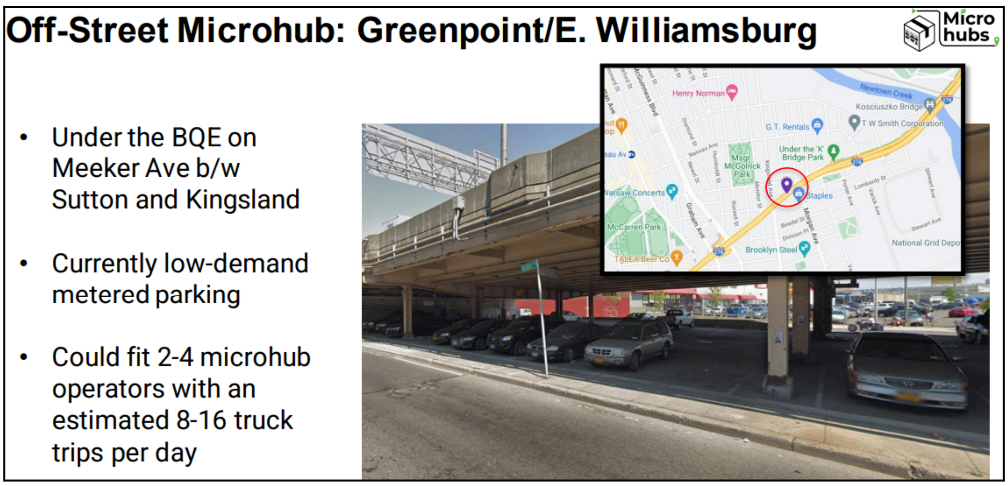


Figure 8. Greenpoint location for off-street microhub.
Source: NYC DOT, 2024c.

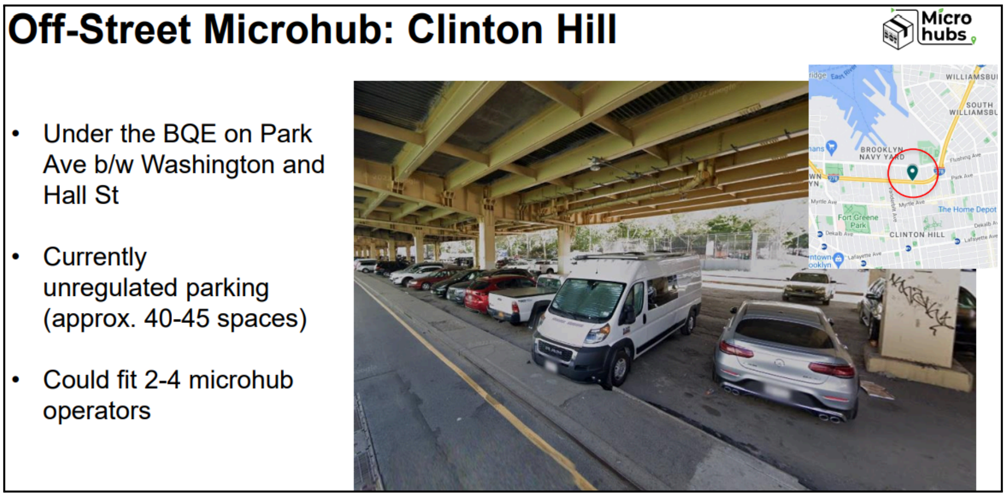


Figure 9. Clinton location for off-street microhub.
Source: NYC DOT, 2024b.

The pilot is grounded in Local Law 166 (2021), which mandates the creation of micro-distribution centers to promote environmentally friendly delivery methods across New York City. The legislation, which came into effect in December 2021, required NYC DOT to launch a pilot program (Figure 10) for micro-distribution centers by July 2023 and to publish a report on its findings by the end of 2022. (NYC DOT, 2023). Furthermore, the NYC DOT has proposed amendments to Section 4-08 of the Traffic Rules[4] to establish and implement permits for the use of microhubs (NYC DOT, 2024e). These regulatory changes aim to address operational barriers such as space constraints, access to amenities like charging stations and restrooms, and rules governing cargo bike use. Public engagement has been a key component of the pilot's implementation strategy. A public hearing held in October 2024 provided an opportunity for community members and local stakeholders to voice concerns and contribute to shaping an equitable and inclusive integration of microhubs across neighborhoods (NYC DOT, 2024e). The program remains ongoing and is being implemented through a multi-stakeholder partnership structure (Figure 11).

[4] In New York City, agencies can make changes or additions to the city rules that are an important part of how government interacts with the public. New Yorkers can review proposed rules and voice their opinions about those rules before they are adopted into law (NYC DOT, 2024d).

Pilot Schedule

Spring/ Summer 2023	**Finalize Design & Implementation Plan for Pilot Phase 1** • Finalize agreement terms, permit rulemaking, site selection, and design of microhubs. Share information with stakeholders and potential partners through outreach campaign such as briefings, digital outreach and in-person engagement
Summer/Fall 2023 – 2024	**Launch Pilot Phase 1** • Install sites and gather feedback on initial pilot implementation • Implement data collection and monitoring of microhub operations • Refine strategies for equitable implementation and enforcement • Finalize design & implementation plan for Phase 2 based on lessons learned • Engage public on pilot expansion through outreach campaign
Fall 2024 – 2026	**Launch Pilot Phase 2** • Add new participants and locations based on demand and need • Explore new technology and amenity options • Gather data on effectiveness of pilot program
Fall 2026	**Report Pilot Outcomes and Recommendations** • Evaluate permanent program feasibility, structure, and goals

Figure 10. NYC DOT Pilot Schedule.
Source: NYC DOT, 2023.

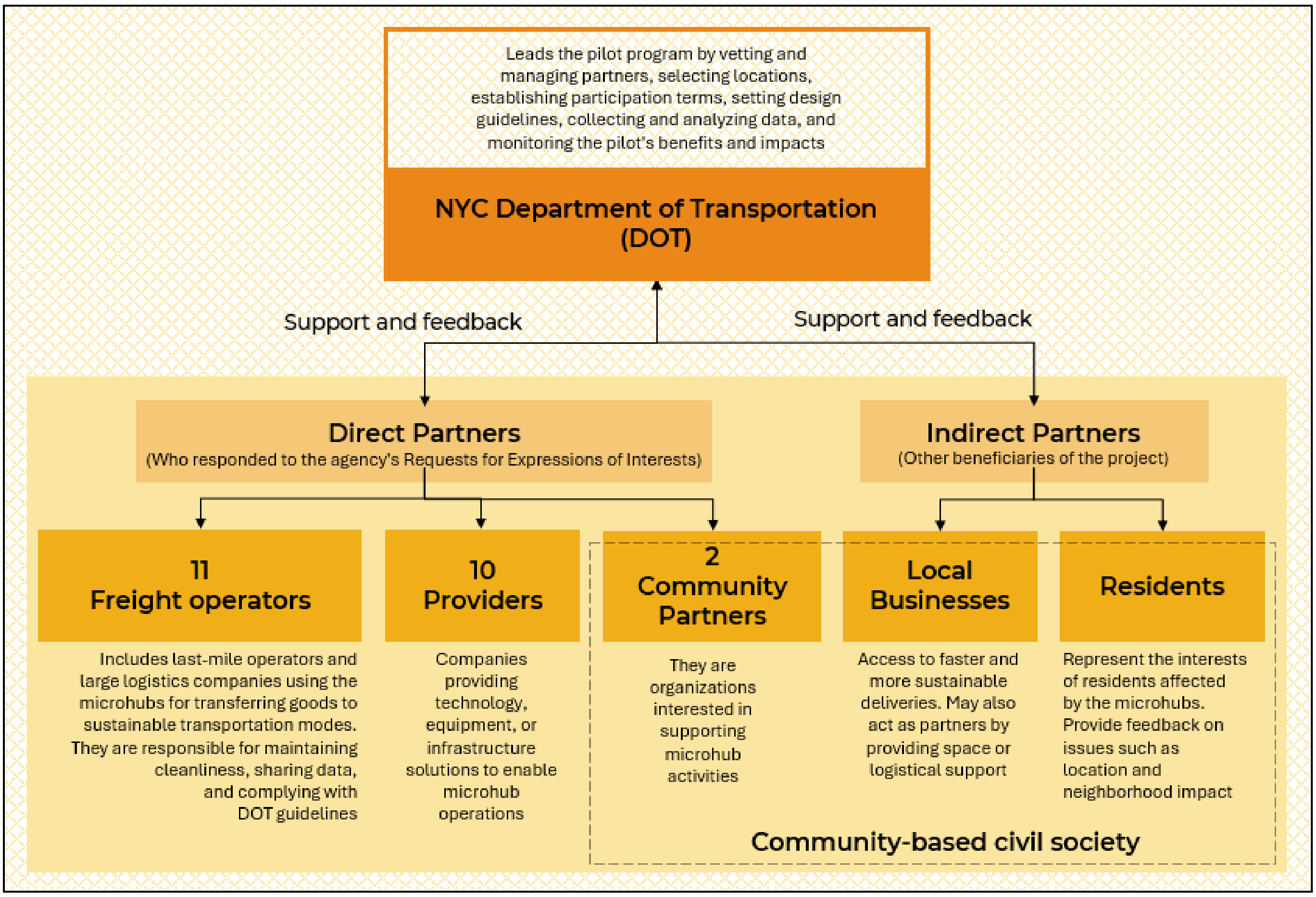


Figure 11. Stakeholder map of NYC microhub structure.
Source: by the author, inspired by NYC DOT, 2023.

3. Framing the Context: Case Study Brussels-Capital Region (BCR)

This section presents the current state of play of urban mobility and logistics in the case study Brussels-Capital Region, focusing on policies and ongoing initiatives supporting sustainable mobility and last-mile delivery improvements.

Among Belgium's three regions, BCR is the smallest in land area, covering just 162 km², yet the most urbanized, with high population density and extensive building coverage across its 19 municipalities, including the City of Brussels. Although it is home to just 10.6% of Belgium's total population, BCR generates nearly 20% of the national GDP, driven by a dynamic and competitive economy. However, challenges remain: rapid population growth from international migration, limited affordable housing, low household disposable income, and persistent car reliance despite strong public transport infrastructure (OECD, 2024).

In response, BCR has adopted a planning approach anchored in strategic frameworks such as the Regional Development Plan (PRD) and the Regional Land Use Plan (PRAS). These documents guide urban development by establishing priorities for housing, mobility, economic growth, and environmental protection. The plans aim to balance urban growth with the preservation of green spaces and cultural heritage, while also addressing climate and mobility challenges (perspective.brussels, 2025b).

Central to this vision is a strong emphasis on sustainable mobility, particularly active modes such as cycling. The region has used this focus to rethink the allocation of public space and integrate more green areas into its urban fabric. Pedestrianization initiatives, further accelerated by the COVID-19 pandemic, have reinforced this trend by supporting new infrastructure and promoting a shift toward people-centered urban design (OECD, 2024).

In the domain of freight and goods mobility, two regional strategies are especially relevant: **Good Move**, BCR's strategic and operational mobility plan, and **Shifting Economy**, its economic transition framework (Brussels Mobility, 2024b). As part of these two plans' implementation, BCR also launched the **Urban Logistics Green Deal**, a collaborative initiative involving public and private stakeholders working to accelerate the shift toward sustainable logistics solutions (Mobilise, 2019).

To operationalize these strategies, BCR has also developed a series of thematic strategic plans, or "roadmaps," that offer a cross-cutting approach to implementing Good Move's goals. These roadmaps include plans for cycling, pedestrian infrastructure, goods transport, road safety, parking, taxis, and public lighting (OECD, 2024). Among these instruments is the Good Move plan, which serves as the region's main reference for guiding sustainable mobility policies.

3.1. The regional mobility plan: Good Move

Good Move is BCR's main mobility plan, aiming to improve neighborhood livability and address social, economic, and environmental challenges through a user-centered approach (ITF, 2021). This plan consists of three components: a **City Vision** for long-term goals, a **Mobility Vision** promoting active and public transport, and an **Operational Action Plan** with 50 actions grouped under six programs—**Good Neighborhood, Good Network**, **Good Service**, **Good Choice**, and **Good Partner** (Brussels Mobility, 2021).

Two actions are particularly relevant to this research: **Action A.5**, supporting local logistics real estate. In this context, nano-hubs help consolidate deliveries at the neighborhood level, reducing vehicle movements and enabling cleaner last-mile options such as cargo bikes and electric vans (Figure 12). Complementing this, **Action C.12** supports strengthening regional logistics hubs. Here, nano-hubs function as intermediary nodes, small-scale facilities that connect larger regional hubs to denser urban areas, supporting a more integrated and sustainable logistics network (Figure 13) (Brussels Mobility, 2021).

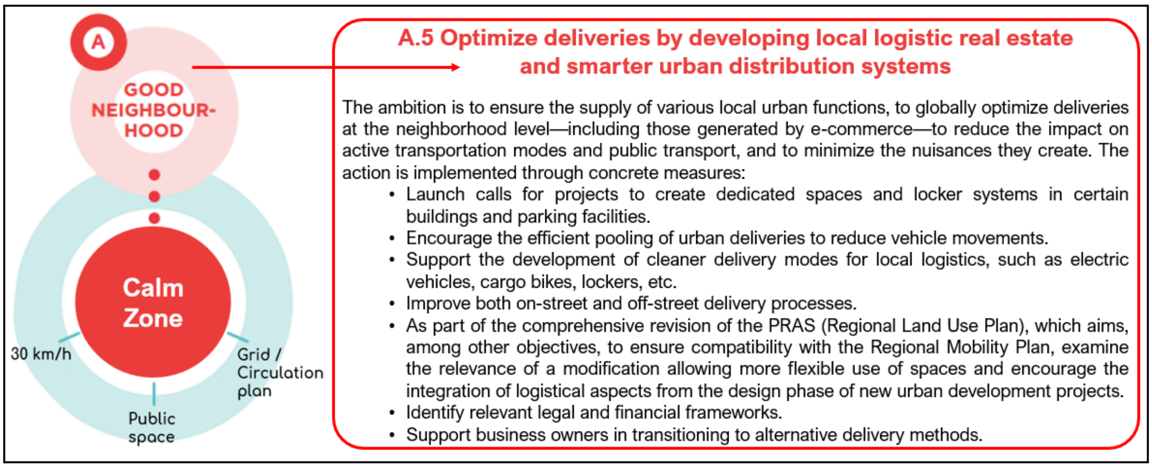


Figure 12. Good Neighborhood and Action A.5.
Source: Adapted from Brussels Mobility, 2021.

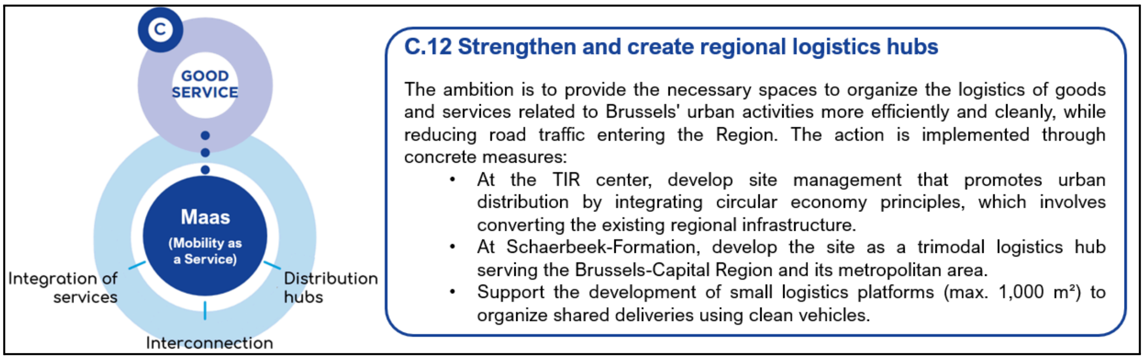


Figure 13. Good Service and Action C.12.
Source: Adapted from Brussels Mobility, 2021.

Recent evaluations published by Brussels Mobility at the end of 2023 (2023a, 2023b) provide insight into the ongoing implementation of **Actions A.5 and C.12**, highlighting both progress and persistent challenges.

Under **Action A.5**, the development of local logistics hubs has gained strategic importance. Optimizing deliveries has become a regional priority, reflected in initiatives such as *Shifting Economy*, *Green Deal Logistics*, *Good Food*[5], and *Renolution*[6]. Microhub implementation is advancing through mobility hub projects initiated in 2024. However, designing such hubs requires addressing diverse challenges, including security, operational efficiency, ease of use, and durability. Flexible space allocation and integration into urban planning are under review in the ongoing revision of the Regional Land Use Plan (PRAS), with public consultation set for 2025. Complementary studies are also underway, including regulatory adjustments for night deliveries that suggest regulatory changes to extend hours, and a feasibility study on a shared e-commerce locker network is underway. In parallel, initiatives like *Cargo Bike* and *Bike Delivery* have already supported over 300 businesses through grants and low-emission delivery solutions (Brussels Mobility, 2023a).

As for **Action C.12**, the scarcity of logistics real estate remains a key challenge, reinforcing the need for coordinated stakeholder engagement. One major effort is the planned transformation of the **TIR logistics site** (Transports Internationaux Routiers), a warehousing complex related to international road transport, located within the Port of Brussels, into a sustainable urban logistics hub of regional significance (Port of Brussels, 2024). In addition, smaller, decentralized logistics platforms are being recognized as essential for advancing cycle logistics. Their implementation requires regulatory flexibility to operate outside designated zones such as **ZAP** (Zones d'Activité pour l'Artisanat et les Petites Entreprises) and **ZIU** (Zones d'Industrie Urbaine), which are specific areas reserved for small-scale business activities and urban industry (Brussels Mobility, 2023b).

3.2. Shifting Economy

The **Shifting Economy** strategy complements Good Move by integrating logistics within Brussels' broader economic transition goals. It emphasizes the importance of logistics hubs and shared, or "mutualized," spaces in fostering more sustainable and resilient growth. Three objectives within this strategy are especially relevant to this research. First, **LOG 7 calls for the development of logistics hubs** to meet the needs of modern supply chains, reinforcing the region's commitment to enhancing urban logistics infrastructure. Second, **LOG 9 focuses on repositioning the TIR Center** as a

[5] The Good Food plan aims to build sustainable food supply chains by developing a city-serving logistics network and linking Brussels' demand with the Belgian food supply (Brussels Environment, 2022).

[6] Renolution is the Brussels Capital Region's building renovation strategy. Within logistics, it aims to manage triple the business activity while minimizing traffic impact (Brussels Environment, 2019).

central logistics node. This transformation opens possibilities for integrating the site into a wider network of microhubs, enabling a more decentralized and environmentally efficient delivery system. Finally, **LOG 10 supports the creation of mutualized logistics spaces**, promoting stakeholder collaboration and aligning directly with the microhub model's emphasis on shared infrastructure (Brussels Environment, 2023).

3.3. Other ongoing initiatives

In recent years, the Brussels-Capital Region has increasingly embraced cargo bikes as part of its shift toward sustainable urban logistics. Alongside global trends, new laws and incentives have encouraged the use of **nano-hubs** in conjunction with cargo bike deliveries (Buldeo Rai et al., 2019). The region now offers subsidies for cargo bikes, making sustainable delivery services more accessible to companies. Collaborative projects such as *cAIRgo Bike* have been a significant contribution in building the ecosystem needed to scale up cycle logistics by providing parking infrastructure, shared delivery systems, training, and business support (Brussels Mobility, 2024a, 2024b).

According to *cAIRgo Bike* figures, up to 25% of all goods and 50% of light goods in Brussels could be delivered by cargo bike (Brussels Mobility, 2024a). With incentives of up to €4,000 for cargo bike purchases, the program has significantly supported small and medium-sized businesses. As of 2024, these incentives have become part of the Low Emission Zone assistance scheme, reinforcing their long-term impact (Brussels Mobility, 2024a). During its pilot phase (2020-2023), cAIRgo Bike reached 220 organizations, including 40 large companies, trained over 330 professionals, and enabled more than 150 to test cargo bikes in real-world conditions. The project also facilitated awareness-raising through events, consultations, and trial sessions with over 700 participants. Reported benefits include lower costs compared to motorized vehicles, improved mobility in traffic, and environmental benefits, including reduced pollution and CO_2 emissions (PORTICO, 2024).

Although cAIRgo Bike has concluded, its outcomes continue to influence new initiatives. For example, **Archipel** is a collaborative project that brought together companies that are members of Green Deal Logistics with the goal of implementing a network of hubs and better leveraging the potential of bicycles for last-mile delivery (Brussels Mobility, 2024a). Another example is **CULT+,** whose objective is to establish a network of shippers and carriers working together to better consolidate freight flows and reduce the number of freight kilometers traveled. Both projects were initiated with support from Bloomberg Philanthropies (Philippe Lebeau & Nils Hooftmans, 2024).

One of the most recent developments is the **RAPTOR call for proposals**, which is a practical realization of the Good Move plan's vision, focusing on sustainable logistics and benefiting the livability in the neighborhoods of the BCR. This call for proposals is focused on addressing urban mobility challenges and bringing innovative mobility solutions to the cities (Buxo, 2024). Among these solutions are the development of a network of **nano-hubs** to reduce the environmental impact of transport, optimize public space use, and improve urban quality of life. These facilities are defined by Brussels Mobility as strategically located hubs intended to support sustainable last-mile delivery, particularly using bicycles and other low-emission vehicles. The aim is to establish a "white label"[7] network of hubs, each designed to be compact, ranging from 10 to 15 m² (Brussels Mobility, 2024b).

In Brussels, nano-hubs are currently being deployed using models developed by **OVO**, a Swiss micro-logistics company. These **OVO Nano-Hubs** (see Figure 14) operate from spaces as small as half a parking spot and are designed for quick, just-in-time transloading without the need for extended storage or sorting. Equipped with smart software and secure drop-off systems, they facilitate seamless handovers between carriers and cargo bike couriers, supporting both B2B and B2C operations. Their modular design responds to challenges of limited space, regulatory constraints, and real estate pressure in dense city centers (OVO, 2025).

Figure 14. Human scale and OVO Nano-Hub.
Source: Solar Impulse Foundation, 2025.

Despite these advances, key barriers remain. **Limited space availability, regulatory and real estate constraints, and challenges in integrating nano-hubs into existing urban frameworks continue to slow widespread adoption** (Kania et al., 2022; Schachenhofer et al., 2023). These obstacles are particularly relevant in Brussels, which aims to shift towards more sustainable last-mile solutions, such as adopting cargo bikes and implementing nano-hubs. This research situates the discussion within that context, highlights nano-hubs' potential as a transformative option for urban environments and cycle logistics, and supports informing stakeholders in building a more sustainable last-mile delivery system. Building on this groundwork, the next chapter outlines the research design, detailing the methods, data sources, and analytical steps for assessing nano-hub integration in the Brussels-Capital Region.

[7] It refers to a standardized product that can be used by different operators without requiring them to design their own solutions from scratch (Tardi, 2025). In the context of this project, a white-label hub network provides a neutral and accessible model for use by diverse stakeholders.

4. Research Design

4.1. Research approach

This master's thesis adopts a **mixed-methods approach**, combining quantitative and qualitative data to provide deeper insights than either method alone (Creswell et al., 2018). Quantitative techniques allow for statistical analysis and measurable comparisons, while qualitative methods aim to describe and interpret phenomena in depth (Hancock et al., 2009). By integrating both, the study achieves a more balanced understanding of the research topic (Bordens & Abbott, 2011; Creswell et al., 2018). This methodological triangulation allows for a more robust exploration of the subject matter, enhancing the validity and reliability of findings (Stuart et al., 2002; Yin, 2003). The main idea is to cross-verify information, identify potential discrepancies, and gain a more holistic view of the phenomenon under study (Creswell et al., 2018).

The following sections explain how these methods are applied and interlinked throughout the research. An overview of the methodological structure is presented in Table 3.

Table 3. Overview of methodology and data collection for reaching research objectives.
Source: by the author.

Analytical Dimension	**Objective**	**Method**	**Type of Result Collected**
Context and Barriers	**1.** **Identify the challenges and opportunities of integrating nano-hubs** into dense urban areas, particularly in terms of public space usage, urban planning, and regulatory constraints.	1.1. State of the Art and Contextual Analysis 1.2. Interviews with Stakeholders 1.3. Document Analysis: urban policies, regulations, and strategic plans	1.1. Identification of key barriers and enablers 1.2. Stakeholder perspectives on the future nano-hub project 1.3. Policy and regulatory constraints for Brussels-Capital Region
Spatial Suitability	**2**. **Evaluate the spatial suitability of nano-hubs in Brussels** to identify optimal locations that balance operational efficiency and urban livability.	2.1. Spatial Analysis using a GIS-MCDM framework	2.1. Identification of strategic locations for nano-hubs
Strategic Implementation	**3.** **Propose context-sensitive and sustainable strategies for integrating nano-hubs** in Brussels, focusing on long-term sustainability	3.1. Synthesis of findings from the spatial analysis	3.1. Context-sensitive and actionable strategies for sustainable nano-hub integration

4.2. Data collection

4.2.1. Interviews with stakeholders

As a preparation for the interviews, the researcher became aware of ongoing initiatives and events related to cycle logistics in Brussels, which supported an exploration of the local context. As the research project took shape, participation in cycle logistics-related events was used as a means to identify key stakeholders and deepen the understanding of context-specific dynamics. By actively engaging with the local network, the researcher was able to gather valuable insights and refine the study's direction. Between April 2024 and March 2025, five relevant events were attended (Table 4).

Table 4. Attended events in Brussels.
Source: by the author.

Name	Type	Person / Association involved	Date	Place
Urban logistics and sustainable transition: Challenges, opportunities, and inspiring initiatives	Lecture	**Urbike**	21/4/2024	Brussels
Switch to cycle logistics: how to support change in your company?	Webinar	**Urban Logistics Green Deal**	9/10/2024	Brussels
Route 33	Event	**The Belgian Cycle Logistics Federation (BCLF)**	26/11/2024	Brussels
Green Deal low-emission logistics networking event	Event	**Urban Logistics Green Deal**	21/2/2025	Brussels
Cycle Logistics Webinar: The Path to Efficiency and Sustainability	Webinar	**The Belgian Cycle Logistics Federation (BCLF)**	11/3/2025	Brussels

Three unstructured interviews were conducted with local stakeholders identified during these events (Table 5) to explore the development of the nano-hubs project in the Brussels-Capital Region. Given that the project was still in its early stages at the beginning of 2025, unstructured interviews were selected for their flexibility and effectiveness in generating preliminary insights during the exploratory phase (Chauhan, 2022).

Table 5. Overview of unstructured interviews.
Source: by the author.

Interviewee ID	Organization	Role in the project	Sector/Area of Expertise	Type of Stakeholder	Date of interview
Interviewee 1	**Brussels Mobility Department**	Mobility Specialist	Urban logistics & shared mobility	Public sector	29-11-2024
Interviewee 2a, 2b, 2c	**MOBILISE**	Researchers and intermediaries between theory and practice	Urban mobility and sustainable logistics	Academic sector	05-12-2024
Interviewee 3	**Urbike**	Expert in sustainable urban logistics	Cycle logistics	Private sector	10-01-2025

4.2.2. Document analysis: urban policies, regulations, and strategic plans

According to Bowen (2009), document analysis is a structured qualitative method used to examine various types of materials, including printed and digital sources. It involves interpreting and analyzing documents to extract insights and support empirical understanding. In the context of policy analysis, particular attention was given to identifying which elements convey meaning and how that meaning is constructed (Yanow, 2007).

This master's thesis examined official documents, reports, and publications related to urban logistics in Brussels. The review included materials from key public agencies—*Brussels Mobility* and *Brussels Environment*—as well as relevant policy frameworks such as *Good Move*, *Shifting Economy*, and the *Urban Logistics Green Deal*. The analysis also encompassed official seminars, including presentations, reports, videos, and training materials made available by *Brussels Environment* on their webpage (Brussels Environment, 2025).

4.2.3. Spatial analysis: GIS-MCDA framework for nano-hub site selection

This study adopts a GIS-based Multi-Criteria Decision Analysis (GIS-MCDA) framework to identify optimal sites for implementing nano-hubs in the Brussels-Capital Region. The approach integrates **spatial analysis**, **fuzzy logic**, and **decision-making techniques** to rank candidate locations based on a set of predefined criteria. It builds directly upon the framework developed by Aljohani and Thompson (2020), adapted here to address the specific challenges of cycle logistics in dense urban environments.

Geographic Information Systems (GIS) support the spatial dimension of this analysis by enabling the mapping and visualization of results (Saha & Frøyen, 2021). **Multi-Criteria Decision Analysis (MCDA)** provides a structured way to evaluate different criteria by assigning weights to each factor based on their relative importance (Hajduk, 2022; Taherdoost & Madanchian, 2023). Site selection in inner-city areas requires a context-sensitive strategy, as suitable locations differ from those in peripheral zones (Aljohani and Thompson 2020). Effective last-mile planning must therefore consider the diverse and sometimes conflicting priorities of stakeholders, extending the focus beyond delivery performance to also consider the city's livability (Muriel et al., 2022).

Over the years, studies have expanded MCDA applications beyond financial metrics, incorporating sustainability, livability, and political considerations to reflect the complexity of urban logistics planning (Yan Chen & Lili Qu, 2006; Farahani et al., 2010; İ. Önden et al., 2023). Despite these advancements, many decision-support models still overlook the spatial dimension of site selection (I. Önden et al., 2018; Özceylan, Çetinkaya, et al., 2016; Özceylan, Erbaş, et al., 2016; Sopha et al., 2016). In particular, the complexity of siting logistics hubs in densely populated urban areas remains largely unaddressed. Aljohani and Thompson (2020) point to this gap, arguing that no previous research has fully integrated GIS and MCDA to support freight consolidation site selection in inner-city contexts. A review of 61 studies citing their work revealed no significant methodological refinements or extensions of their GIS-MCDA framework (Google Scholar, 2025).

Given its compatibility with this study's goals, the GIS-MCDA framework proposed by Aljohani and Thompson (2020) was adopted and extended to the specific context of Brussels, focusing on small-scale hubs designed for cycle logistics. The adapted methodology incorporates additional layers of analysis, including social safety indicators and environmental externalities (e.g., crash risk and black carbon exposure), local regulatory constraints (e.g., protected areas and land-use compatibility), and the strategic reuse of underutilized urban infrastructure (sleeping assets) as potential nano-hub locations.

To complement these refinements, a new analytical component—**Nano-Hub Accessibility Analysis: Shared-Use Potential**—was introduced. This new stage uses 15-minute cycling isochrones to assess the proximity of existing logistics operators to each shortlisted site, helping to identify hubs best positioned for multi-operator use and supporting a more context-sensitive decision-making process.

The original Aljohani and Thompson (2020) framework consists of six stages:

(1) development of evaluation criteria;

(2) weighting of criteria using the Fuzzy Analytic Hierarchy Process (F-AHP);

(3) creation of decision maps in QGIS;

(4) normalization of criteria values using fuzzy logic;

(5) land suitability analysis; and

(6) site ranking using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

Building on this structure, this study introduces a **seventh stage**:

(7) Stage 7 extends the framework beyond individual site suitability to network-level performance, ensuring that the final site selection supports functional integration within Brussels's cycle logistics system.

Geographic data for the study area was collected in different formats and from various sources, including commercial real estate directories and local government databases. In cases where specific datasets were unavailable, the author generated original data or used proxy indicators to approximate the missing information, ensuring that all required criteria for the analysis could be represented in the GIS environment (see Table 6).

Table 6. Geographic data used in the spatial analysis[8].
Source: by the author.

Data considered in the spatial analysis	Sources	Original data format
○ Cycle Logistics Carriers partners with BCLF	By the author, based on BCLF (2024a) and direct engagement with stakeholders during cycle logistics events	CSV file
○ Public car parks in BCR	Brussels Mobility, 2022	GeoJSON
○ Temporary occupations of vacant buildings in BCR	By the author based on Heydari, 2022	CSV file
○ Share of households with a company car[9]	Based on Buldeo Rai et al., 2024; May, 2017; and STATBEL, 2023	GeoJSON
○ Mixed-use zones	perspective.brussels, 2025a	Shapefile
○ High-intensity mixed-use zones	perspective.brussels, 2025a	Shapefile
○ Urban industrial zones	perspective.brussels, 2025a	Shapefile
○ Port- and transport activity zones	perspective.brussels, 2025a	Shapefile
○ Urban enterprise zones	perspective.brussels, 2025a	Shapefile
○ Regional-interest zones	perspective.brussels, 2025a	Shapefile
○ Commercial-core edge	perspective.brussels, 2025a	Shapefile
○ Mixed-use variation point	perspective.brussels, 2025a	Shapefile
○ Road network of regional roads in BCR	Datastore. brussels, 2024	Shapefile
○ 30 Zones in BCR	Brussels Mobility, 2022b	GeoJSON
○ Green areas: zones intended mainly for the development of nature and bodies of water, with limitations on construction	perspective.brussels, 2025a	Shapefile
○ Protected Heritage, Protection areas (Perimeter around monuments or sites), and UNESCO protections areas	perspective.brussels, 2025a	Shapefile
○ Water surface and open water rivers	perspective.brussels, 2025a	Shapefile
○ Average rental price of a common Brussels apartment (2024)	FEDERIA, 2025	CSV file
○ Commercial central strips	perspective.brussels, 2025a	Shapefile
○ Bicycle routes in BCR	Brussels Mobility, 2022a	Shapefile
○ Air quality - exposure to Black Carbon[10]	Brussels Environment, 2018	GeoJSON
○ Road accidents	STATBEL, 2022	Shapefile

[8] More information about the datasets is available in Appendix A.

[9] The data used includes both privately registered vehicles and company cars. Since company cars are registered under enterprises without specifying their usage type, there are no publicly available data exclusively on company cars for the Brussels-Capital Region (STATBEL, 2023).

[10] This data was obtained as part of the ExpAIR project of Brussels Environment (Brussels Environment, 2018).

5. Results and Analysis on Integrating Nano-hubs into Brussels

5.1. Synthesis of findings from literature, context, and stakeholder insights

From the **theoretical foundation**, the literature highlighted the potential of cargo bikes and nano-hubs for sustainable last-mile delivery, the operational and spatial benefits of shared-use logistics facilities, and the concept of reactivating sleeping assets to reduce public space competition. Cargo bikes offer clear environmental and social benefits over motorized delivery modes, but their effectiveness depends on strategically located, small-scale logistics facilities that minimize range limitations and enable efficient consolidation (Lebeau et al., 2023; Cowie & Fisken, 2023). Studies also emphasize the efficiency gains of shared-use hubs, where multiple operators can pool infrastructure and resources (Hribernik et al., 2020; Mohamed et al., 2023), and stress that siting decisions should consider social and spatial integration alongside technical and economic performance (Assmann et al., 2019). This broader perspective informed the expansion of CR11 to account for integration with the urban environment. The concept of sleeping assets—underused spaces and infrastructure that can be repurposed for logistics—offers a less intrusive and more flexible approach to siting nano-hubs in dense areas, supporting adaptability and public acceptance in early-stage projects (Schachenhofer et al., 2023).

The **document analysis** provided the institutional framework in which nano-hubs would operate. Brussels' strategic plans—*Good Move*, *Shifting Economy*, and the *Urban Logistics Green Deal*—explicitly promote compact, shared, and strategically located hubs. Within *Good Move*, Action A.5 promotes neighborhood-scale hubs to consolidate deliveries, while Action C.12 positions nano-hubs as intermediary nodes linking regional logistics facilities to dense areas. These actions are complemented by *Shifting Economy* objectives (LOG 7, LOG 9, LOG 10) that call for shared logistics spaces, the transformation of the TIR site into a central hub, and an integrated microhub network. Ongoing initiatives such as *cAIRgo Bike*, *Archipel*, *CULT+*, and the *RAPTOR* call for proposals illustrate a shift toward flexible, small-footprint, multi-operator infrastructure supported by subsidies and pilot projects. Persistent barriers include zoning restrictions, scarce available real estate, and public space usage, all of which informed the criteria and parameters of the spatial analysis.

The **stakeholder interviews** enriched this context with operational insights. A primary interview was conducted with a mobility specialist (interviewee 1) from *Brussels Mobility,* the regional public department responsible for transport and mobility in the Brussels-Capital Region. In the interview, the specialist outlined Brussels' Nano-hub project as an initiative under the Good Move Plan to optimize last-mile logistics using cargo bikes for deliveries. The project involves the implementation of nano-hubs, with two pilots scheduled for February 2025 and eight more by mid-2025. In Brussels, the nano-hubs will function as shared facilities, accessible via an app-based booking system that ensures exclusive use during reserved time slots. Brussels Mobility is the main coordinator, facilitating collaboration among stakeholders. Brussels' nano-hub pilots are manufactured by a Swiss company called OVO, and they are large aluminum boxes, similar to the ones used for bike storage ("box vélo") already being used in Brussels (Figures 15 and 16).

Figure 15. "Box vélo" for bike storage in Brussels. Source: 1030 Schaerbeek, 2021.

Figure 16. Nanohub for cycle logistics in Brussels. Source: By the author.

Interviewee 1 has identified key challenges in implementing the project. Firstly, securing funding was a critical hurdle that has already been successfully overcome, enabling the project to move forward. The second major challenge was to find a suitable operator to manage the hubs effectively, as the Department of Brussels Mobility recognizes that, as a public agency, they are not equipped to run these facilities themselves. Finally, ensuring sufficient demand and consistent usage is important to justify the occupation of valuable urban space—a concern reinforced by the failure of similar projects in other cities, where underutilization led to facility removal. The department is aware that inadequate use could threaten the project's viability. These concerns were further examined in a second interview with three researchers from VUB's *Mobilise Mobility and Logistics Research Group* (interviewees 2a, 2b, and 2c), who offered academic perspectives on nano-hub implementation and functionality. They stressed the importance of assessing how well hubs meet operators' needs and how they can be adapted to ensure better alignment with operators' requirements. The researchers also emphasized involving multiple stakeholders to ensure hubs serve various users rather than a single operator, fostering broader collaboration. A major challenge identified was securing suitable locations. After more than a year of searching sites, many were rejected by public agencies for different reasons. Integrating private infrastructure into public space proved particularly difficult, often facing resistance. In response, the project direction has shifted toward prioritizing regional spaces, where implementation is more feasible, while also exploring municipal partnerships and private areas. One example is a private site on the VUB Main Campus in Etterbeek, now hosting the first implemented nano-hub. Further insights were provided by interviewee 3, a future operator of the nano-hubs. He emphasized the importance of considering parcel destinations when selecting hub locations, particularly shopping areas, which act as major delivery receivers. He suggested identifying delivery hotspots, he argued, would help align hub placement with areas of highest demand.

Additional information was gathered through **participation in cycle logistics–related events** in Brussels, which offered a deeper understanding of the sector's dynamics and challenges. By the end of February 2025, only one hub had been implemented, while the second pilot was postponed. The locations of future hubs were not shared, but it was confirmed that the project is funded for one year, with the budget covering 10 nanohubs. Public agencies also plan to install 34 nanohubs in the coming years. These events provided opportunities to engage with stakeholders and to identify the actors shaping Brussels' cycle logistics ecosystem. This input informed the stakeholder map (Figure 17), which outlines the roles, relationships, and influence of the 20 actors identified in the research, serving as a guide for survey distribution in the GIS-based spatial analysis.

In summary, these findings collectively shaped enhancements to the Aljohani and Thompson (2020) framework, such as the **introduction of the sleeping assets concept into the criteria**, a **review of land use to identify zones with potential hub siting**, the expansion of CR11 to address integration with the urban environment (considering how hubs interact with neighborhood character without generating significant disturbance on livability), and the **addition of Stage 7 to evaluate network-level shared-use potential**. These refinements ensure that the GIS-MCDA framework aligns with the spatial, operational, and governance realities of integrating nano-hubs into dense urban environments, providing a stronger, context-sensitive foundation for decision-making.

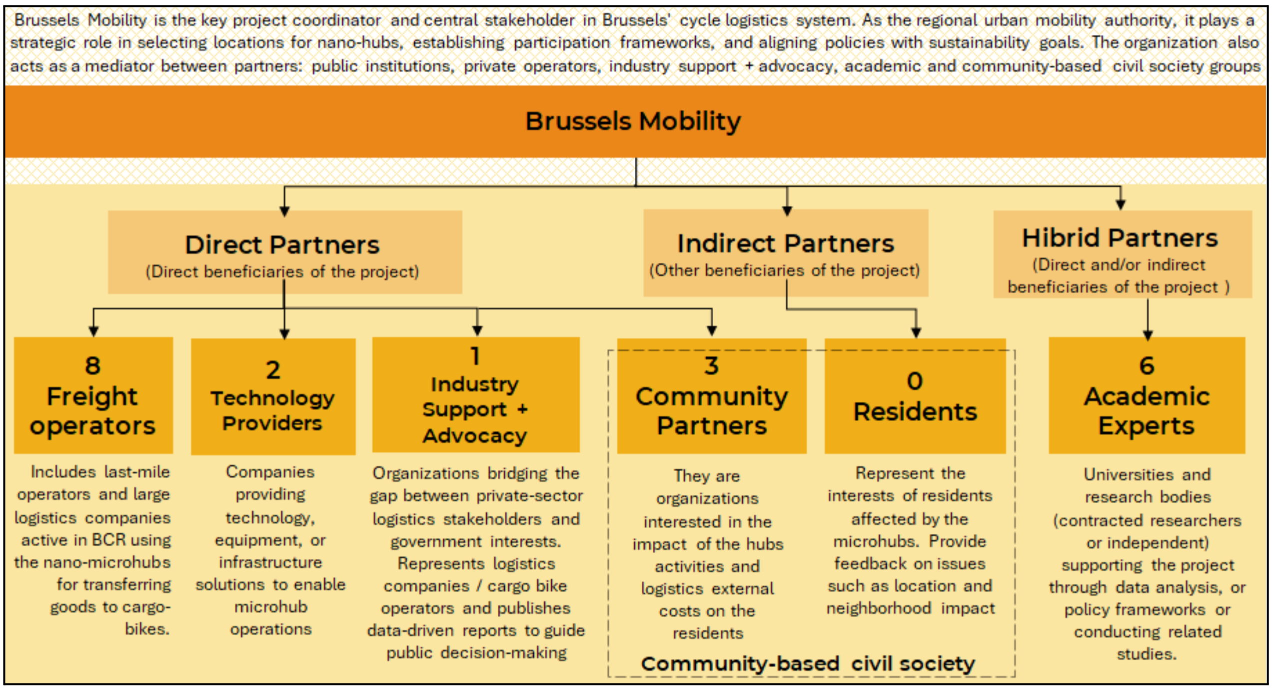


Figure 17. Stakeholder map of the nano-hubs project in Brussels. Source: produced by the author.

5.2. GIS-based spatial analysis

This section builds on the development of an adaptation of the approach developed by Aljohani and Thompson (2020): the GIS-based Multi-Criteria Decision Analysis (GIS-MCDA) framework, and adapts it to the specific context of logistics in Brussels and nano-hubs for cycle logistics. The adapted GIS-MCDA framework consists of seven stages (Figure 18). This framework integrates spatial evaluation models, considers the social concerns of both residents and local governments, evaluates freight land-use characteristics, and addresses the operational needs of freight carriers. By combining these elements, the framework aims to identify the most suitable location for establishing a small-scale logistics facility in congested inner-city areas.

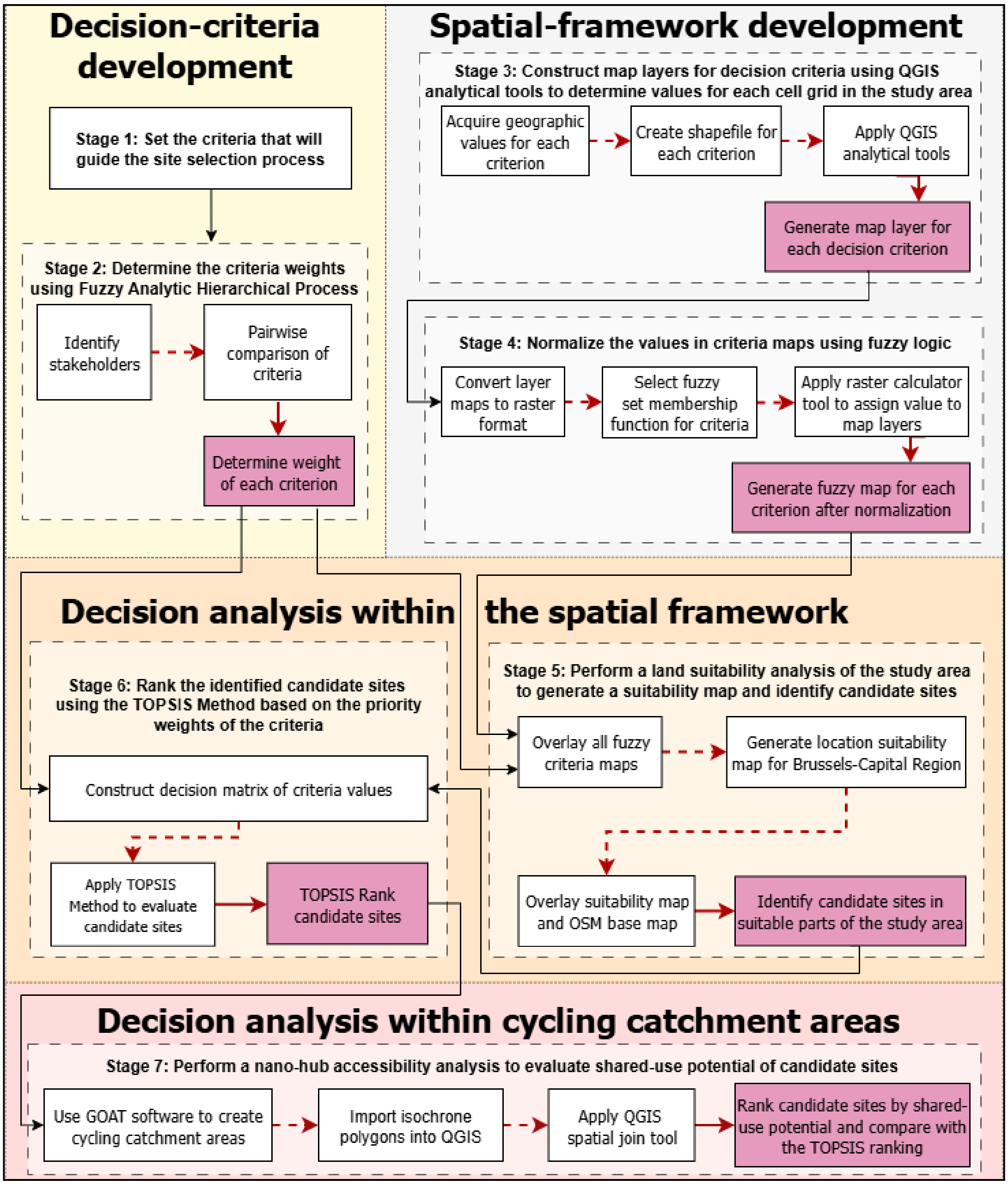


Figure 18. Stages of the GIS-MCDA Framework for the Optimal Location for a Logistics Facility. Source: Adapted from Aljohani and Thompson, 2020.

Stage 1: Identify decision criteria for location assessment

Following the structure proposed by Aljohani and Thompson (2020), the criteria are grouped into three categories: A. *Logistics Land Use and Attributes*, B. *Transport Accessibility Indicators*, and C. *Suitability Indicators*. These categories capture, respectively, (i) characteristics of the urban fabric, (ii) operational desirability from a logistics perspective, and (iii) the capacity of the surrounding transport network to serve the hub efficiently. Table 7 presents the original criteria alongside the adapted versions, providing a brief description of each and the datasets used. Detailed explanations of the criteria data processing are provided in Appendix A. The suitability criteria used in this study were derived from a combination of literature, stakeholder insights, and Brussels-specific policy priorities and were adapted to the scale and nature of cycle logistics and nano-hub operations.

Table 7. Decision criteria used for nano-hub site selection.
Source: Adapted from Aljohani and Thompson (2020).

Original Criteria	Category	Adapted Criteria	ID	Brief Description	Datasets Used in the Analysis
Existing Distribution Centres/ Warehouses in the Area	**A. Logistics Land-Use and Attributes**	Existing Distribution Centres/ Warehouses in the Area[11]	**CR01**	Areas with a high density of cycle logistics operators' hubs, from which deliveries are made by cargo bikes, reflecting the proximity-based nature of nano-hubs	○ Cycle-logistics carriers' locations
Parking Infrastructure in the Area		*Sleeping assets*[12]: Idle real estate in the area	**CR02a**	Areas with a larger presence of parking infrastructure	○ Public car parks in BCR
			CR02b	Areas with a larger presence of empty buildings or unused spaces within occupied buildings or other urban spaces with unused times	○ Temporary occupations of vacant buildings in BCR
Demographic Attributes		Target Demographic Attributes	**CR03**	Areas located close to residential zones with high demand for deliveries, considering online shopping behavior	○ Share of households with a company car
Primary Land Use Zones		Primary Land-Use Zones	**CR04**	Areas with compatible land-use designations to implement nano-hubs and avoid conflicts with sensitive surroundings	○ Mixed-use zones ○ High-intensity mixed-use zones ○ Urban industrial zones ○ Port- and transport activity zones ○ Urban enterprise zones

[11] In the original framework, criterion CR01 refers to large freight hubs serving multiple vehicle types.
[12] Originally limited to parking infrastructure, the criterion CR02 is expanded to include other types of *Sleeping Assets* suitable for logistics operations.

					○ Regional interest zones ○ Commercial core edge ○ Mixed-use variation point
Proximity to Major Freight Corridors	**B. Transport Accessibility Indicators**	Proximity to Major Freight Corridors	**CR05**	Areas located close to important regional roads for freight transport	○ Road network of regional roads in BCR
Traffic Intensity of Major Roads in the Area		Traffic Intensity of Major Roads in the Area	**CR06**	Low-traffic areas, within 30 km/h zones, to ensure safe conditions for cargo-bike operations	○ 30 Zones in BCR
Access Restrictions in the Area		Access Restrictions in the Area	**CR07**	Areas with access restrictions for motorised freight vehicles, which should be avoided to ensure smooth transfers to nano-hubs	○ Green areas: zones intended mainly for the development of nature and bodies of water, with limitations on construction ○ Protected Heritage, Protection areas (Perimeter around monuments or sites), and UNESCO protections areas ○ Water surface, open water rivers
Facility Rental Costs	**C. Suitability Indicators**	Facility Rental Costs	**CR08**	Areas with low rental costs are preferable (for the case of implementing the nano-hubs in residual areas inside/annexed to buildings)	○ Average rental price of a common Brussels apartment (2024)
Existing Goods Receivers in the Area		Existing Goods Receivers in the Area	**CR09**	Areas with a high density of commercial establishments—goods receivers	○ Commercial central strips—goods receivers
Proximity to Cycling Infrastructure		Proximity to Cycling Infrastructure	**CR10**	Areas with cycling infrastructure in BCR	○ Bicycle routes in BCR
Impact on Nearby Residents		Integration with Urban Environment[13]	**CR11**	Areas with minimized socio-environmental disruptions are preferable: optimal compatibility between livability standards and minimal environmental externalities for logistics operations.	○ Air quality—exposure to Black Carbon ○ Road accidents

[13] In the original framework, criterion CR11—Impact *on Nearby Residents* recommended locating microhubs in low-density areas to minimize disturbances from freight activities. However, the Aljohani and Thompson (2020) study primarily addressed larger facilities serving various vehicle types, which differs from the focus of this research on cargo bike-based nano-hubs—compact facilities roughly the size of a parking space. Given their smaller footprint and lower operational impact, this criterion is adapted to emphasize integration with the urban environment, reflecting the potential for nano-hubs to coexist harmoniously within dense, mixed-use areas. This perspective aligns with the need to view logistic hubs not only as infrastructure but as elements embedded in the city's spatial and social fabric. Still, empirical evidence on this topic remains scarce. **The only study identified that specifically examines nano-hubs of a similar typology in the Brussels-Capital Region (BCR) is by Kania et al. (2022)**, who highlight gaps in understanding their diverse functions, spatial characteristics, and the restrictive planning regulations that hinder scaling beyond pilot projects.

Stage 2: Determine criteria weights using Fuzzy Analytic Hierarchy Process

The next step determines the relative importance of each criterion by assigning weights through the Fuzzy Analytic Hierarchy Process (F-AHP). The Analytic Hierarchy Process (AHP) is a structured decision-making method that combines logical analysis with intuitive judgment, enabling the evaluation of multiple alternatives through systematic pairwise comparisons. These comparisons produce priority rankings, help identify the most favorable options, and include mechanisms to address inconsistencies in human judgment (Saaty & Vargas, 2012). The fuzzy extension of AHP incorporates a fuzzy scale to better capture uncertainty and subjectivity in stakeholder assessments (Zadeh, 1965). The procedure followed three main steps:

(1) **Identification of Stakeholders**: Selection of participants to conduct pairwise comparisons of criteria.
(2) **Pairwise comparison:** Systematic comparison of each criterion pair using a fuzzy scale to express relative importance.
(3) **Weight calculation**: Derivation of criterion weights from stakeholder inputs, reflecting their relative significance in the decision-making process.

Following the methodology of Aljohani & Thompson (2020), an online survey was developed to collect pairwise comparisons of the criteria using a simple scale. The survey (Appendix B) was created with Qualtrics, a widely used platform for designing and distributing questionnaires in academic research (Ginn, 2018; Qualtrics, 2025). It was electronically distributed to 20 stakeholders identified in the stakeholder map (see Figure 17). **The survey was open from 14 to 31 March, yielding eight responses[14].** Participants represented the public sector, private sector, academia, and community-based civil society. A summary of respondent profiles is presented below.

- **Freight operators (Private Sector):** Two professionals from companies working with cycle logistics.
- **Industry Support + Advocacy (Public-Private Organization):** One representative from an organization operating at the intersection of industry collaboration and public policy advocacy.
- **Academic Experts:** Four researchers from institutions including VUB and ULB.
- **Community Partners (Civil Society):** One member of an ASBL (non-profit) organization serving public or community interests.

The survey aimed to assess the relative importance of factors for selecting optimal nano-hub locations in the Brussels-Capital Region. Stakeholders compared pairs of criteria (e.g., CR01 vs. CR02,

[14] Health-related constraints during the research period prevented the enrichment of this sample through focus groups or interviews.

CR01 vs. CR03) and indicated not only which criterion they considered more important but also to what extent. To ensure accessibility, the questionnaire was written in clear, straightforward language.

A Saaty scale was used to rate importance, with values applied in the F-AHP process to compare criteria (Saaty, 1977; Saaty & Vargas, 2012). This 1–9 scale captures subjective judgments in a structured format, facilitating complex decision-making. The scale values are:

- 1 = Equally important
- 3 = 1st Factor is slightly more important
- 5 = 1st Factor is moderately more important
- 7 = 1st Factor is much more important
- 9 = 1st Factor is extremely more important
- 1/3 = 2nd Factor is slightly more important
- 1/5 = 2nd Factor is moderately more important
- 1/7 = 2nd Factor is much more important
- 1/9 = 2nd Factor is extremely more important

The first step in processing the survey results was to clean the data by removing incomplete responses. One partial response (63% complete) was excluded to ensure dataset integrity, leaving **seven fully completed surveys** for analysis. Outliers and inconsistencies in ratings were also checked to ensure accuracy and reliability.

The stakeholder input provided the basis for a Fuzzy Analytic Hierarchy Process (F-AHP) following the approach of Aljohani and Thompson (2020), using the Chang Extent Analysis Method (EAM) (Chang, 1996) to derive fuzzy weights from the pairwise comparison data, accounting for imprecision in expert judgments (Kahraman et al., 2003). Calculations were automated and performed in the *R environment*[15] (Appendix C) (R Core Team, 2024). An outline of the Fuzzy AHP procedure used in this study is presented below:

(1) **Data Import:**

- The input criteria were compared in pairs by stakeholders via Saaty's scale (Appendix D).

(2) **Conversion to Triangular Fuzzy Numbers (TFNs):**

- To capture uncertainty in judgments, crisp values were converted into TFNs, represented as *(l, m, u)*, where:
  - *l* is the lower bound (pessimistic view),

[15] The R script for this analysis was developed by Luiz Ladeira, a specialist in computational methods, under the author's supervision and guidance. The methodological framework followed the approach of Aljohani and Thompson (2020).

- *m* is the middle value (most likely value)
- *u* is the upper bound (optimistic view)

- Fuzzy mapping of Saaty scale:
  - 1 = Equally important -> (1,1,1)
  - 3 = Slightly more important -> (1,3,5)
  - 5 = Moderately more important -> (3,5,7)
  - 7 = Much more important -> (5,7,9)
  - 9 = Extremely more important -> (7,9,9)

  And their reciprocals:
  - 0.33 (1/3) = Second factor slightly more important -> (1/5, 1/3, 1)
  - 0.20 (1/5) = Second factor moderately more important -> (1/7, 1/5, 1/3)
  - 0.14 (1/7) = Second factor much more important -> (1/9, 1/7, 1/5)
  - 0.11(1/9) = Second factor extremely more important -> (1/9, 1/9, 1/7)
- The wider ranges for moderate judgments reflect higher uncertainty, while extreme judgments have narrower ranges, indicating greater confidence. TFNs maintain the property $l \leq m \leq u$.

(3) **Aggregation of Stakeholder Judgments**:

- Multiple stakeholder inputs were combined into a single fuzzy pairwise comparison matrix using the geometric mean, which is appropriate for ratio-scale data and mitigates bias from outliers (Saaty & Vargas, 2012).
  - Reciprocal adjustments: If one stakeholder rated CR01 > CR02 as 5 and another rated CR02 > CR01 as 1/3, the latter was converted to its reciprocal (3) for consistency.
  - Fuzzy **aggregation:** For each criterion pair, geometric means of all TFNs were calculated, producing three matrices (*l_matrix*, *m_matrix*, *u_matrix*) representing the lower, middle, and upper bounds.

(4) **Fuzzy Weight Calculation:**

- Weights were calculated via Chang's Extent Analysis Method (Chang, 1996):
  - Crisp values were calculated as: $COA = (l + m + u) / 3$
  - Normalization: Crisp weights were normalized so that their sum equaled 1 (or 100%).

(5) **Ranking and Output**:

- Criteria were ranked in descending order of weight to identify those most influential in decision-making, as shown in Table 8.

Table 8. Fuzzy AHP Criteria Weights for Nano-hub Location Selection.
Source: by the author.

Rank	ID	Description	S_lower	S_middle	S_upper	Weight	Percentage
1	CR03	Target Demographic Attributes	0.091481	0.133417	0.182795	0.297429	29.74289
2	CR09	Existing Goods Receivers in the Area	0.086884	0.124176	0.169783	0.248512	24.85125
3	CR07	Access Restrictions in the Area	0.07227	0.098637	0.132573	0.11991	11.99101
4	CR02	'Sleeping Assets' (Idle Real Estate in Area)	0.0687	0.089694	0.118544	0.077242	7.724247
5	CR06	Traffic Intensity of Major Roads in the Area	0.071694	0.090764	0.11567	0.073427	7.342719
6	CR11	Integration with Urban Environment	0.064939	0.085084	0.118166	0.069596	6.959635
7	CR08	Facility Rental Costs	0.064296	0.084658	0.112568	0.057601	5.760105
8	CR05	Proximity to Major Freight Corridors	0.067316	0.085785	0.10729	0.047338	4.733769
9	CR04	Primary Land-Use Zones	0.062561	0.076546	0.094521	0.008647	0.86472
10	CR01	Existing Distribution Centres/Warehouses in Area	0.054742	0.066529	0.084035	0.00015	0.014978
11	CR10	Proximity to Cycling Infrastructure	0.05308	0.064712	0.08338	0.000147	0.014676

Stage 3: Construct map layers for criteria using QGIS software

Unlike Aljohani and Thompson (2020), this study employed QGIS instead of ArcGIS, as QGIS better supports the principles of openness, transparency, and reproducibility that guide academic research (QGIS Development Team, 2025). It also provides a suitable environment and the required plugins for conducting the multi-criteria spatial decision analysis applied in this thesis.

Following the framework, the objective in Stage 3 was to spatially represent each criterion as a GIS layer.

(1) **Data acquisition and layer creation**:

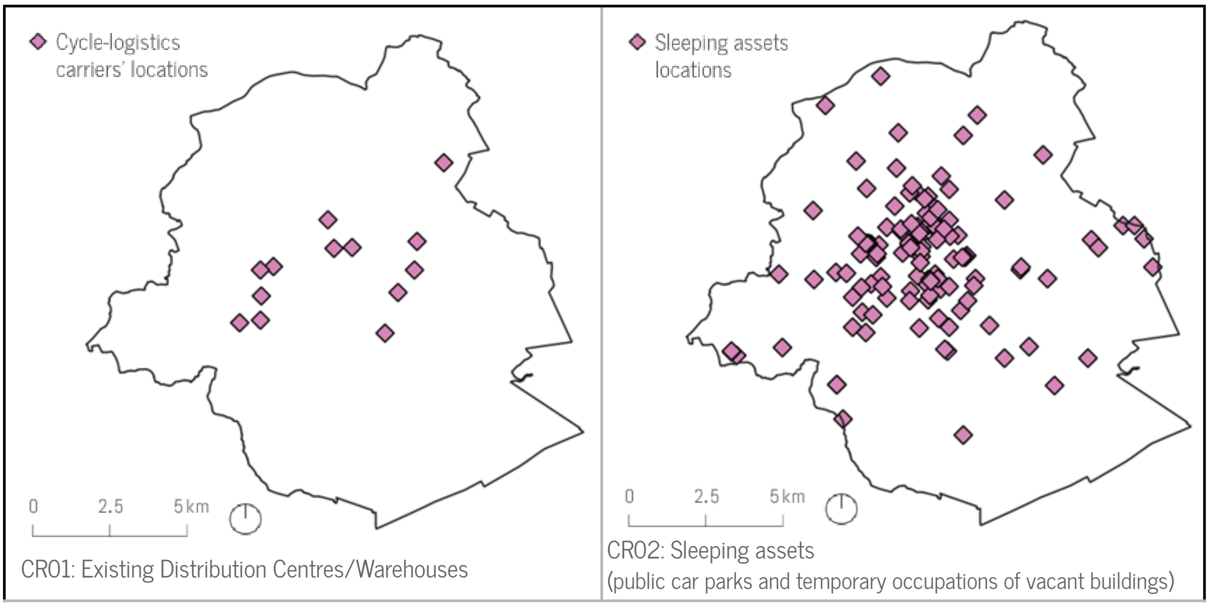
Spatial data for each criterion were collected (see Table 6), processed, and stored as vector layers in Shapefile format. The 11 criteria were represented through points, lines, or polygons (Figure 19). For criteria with subcategories, layers were merged using the tools *Merge vector layers* or *Join attributes by field value*, producing a single layer for each criterion (except CR11, which was combined at a later stage).

(2) **Raster conversion:**

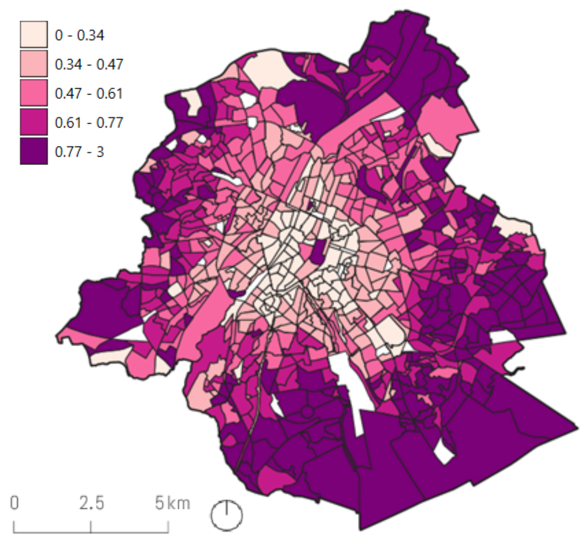
Each vector layer was converted into a raster layer with a 100 m × 100 m grid resolution to standardize data formats. Following Aljohani and Thompson (2020), rasterization methods were selected based on the data type (points, lines, or polygons) and grouped into three classes (Table 9).

Table 9. Processing methods for rasterization.
Source: by the author based on Aljohani & Thompson (2020).

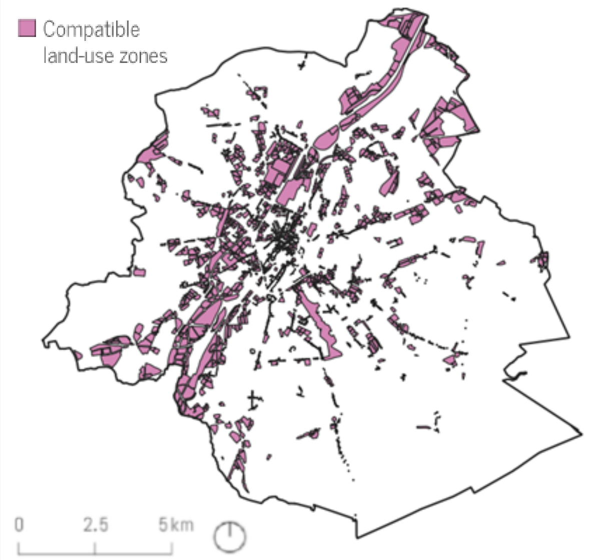
Class categorization	**QGIS analytical tool applied to create raster layers**	**Purpose**
(1) **Density-Based Clustering**	Point Density[16]	Measures **spatial concentration**—more points indicate higher suitability
(2) **Distance-Based Clustering**	Euclidean Distance	Measures **proximity**—closer to beneficial features or further from negative ones increases suitability
(3) **Attribute-Based Clustering**	Inverse Distance Weighting (IDW) interpolation	Assigns attribute values to each grid cell and **interpolates** them, creating a smooth, continuous surface across the area



[16] QGIS doesn't have the same name for this tool, but ArcGIS's Point Density (used by the authors) can be implemented in QGIS software with the tool Kernel Density Estimation (KDE), which has the same functionality (QGIS, 2025a).

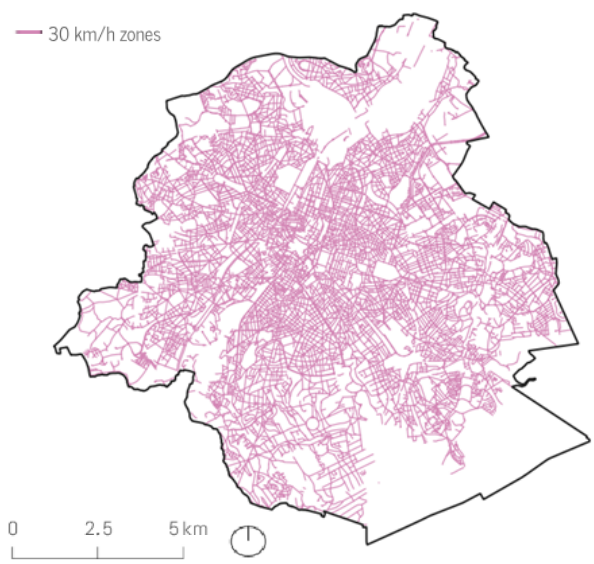


CR03: Target Demographic Attributes
(share of households with a company car)

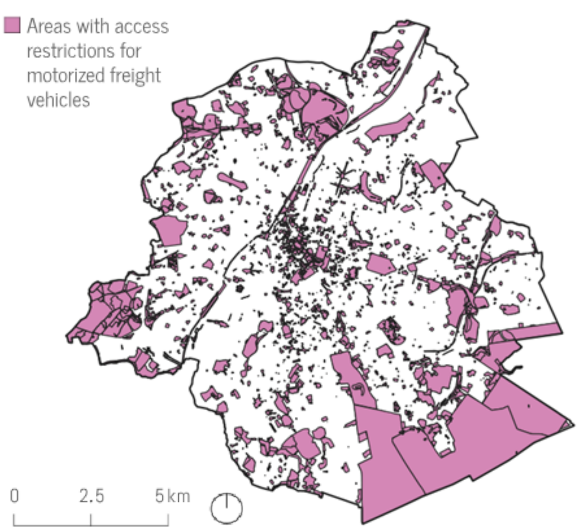


CR04: Primary Land-Use Zones

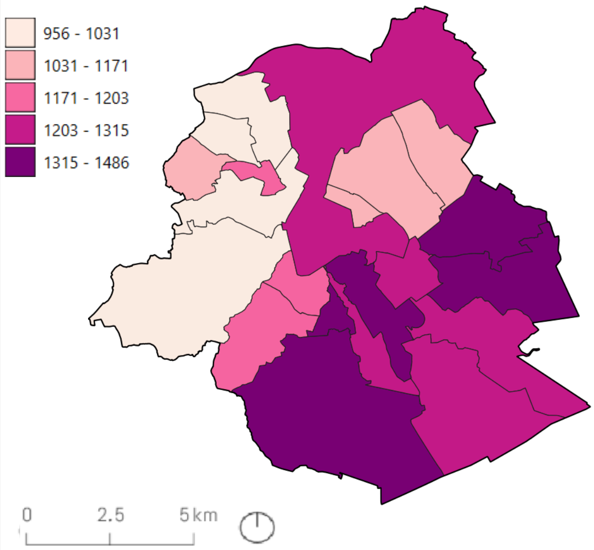
CR05: Proximity to Major Freight Corridors



CR06: Traffic Intensity of Major Roads



CR07: Access Restrictions
(green areas, heritage/protected areas, and water surfaces)



CR08: Facility Rental Costs
(average rental price of a common Brussels apartment)

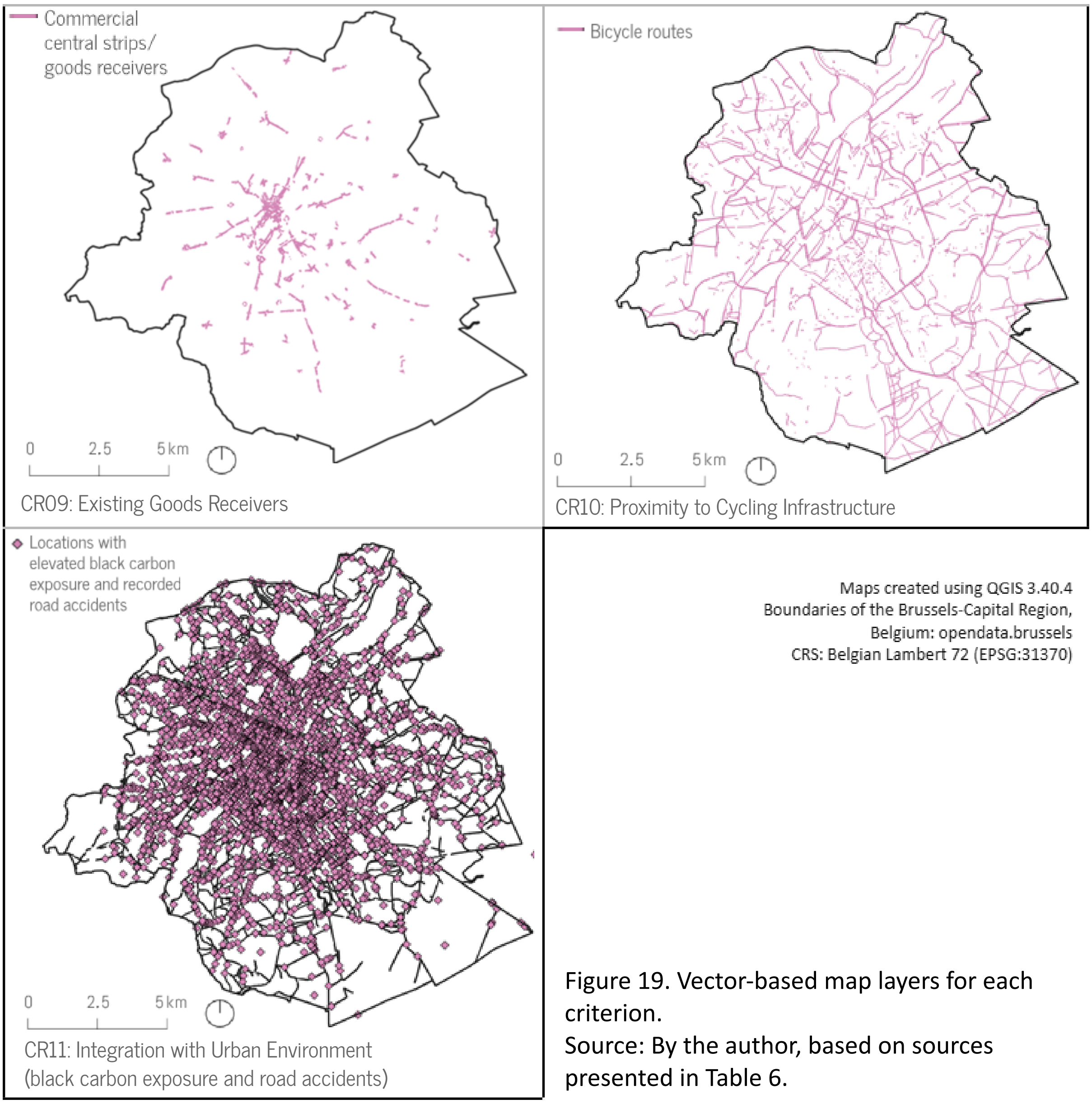


Figure 19. Vector-based map layers for each criterion.
Source: By the author, based on sources presented in Table 6.

Stage 4: Normalize criteria maps using fuzzy logic

For each criterion, the selected raster method assigned a value to every grid cell, standardizing data across maps for comparability. Fuzzy logic was applied to address the ambiguity in spatial decision-making, allowing cells to have partial membership in multiple suitability classes (Zadeh, 1965). This method is particularly interesting in urban contexts, where boundaries between "suitable" and "unsuitable" areas are rarely distinct.

Different function types are available in QGIS software (version QGIS 3.34). For this study, **sigmoidal** (for non-linear relationships) and **linear** (for proportional relationships) functions were selected based on each criterion's behavior (Table 10). Moreover, it was important to take into account the alignment with the criterion's logic: **increasing function** (the higher the input value, the more suitable the location is) and **decreasing function** (the higher the input value, the less suitable the location is) (Eastman, 1999).

Table 10. Input data, analytical tools, and fuzzy membership functions applied to the criteria in QGIS. Source: by the author based on Aljohani & Thompson, 2020.

Indicator Criteria ID	**Desirable Scenario**	**Input Data Type**	**Rasterization Method** (GIS Analysis Tool)	**Justification for GIS Analysis Tool**	**Fuzzy Membership Function**	**Data Value → Suitability Relationship**
CR01	High density of cycle logistics operators	Vector – point layer	**Point Density (KDE)**	Highlight areas with a high concentration of cycle logistics operators	Linear (increasing)	Direct proportionality: More operators → linearly higher suitability
CR02	Availability of sleeping assets (parking/ vacant buildings	Vector – point layer	**Point Density (KDE)**	Highlights areas with a high concentration of underutilized spaces	Linear (increasing)	Direct proportionality: More idle space → linearly higher suitability
CR03	Close to target residential hotspots for deliveries	Vector – Polygons layer with attribute value (household data)	**Inverse Distance Weighting (IDW)**	Translates neighborhood-level car ownership into a continuous surface	Sigmoid (increasing)	Optimal mid-range: Avoid areas with too few (low demand) or too many (high car ownership → potential congestion)
CR04	Distance to favourable land-use zones	Vector – polygon layer	**Euclidean Distance**	Maximize proximity to favorable zones	Sigmoid (decreasing)	Proximity-based suitability: Proximity to favorable zones → high suitability; locations inside a favorable zone (0m distance) are ideal
CR05	Distance to regional roads	Vector – line layer	**Euclidean Distance**	Maximize proximity to regional roads	Sigmoid (decreasing)	Proximity-based suitability: Proximity to regional roads → high suitability; locations on a regional road (0m distance) are ideal
CR06	Low-traffic areas preferred for cyclists	Vector – line layer with attribute value (speed limit)	**IDW**	*Interpolate*[17] speed limits values from road segments into a continuous surface	Linear (decreasing)	Hierarchical variation: higher suitability → speeds ≤ 30 km h^{-1}, declining linearly → Between 30 and 50 km h^{-1}; and score = 0 → speed ≥ 50 km h^{-1}

[17] The IDW approach incorporates attribute values into the analysis. For CR06, it spreads the influence of each road segment's traffic condition into the nearby urban space, simulating how traffic affects accessibility and cyclist comfort beyond the street itself. Therefore, IDW enables a more nuanced representation of the urban traffic landscape, prioritizing zones of low traffic that are more suitable for cycling-based deliveries.

CR07	Distance from areas with access restrictions	Vector – polygon layer	**Euclidean Distance**	Minimize proximity to conflict areas	Sigmoid (increasing)	Distance-based avoidance Farther from restricted zones → more suitable
CR08	Distance to areas with lower rental costs	Vector – polygon layer with attribute value (Rental cost data)	**IDW**	Translates rental cost values into a continuous surface	Sigmoid (decreasing)	Gradual variation: Represents a cost-suitability gradient; lower rental cost → more suitable
CR09	High density of delivery destinations—goods receivers	Vector – line layer transformed to a point layer	**Point Density (KDE)**	Highlight areas with a high concentration of delivery destinations—goods receivers	Sigmoid (increasing)	Line layer of receiver frontages; higher density → higher suitability
CR10	Distance to bike routes	Vector – line layer	**Euclidean Distance**	Maximize proximity to bike infrastructure	Sigmoid (decreasing)	Proximity-based suitability: closer a cell is to cycling infrastructure → high suitability; locations on bike routes (0m distance) are ideal
CR11	Compatibility with livability standards	**Mixed:** Vector – point layer (Road Accidents) **+** Vector – polygon layer with attribute value (Black Carbon Exposure data)	**Point Density** (Road Accidents) + **IDW** (Black Carbon) → Combine both	Convert to points (or use line midpoints), interpolate with IDW to spread values smoothly	Sigmoid (decreasing)	Distance-based avoidance: Far from areas with higher levels of air pollution and higher recorded accidents → more suitable

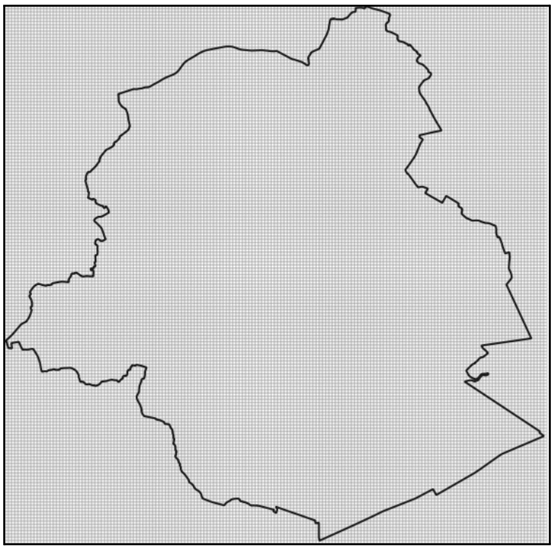
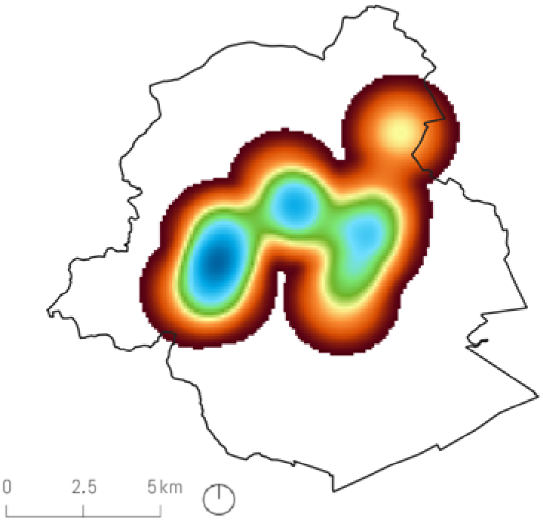
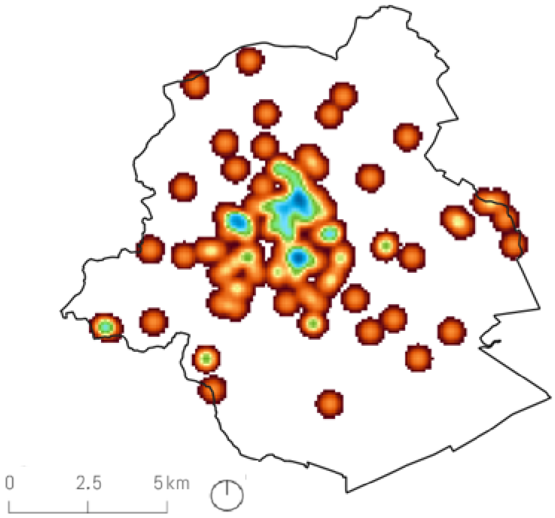


Figure 20. Reference 100x100 m grid within the boundaries of the Brussels Capital Region. Source: By the author, based on opendata.brussels, 2025.

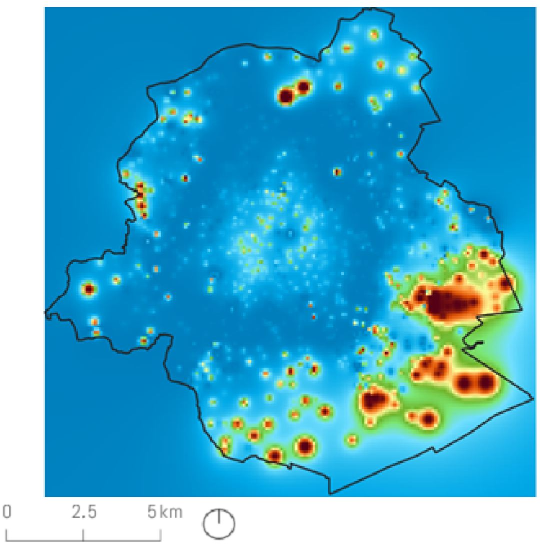
All vector-based map layers were converted to raster format (100 m x 100 m) within the boundaries of the Brussels-Capital Region (Figure 20). Using QGIS's *Raster Calculator*, cell values for each criterion were normalized and rescaled to a 0–255 dimensionless scale, where 0 indicates fully unsuitable and 255 highly suitable. This gradient represents the degree of membership in the "suitability" fuzzy set. The criteria processing and normalization procedures (Stage 3 and Stage 4) are described in detail in Appendix E, and visual results (output raster maps) are shown in Figure 21.



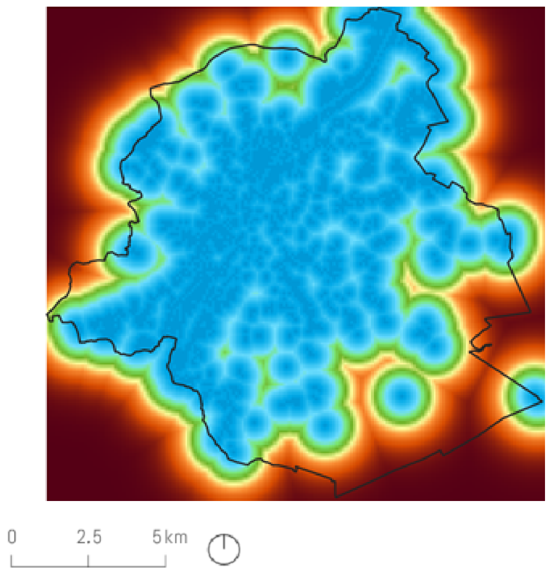
CR01: Cycle-logistics carriers' locations



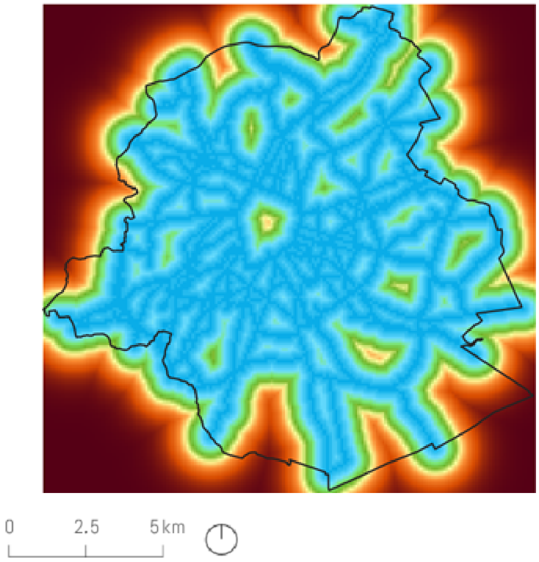
CR02: Sleeping assets



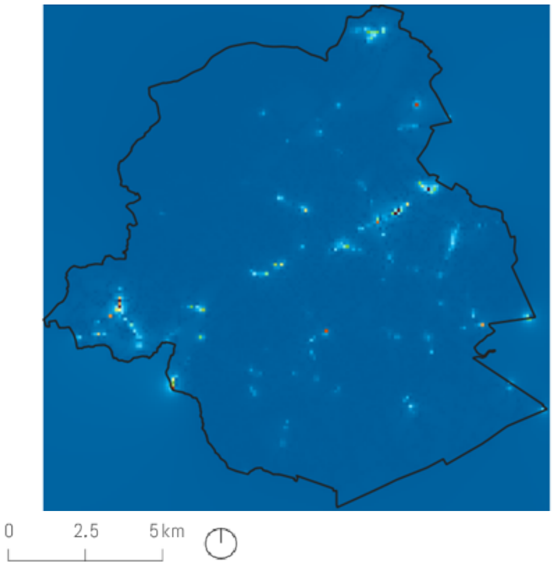
CR03: Share of households with a company car — residential hotspots for deliveries



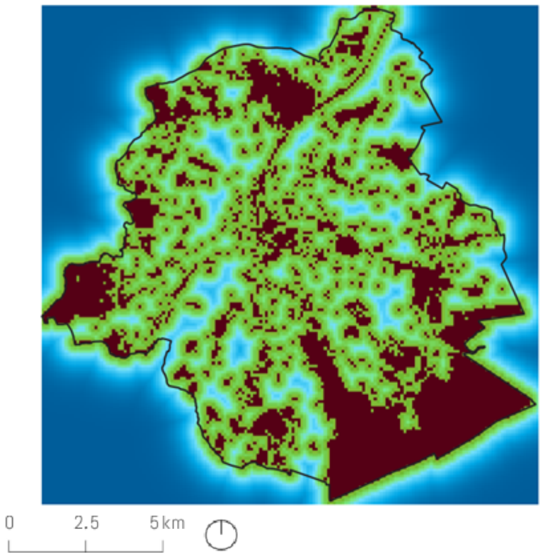
CR04: Compatible land-use zones designations



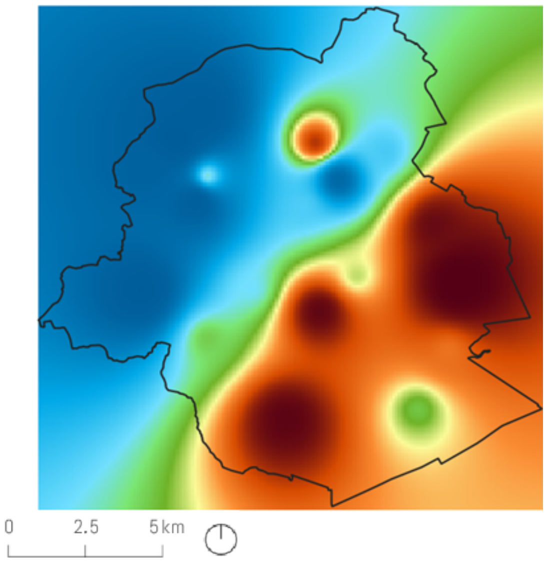
CR05: Road network of regional roads in BCR



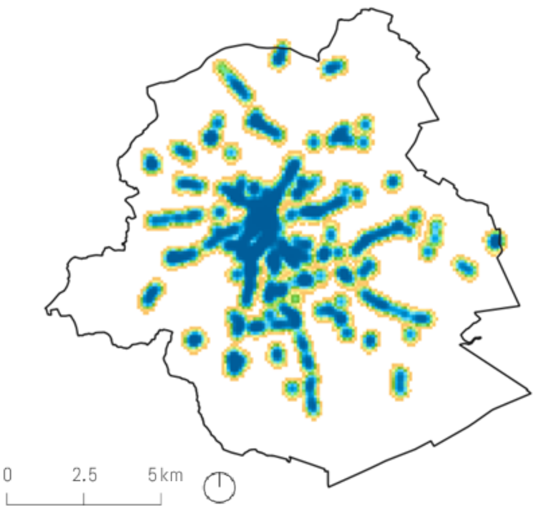
CR06: 30 zones in BCR



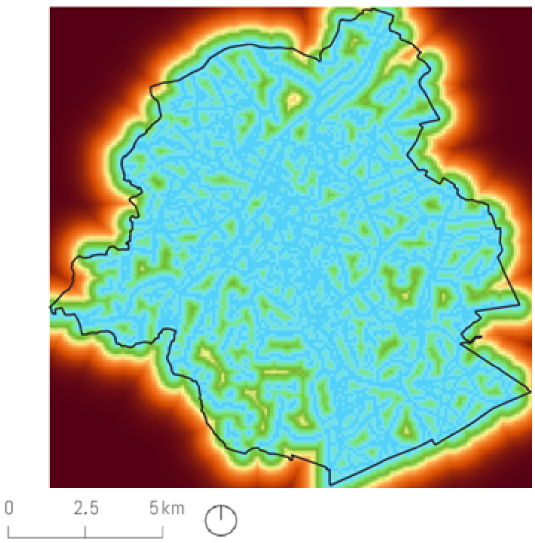
CR07: Areas with access restrictions



CR08: Average rental price



CR09: Commercial central strips—goods receivers



CR10: Bicycle routes in BCR

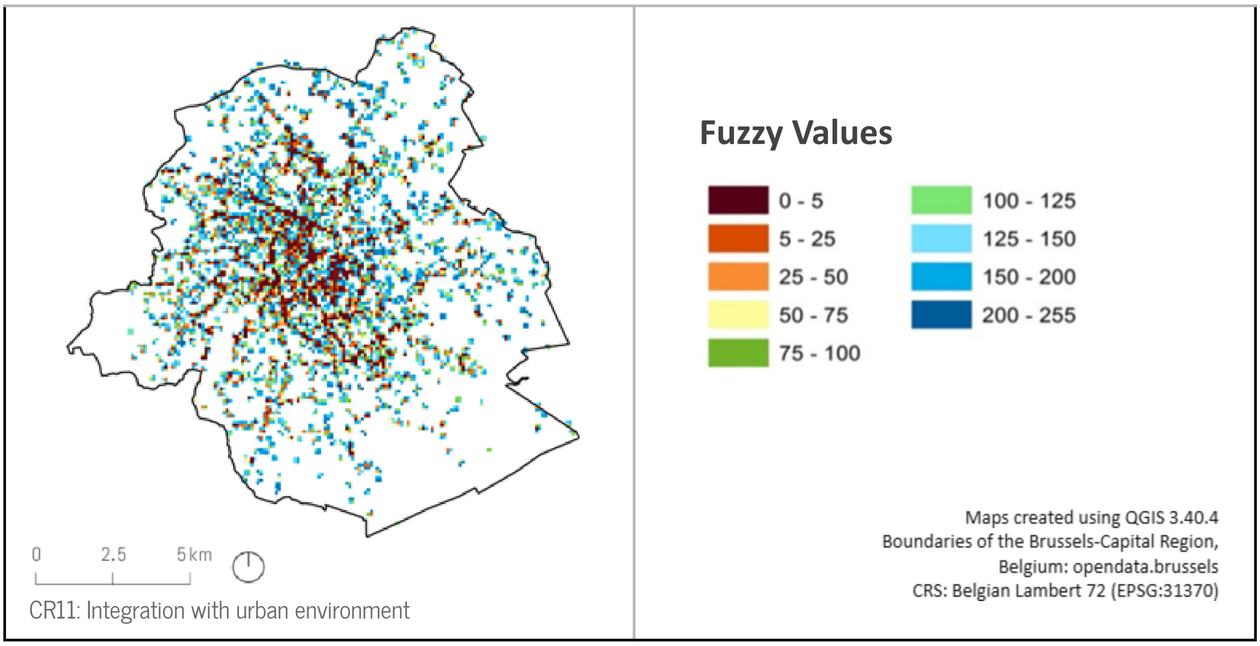


Figure 21. Normalized raster layers.
Source: by the author based on sources presented in Table 6.

Because QGIS lacks ArcGIS's *Point Density* tool (ESRI, 2025b), point layers for CR01, CR02, CR09, and CR11 were rasterized using *Kernel Density Estimation* (KDE). Unlike *Point Density*, KDE assigns values only where the kernel is evaluated, leaving other cells as NoData. These blank areas appeared as white gaps and would have been excluded from further calculations.

To address this, KDE outputs were processed in Raster Calculator using the expression $A \times (A \geq 0)$, where A is the raster's first band. The Boolean term ($A \geq 0$) assigns a value of 1 to valid cells and 0 to NoData, replacing the sentinel with a true zero while preserving non-negative KDE values (WOAH, 2022). This ensured continuous coverage and compatibility for subsequent analyses.

Stage 5: Land suitability analysis for candidate site identification

This stage integrated the eleven criteria into a single suitability surface using the *RasterMCDA* plugin for QGIS 3.34 (Andreas, 2021/2023). Final suitability scores were calculated by summing the product of each criterion's fuzzy value and its corresponding weight, following the framework of Aljohani and Thompson (2020). The plugin replicates ArcGIS's *Weighted Fuzzy AHP Overlay* (ESRI, 2025a), ensuring methodological parity within an open-source environment.

Before running *RasterMCDA*, all raster layers were prepared through:

(1) **Gap filling (NoData → 0):**

Residual *NoData* values were replaced with true zeros using *Raster Calculator*, applying (QGIS, 2025b). For each input layer, *A* is the raster's first band.

$$(A = -3.4028235\times10^{-38})\times 0 + (A \neq -3.4028235\times10^{-38})\times A$$

For each raster, every pixel that equals the layer-specific sentinel[18] (-3.4028235×10^{-38}) is reassigned to 0, and all other values are left untouched.

(2) **0–1 normalization:**

Each raster was scaled to the unit interval [0, 1] using the tool Raster Calculator and applying the expression:

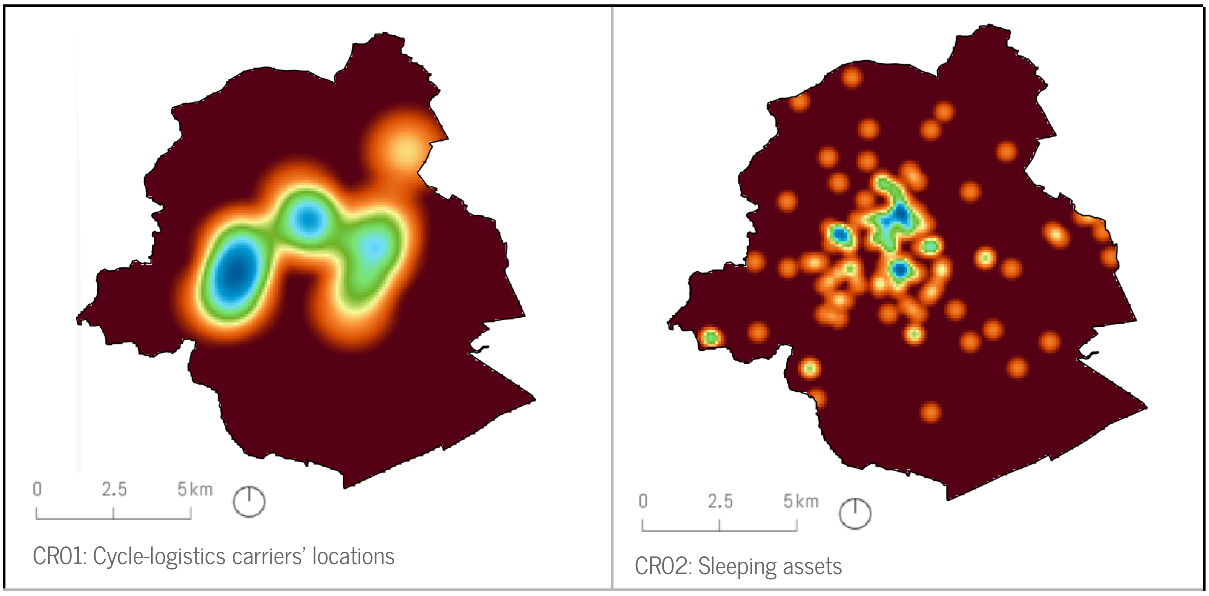
$$New\ norm\ layer = \frac{x - min}{max - min}$$

Where: x is a pixel value, and min/max are the raster's minimum and maximum real values.

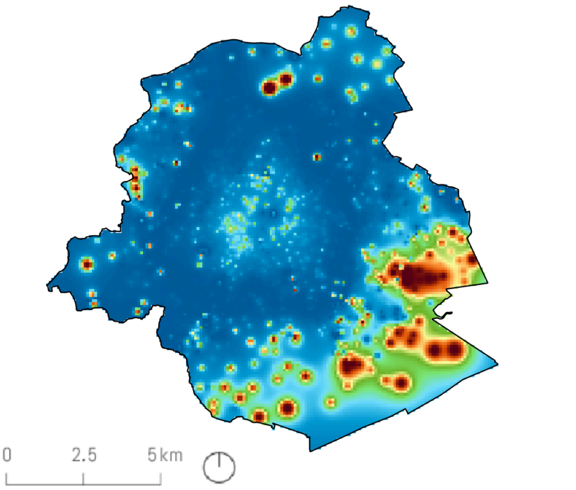
The result was confirmed by accessing the Layer Properties, where Min approached 0 and Max did not exceed 1. Outputs were labeled **CR0i_norm.**

(3) **Final preparation:**

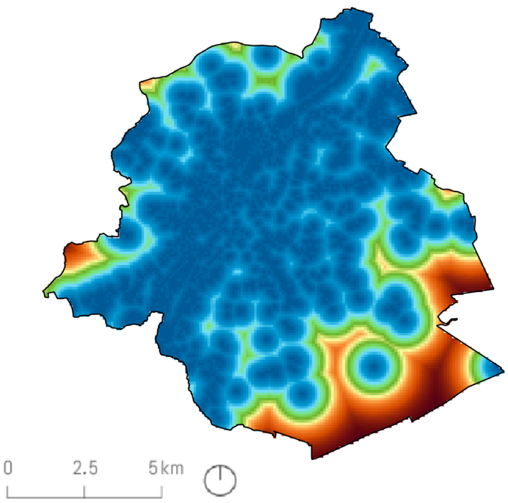
All normalized rasters were clipped to the Brussels-Capital Region polygon using *Clip Raster by Mask Layer* (Figure 22), ensuring a consistent study area and reduced processing time. With no null cells and a standardized value range, the dataset was ready for weighting and overlay analysis in *RasterMCDA*.



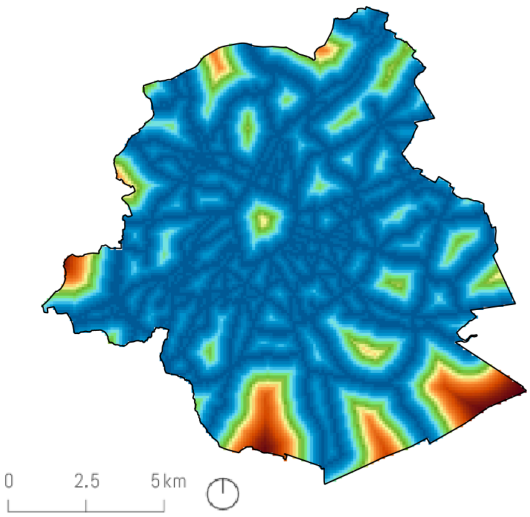
[18] A layer-specific sentinel is the numeric value stored in a raster's metadata that marks cells with "no data" (QGIS, 2025b).



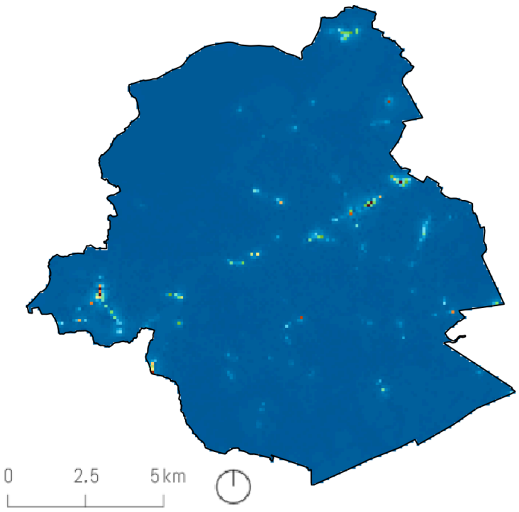
CR03: Share of households with a company car — residential hotspots for deliveries



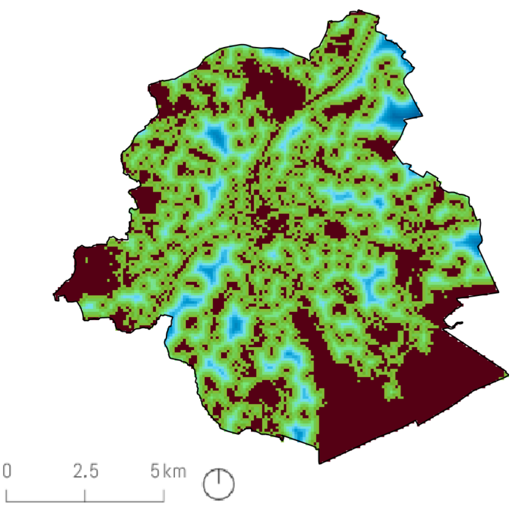
CR04: Compatible land-use zones designations



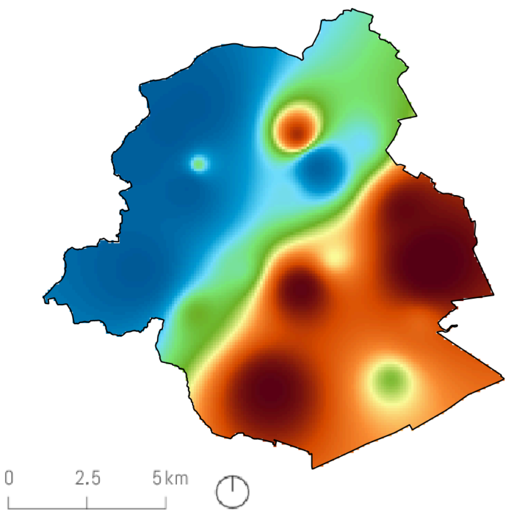
CR05: Road network of regional roads in BCR



CR06: 30 Zones in BCR



CR07: Areas with access restrictions



CR08: Average rental price

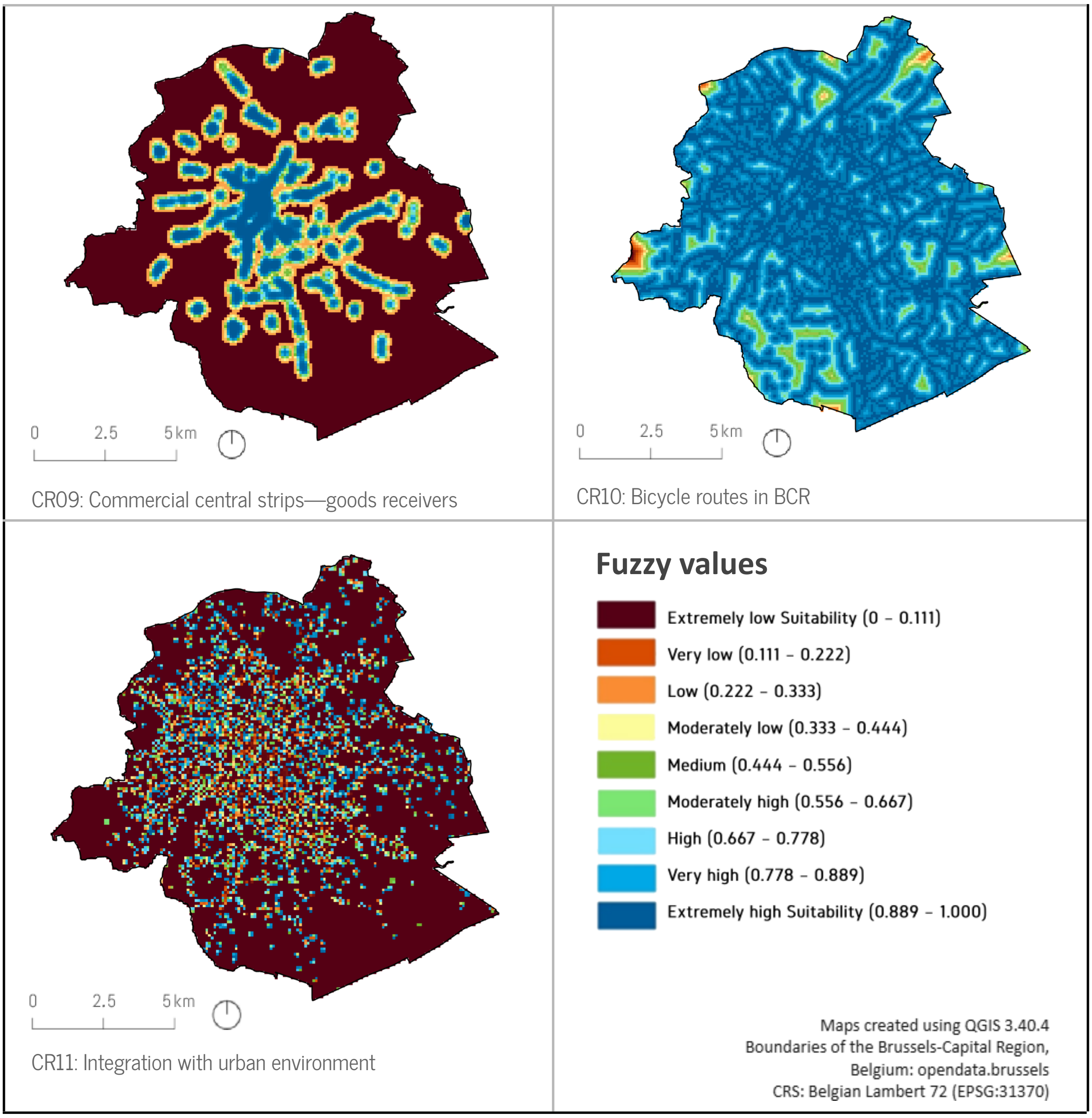


Figure 22. Preprocessed and Clipped Raster Layers for Stage 5 Land Suitability Analysis.
Source: By the author, based on sources presented in Table 6.

Once the eleven preprocessed rasters were loaded in QGIS, the analysis proceeded in the *RasterMCDA* plugin, incorporating the weights derived from stakeholder responses in Stage 2. Table 11 presents the results.

Table 11. Criteria Weights and Classification for the Land Suitability Analysis.
Source: by the author.

Rank	Category	ID	Criteria	Weight values summing 1 (decimal)	Weight (%)
1	Logistics Land-Use and Attributes	**CR03**	Target demographic attributes	0.297429	29.74
2	Suitability Indicators	**CR09**	Existing goods receivers in the area	0.248512	24.85
3	Transport Accessibility Indicators	**CR07**	Access restrictions in the area	0.119910	11.99
4	Logistics Land-Use and Attributes	**CR02**	Sleeping assets (idle real estate)	0.077242	7.72
5	Transport Accessibility Indicators	**CR06**	Traffic intensity on major roads	0.073427	7.34
6	Suitability Indicators	**CR11**	Integration with the urban environment	0.069596	6.96
7	Suitability Indicators	**CR08**	Facility rental costs	0.057601	5.76
8	Transport Accessibility Indicators	**CR05**	Proximity to major freight corridors	0.047338	4.73
9	Logistics Land-Use and Attributes	**CR04**	Primary land-use zones	0.008647	0.86
10	Logistics Land-Use and Attributes	**CR01**	Existing distribution centres/warehouses	0.000150	0.02
11	Logistics Land-Use and Attributes	**CR10**	Proximity to cycling infrastructure	0.000148	0.01

The *Raster* module of the RasterMCDA plugin was opened, and the eleven preprocessed rasters were imported as criteria, with the *Type* column set to *benefit*[19] (Andreas, 2021/2023). Criterion weights, derived in Stage 2, were added so that the *Weight* column summed to exactly 1. The decision rule was set to *Weighted Linear Combination* (WLC), which multiplies each normalized raster by its weight and sums the results:

$$S(x, y) = \sum_{i=1}^{n} i = w_i r_i(x, y)$$

Where w_i is the criterion weight and $r_i(x, y)$ the cell value at the position (x, y).

Running the tool produced a raster in which each 100 m cell expresses overall suitability on a 0–1 scale, generating the land-suitability map for the Brussels-Capital Region (BCR) (Figure 23). After

[19] In this study every criterion raster was preprocessed in Stage 4 so that its values range from least suitable (cost) to most suitable (benefit). For factors that were originally “cost-type”, a decreasing fuzzy function was applied, inverting the scale. As a result, all layers now behave as Benefit layers in RasterMCDA; therefore, the *Type* field for every criterion was set to Benefit during the Weighted Linear Combination step.

creating the continuous suitability surface, the next step was to isolate the highest-scoring locations. The top 5% of cells were selected by identifying the 95th-percentile value (0.825 473) in the raster statistics. Using the *Reclassify by Table* tool, values below 0.825 473 were set to 0, and those from 0.825 473 to 1 were set to 1. The resulting binary raster highlights the most suitable locations in the BCR (value = 1, shown in dark blue in Figure 24).

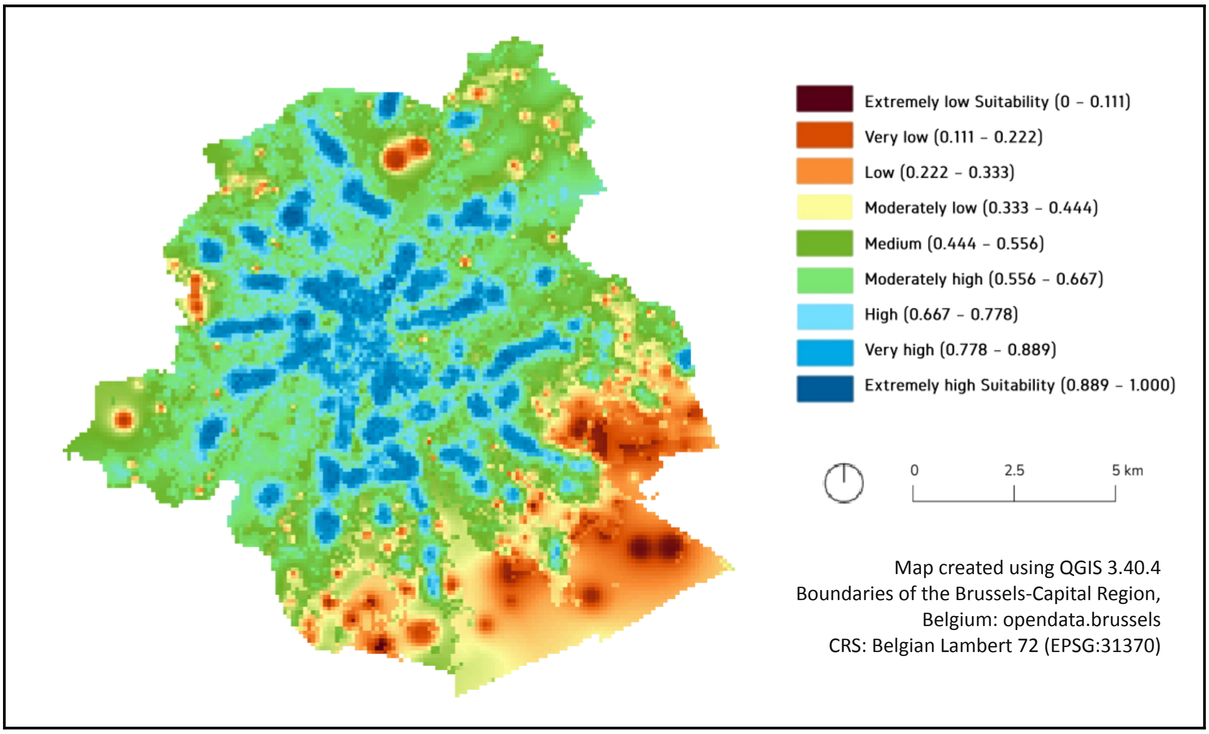


Figure 23. Land suitability score map after using the RasterMCDA plugin to apply weights to the criteria.
Source: by the author.

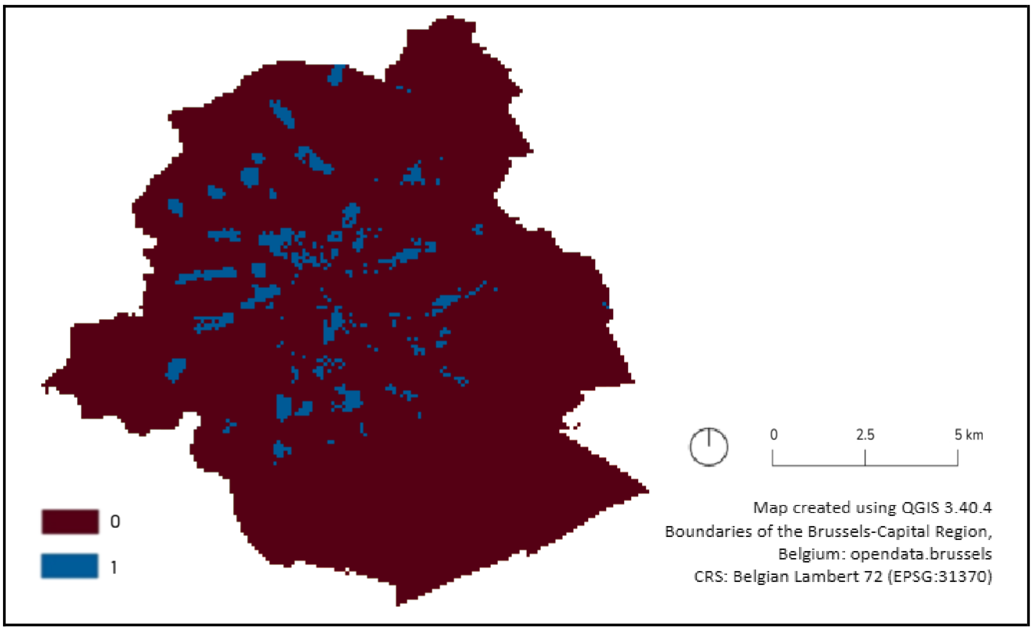


Figure 24. Suitability raster (0–1) showing the top 5% of locations in the BCR (value = 1, dark blue).
Source: by the author.

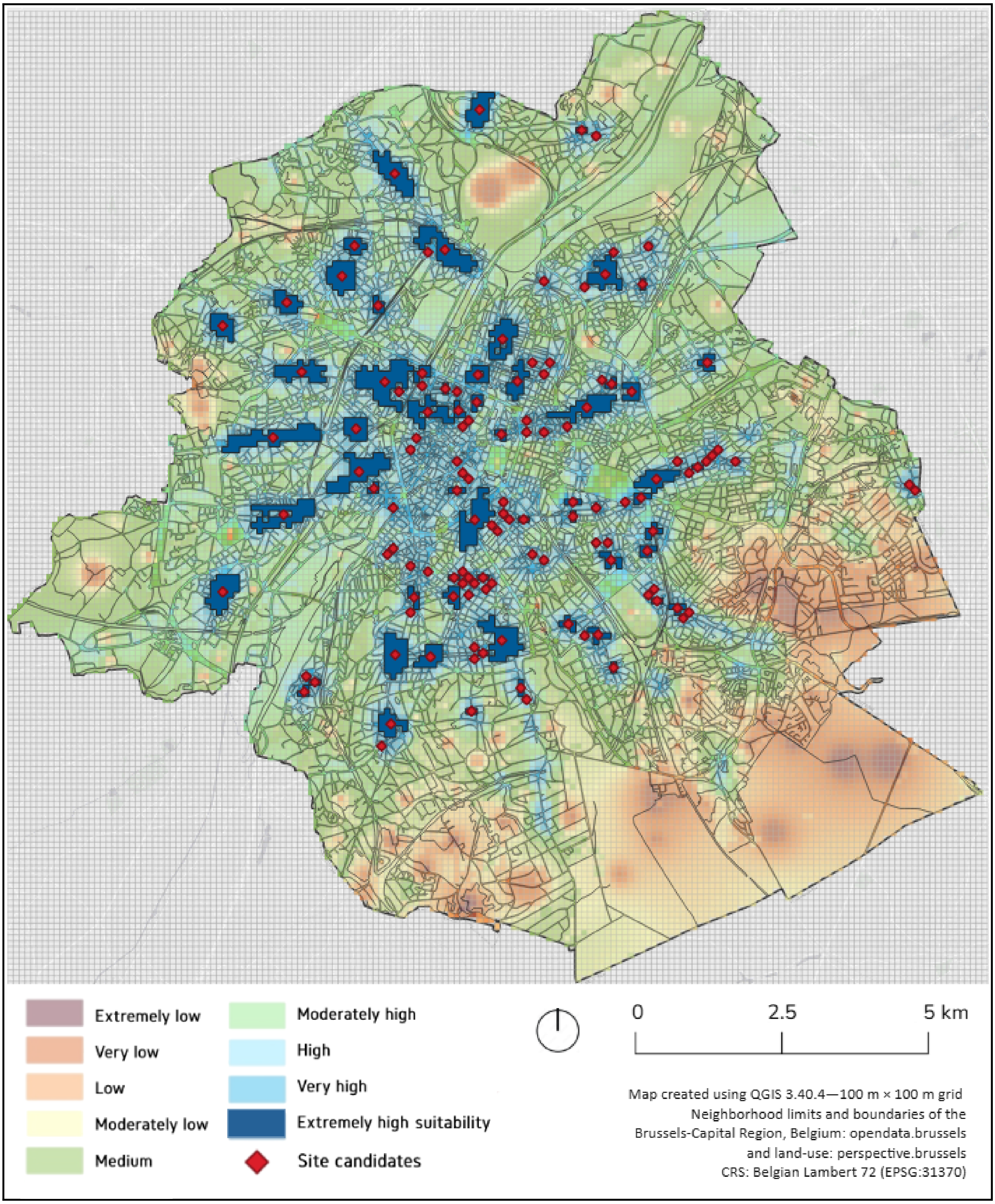


Figure 25. Candidate-site centroids: red points representing high-suitability parcels for locating nano-hubs in the Brussels-Capital Region. Source: by the author.

To prepare these high-suitability cells for further analysis, the binary raster was vectorized with the *Polygonize* algorithm, converting each contiguous block of value = 1 cells into a polygon feature. These polygons were then converted into point features using the *Centroids* tool, yielding 127 candidate site points. This output layer served as the working dataset for Stage 6 (Figure 25).

Stage 6: Rank the identified candidate sites using TOPSIS

The final stage of the GIS-based analysis involves evaluating and ranking potential sites for the nano-hubs. After the 127 nano-hub centroids had been digitized as a point layer, the next task was to give every point a suitability value derived from the "land suitability score map" (Figure 24) created in Stage 5. Doing so transforms the centroids from simple geometric placeholders into fully quantified alternatives that can be filtered and ranked. For each point, the operation is to read the value of the composite raster cell that lies directly underneath it. Because the raster already expresses the weighted, fuzzy suitability of every 100 m × 100 m location in the BCR, this "point-sampling" step merely transfers information. To guarantee a one-to-one match, both layers were first confirmed to share the Belgian Lambert 72 projection (EPSG 31370) and identical spatial extents; the raster needed no further resampling because its 100 m grid was fixed during Stage 5.

In QGIS 3.40.4, the *Sample Raster Values* tool was used to assign land suitability scores to each candidate site. The point layer containing the site candidates was set as the input, and the raster layer with the suitability scores was selected as the source to sample. The algorithm created a new field (*SAMPLE_1* by default) in the attribute table, storing the score for each site. The resulting layer was then saved for subsequent analyses (Figure 26). For clarity, Table 12 lists all 127 candidate sites sorted in descending order of score, from highest to lowest suitability. The same sampling method was applied to each normalized criterion individually for later use.

Table 12. Candidate-site scores in descending order.
Source: by the author.

ID	Site score
S1	0.972865
S2	0.959173
S3	0.958599
S4	0.943926
S5	0.913056
S6	0.910704
S7	0.909059
S8	0.908236
S9	0.904133
S10	0.903396
S11	0.902857
S12	0.893814
S13	0.890958
S14	0.889970
S15	0.889914
S16	0.889773
S17	0.889287
S18	0.889042

S19	0.888957
S20	0.888673
S21	0.887591
S22	0.887095
S23	0.884689
S24	0.884653
S25	0.884089
S26	0.883856
S27	0.882577
S28	0.881810
S29	0.881275
S30	0.880144
S31	0.879089
S32	0.876686
S33	0.876663
S34	0.873715
S35	0.873449
S36	0.873077
S37	0.871157
S38	0.870004
S39	0.868949
S40	0.868289
S41	0.867406
S42	0.866483
S43	0.866393
S44	0.866092
S45	0.864562
S46	0.864340
S47	0.862639
S48	0.861987
S49	0.861668
S50	0.860138
S51	0.860047
S52	0.859285
S53	0.857638
S54	0.857559
S55	0.853943
S56	0.853935
S57	0.853495
S58	0.853384
S59	0.853268
S60	0.852676
S61	0.852376
S62	0.852084
S63	0.851764
S64	0.851253
S65	0.851112
66	0.850963
S67	0.850219
S68	0.849835
S69	0.849714
S70	0.849197
S71	0.849132
S72	0.847251
S73	0.846949
S74	0.846589
S75	0.846430
S76	0.845828
S77	0.845743

S78	0.844315
S79	0.844074
S80	0.843437
S81	0.843285
S82	0.843129
S83	0.842222
S84	0.842179
S85	0.841836
S86	0.841586
S87	0.841577
S88	0.841251
S89	0.839358
S90	0.838364
S91	0.838211
S92	0.838179
S93	0.838137
S94	0.838079
S95	0.838065
S96	0.837330
S97	0.837118
S98	0.836867
S99	0.836179
S100	0.835754
S101	0.835702
S102	0.835133
S103	0.834485
S104	0.833598
S105	0.832795
S106	0.832640
S107	0.832206
S108	0.832126
S109	0.831724
S110	0.831550
S111	0.829875
S112	0.829474
S113	0.829406
S114	0.829222
S115	0.828783
S116	0.828557
S117	0.828412
S118	0.828342
S119	0.827854
S120	0.827435
S121	0.826698
S122	0.826622
S123	0.826555
S124	0.826311
S125	0.825818
S126	0.825660
S127	0.818005

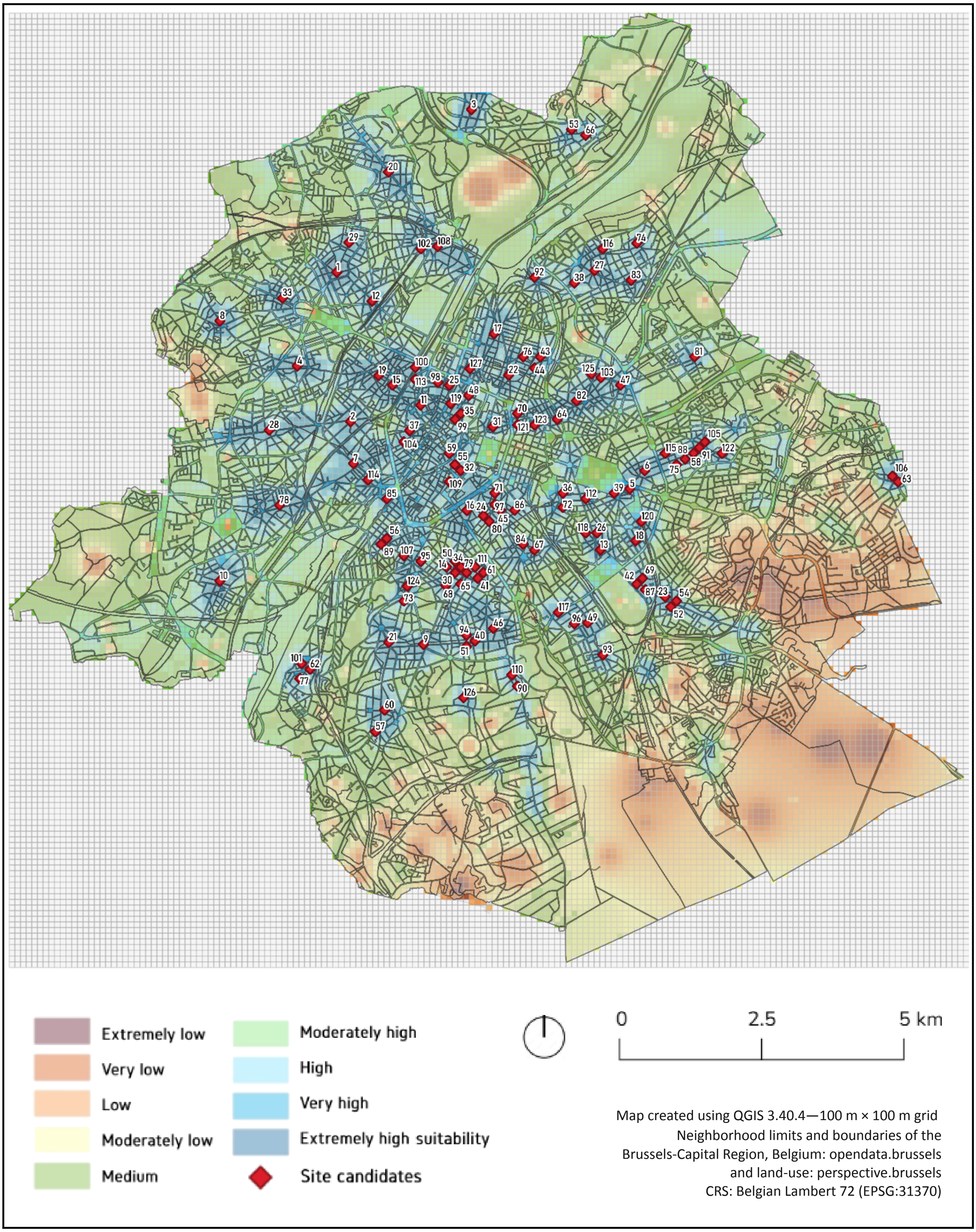


Figure 26. Candidate-site locations with IDs corresponding to Table 12. For clarity in visualization, the "S" prefix used in the table has been removed from the map labels.
Source: by the author.

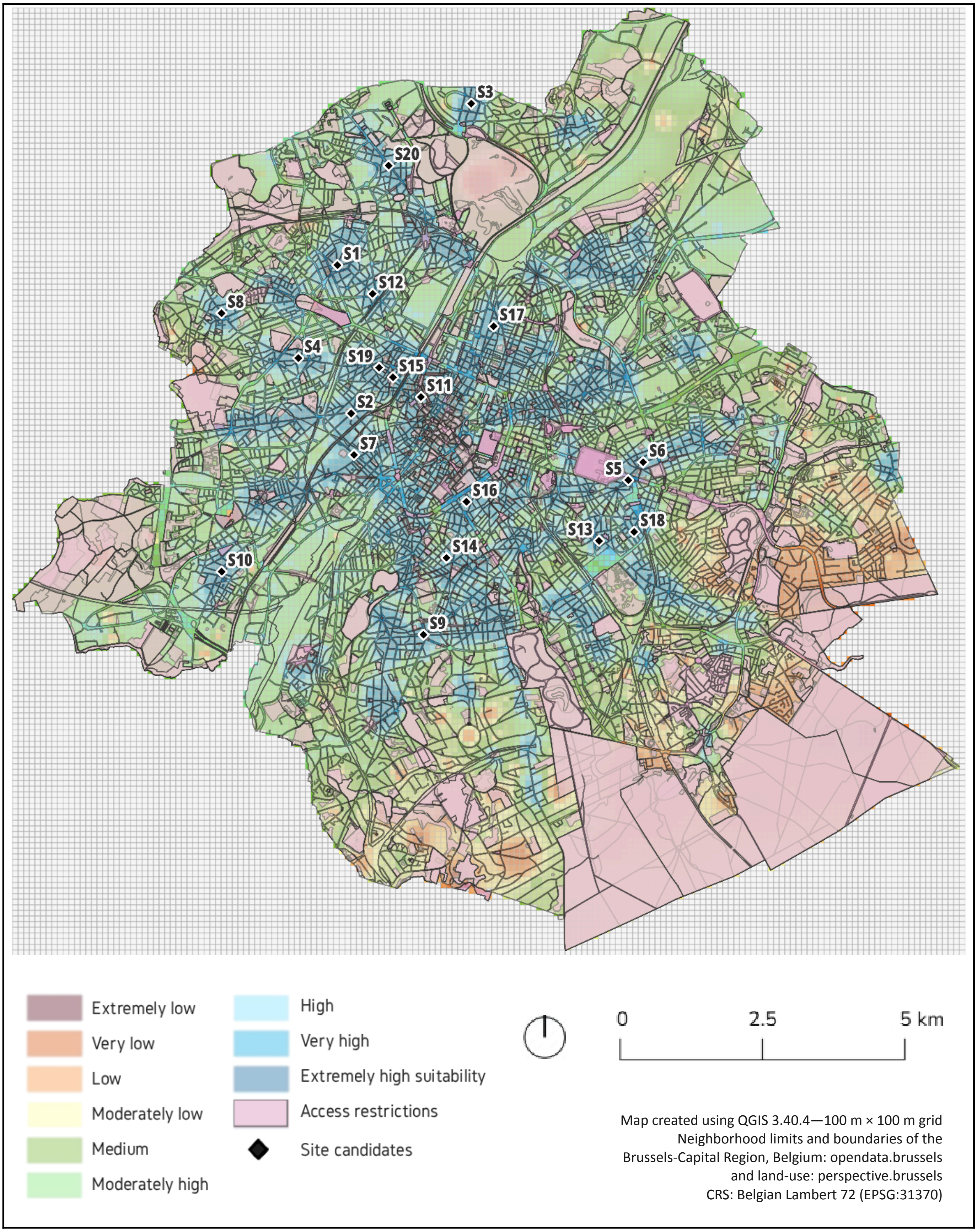


Figure 27. 20 shortlisted candidate-site locations with ID.
Source: by the author.

Because some of the 20 shortlisted candidate sites could still fall inside zones where development is restricted, the *CR07 – Access restrictions* layer was overlaid to confirm that every candidate lies in an area where placing a nano-hub is allowed. Additionally, to keep Stage 6 analytically tractable while still honoring operational realities, the 127 candidate centroids were trimmed to the **twenty most suitable nanohub locations** (Figure 27). This decision was based on the following aspects:

(1) **Keeps the analysis readable:** With 11 criteria, a 20 × 11 decision matrix has 220 numbers—big enough to show useful patterns but still small enough to check by eye. Analyzing all 127 sites would blow the matrix up to almost 1,400 cells and make the results hard to follow.

(2) **Lines up with earlier research**: In their Inner‑Melbourne study, Aljohani and Thompson (2020) also stopped at 20 alternatives. Adopting the same limit lets this study stay consistent with the framework method while accounting for (i) Brussels' larger study area, three times larger ≈ 161 km² compared to the author's study area; and (ii) the smaller footprints of nano-hubs compared to the conventional urban consolidation centers the authors are considering.

For the next step, following the framework, the authors are using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Aljohani & Thompson, 2020). This concept was developed by Hwang & Yoon (1981) and operates on the principle that optimal solutions should simultaneously:

(1) Minimize distance from the **Positive Ideal Solution (PIS)**: Represents the hypothetical alternative that scores best on all benefit criteria (in this study, it is *demographic attributes*, related to residential zones with high demand for deliveries) and worst on all cost criteria (which in this study is *proximity to cycling infrastructure*).

(2) Maximize distance from the **Negative Ideal Solution (NIS)**: Represents the opposite extreme (poor performance on benefit criteria, high scores on cost criteria).

The objective of stage 6 is then to evaluate and rank the 20 candidate locations by computing their relative closeness to the ideal best- and worst-performing sites, based on the 11 criteria.

The starting point for this analysis was the raw decision matrix (X_{ij}) shown in Table 13, containing the set of alternatives (m) and criteria (n) (Barman et al., 2024), as shown in the following equation and according to the TOPSIS theory (Hwang & Yoon, 1981):

$$\text{Raw decision matrix } (X_{ij}) \;=\; \begin{matrix} A_1 \\ A_2 \\ A_i \\ \vdots \\ A_m \end{matrix} \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2j} & \cdots & x_{2n} \\ \vdots & \vdots & 0 & \vdots & 0 & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \vdots & 0 & \vdots & 0 & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix}$$

This matrix includes fuzzy-normalized suitability scores for each of the 20 candidate sites (rows) across the 11 criteria CR01 to CR11 (columns), derived from Stage 4 of the framework analysis. This matrix was built by sampling the corresponding raster on QGIS. Sample raster values were combined with the 20 shortlisted candidate sites (Figure 28). All layers were checked to confirm that they share the same CRS (Belgian Lambert 72, EPSG 31370) and grid.

Table 13. Raw scores for each candidate site (S1–S20) across the 11 criteria (CR01–CR11).
Source: by the author

	Criteria										
Site	**CR01**	**CR02**	**CR03**	**CR04**	**CR05**	**CR06**	**CR07**	**CR08**	**CR09**	**CR10**	**CR11**
S1	0.830109	0.871418	0.999989	1	1	0.99978	0.776332	0.994201	1	1	0.988082
S2	0.800078	0.81057	0.999716	1	1	0.999765	0.747069	0.991464	1	1	0.98063
S3	0.724391	0.78976	0.999715	1	1	0.999473	0.727661	0.986413	0.999999	1	0.962442
S4	0.710691	0.661365	0.999517	1	1	0.999391	0.727661	0.984298	0.999997	1	0.952103
S5	0.699703	0.647264	0.999274	1	1	0.998811	0.720839	0.983802	0.999995	1	0.927425
S6	0.695541	0.584482	0.998924	1	1	0.998711	0.683657	0.977172	0.999974	1	0.919665
S7	0.663318	0.572155	0.998333	1	1	0.998618	0.658419	0.966718	0.999962	1	0.90446
S8	0.660835	0.551168	0.998165	1	1	0.998602	0.658419	0.96453	0.999958	1	0.899315
S9	0.65669	0.547421	0.998141	1	1	0.998454	0.658419	0.939495	0.999825	1	0.886212
S10	0.652975	0.487645	0.997939	1	1	0.998161	0.658419	0.934229	0.999744	1	0.880078
S11	0.62927	0.482209	0.997762	1	1	0.997974	0.658419	0.891412	0.999738	1	0.874378
S12	0.625628	0.45775	0.997629	1	1	0.99778	0.620278	0.877062	0.999568	1	0.873069
S13	0.614039	0.448381	0.997555	1	1	0.997761	0.620278	0.876318	0.999365	1	0.867522
S14	0.609803	0.445698	0.997496	1	1	0.997695	0.587161	0.876182	0.999298	1	0.862607
S15	0.608049	0.402347	0.996172	1	1	0.997694	0.587161	0.860737	0.999149	1	0.858806
S16	0.590961	0.372233	0.995699	1	1	0.997626	0.574981	0.860602	0.999078	1	0.84926
S17	0.586445	0.353824	0.994375	1	1	0.997527	0.574981	0.814245	0.998998	1	0.844089
S18	0.555175	0.332966	0.994351	1	1	0.997366	0.574981	0.813486	0.998956	1	0.83409
S19	0.555147	0.33212	0.99414	1	1	0.99723	0.574981	0.810821	0.998944	1	0.832562
S20	0.549921	0.317466	0.994043	1	1	0.996919	0.574981	0.809449	0.998862	1	0.828929

To use TOPSIS, a new normalization step was necessary. Even though the input values were fuzzy-scaled, TOPSIS requires **vector normalization**[20] to ensure comparability across dimensions (Hwang & Yoon, 1981). The raw decision matrix was then vector-normalized with the following equation, resulting in $m \times n$ a decision matrix with $m = 20$ candidate sites and $n = 11$ criteria (CR01–CR11).

Vector normalization: $$y_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}}$$

Where:

x_{ij} = raw value of the site j for the criterion i

y_{ij} = normalized value

This was implemented in QGIS using the **Field Calculator**, and the output values were saved in new columns **CR01_norm** to **CR11_norm** (Table 14).

Table 14. Vector-normalized matrix.
Source: By the author

	Criteria										
Site	**CR01_ norm**	**CR02_ norm**	**CR03_ norm**	**CR04_ norm**	**CR05_ norm**	**CR06_ norm**	**CR07_ norm**	**CR08_ norm**	**CR09_ norm**	**CR10_ norm**	**CR11_ norm**
S1	0.283	0.356	0.224	0.224	0.224	0.224	0.266	0.243	0.224	0.224	0.248
S2	0.273	0.331	0.224	0.224	0.224	0.224	0.256	0.243	0.224	0.224	0.246
S3	0.247	0.323	0.224	0.224	0.224	0.224	0.250	0.242	0.224	0.224	0.241
S4	0.243	0.27	0.224	0.224	0.224	0.224	0.250	0.241	0.224	0.224	0.239
S5	0.239	0.264	0.224	0.224	0.224	0.224	0.247	0.241	0.224	0.224	0.232
S6	0.237	0.239	0.224	0.224	0.224	0.224	0.235	0.239	0.224	0.224	0.230
S7	0.226	0.234	0.224	0.224	0.224	0.224	0.226	0.237	0.224	0.224	0.227
S8	0.226	0.225	0.224	0.224	0.224	0.224	0.226	0.236	0.224	0.224	0.225
S9	0.224	0.224	0.224	0.224	0.224	0.224	0.226	0.23	0.224	0.224	0.222
S10	0.223	0.199	0.224	0.224	0.224	0.224	0.226	0.229	0.224	0.224	0.220
S11	0.215	0.197	0.224	0.224	0.224	0.224	0.226	0.218	0.224	0.224	0.219
S12	0.214	0.187	0.224	0.224	0.224	0.223	0.213	0.215	0.224	0.224	0.219
S13	0.21	0.183	0.224	0.224	0.224	0.223	0.213	0.215	0.224	0.224	0.217
S14	0.208	0.182	0.224	0.224	0.224	0.223	0.202	0.215	0.224	0.224	0.216
S15	0.208	0.164	0.223	0.224	0.224	0.223	0.202	0.211	0.224	0.224	0.215
S16	0.202	0.152	0.223	0.224	0.224	0.223	0.197	0.211	0.223	0.224	0.213
S17	0.200	0.144	0.223	0.224	0.224	0.223	0.197	0.199	0.223	0.224	0.211
S18	0.189	0.136	0.223	0.224	0.224	0.223	0.197	0.199	0.223	0.224	0.209
S19	0.189	0.136	0.223	0.224	0.224	0.223	0.197	0.199	0.223	0.224	0.209
S20	0.188	0.130	0.223	0.224	0.224	0.223	0.197	0.198	0.223	0.224	0.208

[20] The fuzzy normalization (Stage 4) and vector normalization (Stage 6) are different; vector normalization used in TOPSIS doesn't constrain values to the [0, 1] interval. Instead, it standardizes criteria measured in different units to make them comparable on a common scale, not necessarily from 0 to 1 (Bouhedja et al., 2024).

In the next step, this result was multiplied by the AHP weight[21] vector ($\sum \omega i_j = 1$), where criteria are expressed as fuzzy suitability scores (0–1, 1 = better). **The weighted decision matrix** (Table 15) was then obtained, in which each weighted criterion, **CR01_w** to **CR11_w,** was calculated in QGIS with the expression:

$$w_{ij} = y_{ij}\,\omega_{ij}$$

Where:

i = 1, 2, 3, ..., m *and* j = 1, 2, 3, ..., n

w_{ij} is the weighted normalized matrix of y_{ij} the normalized matrix and

ω_{ij} is the weight of each criterion.

Table 15. Weighted decision matrix.
Source: By the author

Criteria											
Site	**CR01_w**	**CR02_w**	**CR03_w**	**CR04_ w**	**CR05_ w**	**CR06_ w**	**CR07_w**	**CR08_w**	**CR09_w**	**CR10_w**	**CR11_w**
S1	4.25E-05	0.027498	0.066624	0.001937	0.010604	0.016448	0.031896	0.013997	0.055667	3.32E-05	0.016367
S2	4.1E-05	0.025567	0.066624	0.001937	0.010604	0.016448	0.030697	0.013997	0.055667	3.32E-05	0.016235
S3	3.71E-05	0.024949	0.066624	0.001937	0.010604	0.016448	0.029978	0.013939	0.055667	3.32E-05	0.015905
S4	3.65E-05	0.020855	0.066624	0.001937	0.010604	0.016448	0.029978	0.013882	0.055667	3.32E-05	0.015773
S5	3.59E-05	0.020392	0.066624	0.001937	0.010604	0.016448	0.029618	0.013882	0.055667	3.32E-05	0.015311
S6	3.56E-05	0.018461	0.066624	0.001937	0.010604	0.016448	0.028179	0.013767	0.055667	3.32E-05	0.015179
S7	3.39E-05	0.018075	0.066624	0.001937	0.010604	0.016448	0.0271	0.013651	0.055667	3.32E-05	0.014981
S8	3.39E-05	0.017379	0.066624	0.001937	0.010604	0.016448	0.0271	0.013594	0.055667	3.32E-05	0.014849
S9	3.36E-05	0.017302	0.066624	0.001937	0.010604	0.016448	0.0271	0.013248	0.055667	3.32E-05	0.014651
S10	3.35E-05	0.015371	0.066624	0.001937	0.010604	0.016448	0.0271	0.013191	0.055667	3.32E-05	0.014519
S11	3.23E-05	0.015217	0.066624	0.001937	0.010604	0.016448	0.0271	0.012557	0.055667	3.32E-05	0.014453
S12	3.21E-05	0.014444	0.066624	0.001937	0.010604	0.016374	0.025541	0.012384	0.055667	3.32E-05	0.014453
S13	3.15E-05	0.014135	0.066624	0.001937	0.010604	0.016374	0.025541	0.012384	0.055667	3.32E-05	0.014321
S14	3.12E-05	0.014058	0.066624	0.001937	0.010604	0.016374	0.024222	0.012384	0.055667	3.32E-05	0.014255
S15	3.12E-05	0.012668	0.066327	0.001937	0.010604	0.016374	0.024222	0.012154	0.055667	3.32E-05	0.014189
S16	3.03E-05	0.011741	0.066327	0.001937	0.010604	0.016374	0.023622	0.012154	0.055418	3.32E-05	0.014057
S17	0.00003	0.011123	0.066327	0.001937	0.010604	0.016374	0.023622	0.011463	0.055418	3.32E-05	0.013925
S18	2.84E-05	0.010505	0.066327	0.001937	0.010604	0.016374	0.023622	0.011463	0.055418	3.32E-05	0.013793
S19	2.84E-05	0.010505	0.066327	0.001937	0.010604	0.016374	0.023622	0.011463	0.055418	3.32E-05	0.013793
S20	2.82E-05	0.010041	0.066327	0.001937	0.010604	0.016374	0.023622	0.011405	0.055418	3.32E-05	0.013727

[21] These values are represented on table 14 as "weight values summing 1 (decimal)".

In the TOPSIS model, the ideal best for each column is its maximum, while the ideal worst is its minimum. For benefit-type criteria (where higher values are more desirable), the **ideal best (PIS)** and **ideal worst (NIS)** for each criterion were computed using, respectively:

$$PIS = A_j^+ = max_i\,(\nu_{ij}) \quad \text{and} \quad NIS = A_j^- = min_i\,(\nu_{ij})$$

The resulting values (Table 16) were:

Table 16. Resulting values for the ideal best (PIS) and ideal worst (NIS) for each criterion.
Source: by the author.

Criterion	PIS (max)	NIS (min)
CR01_w	0.000121045	0.000000000
CR02_w	0.064033796	0.043325951
CR03_w	0.289211889	0.139987706
CR04_w	0.007800313	0.006439996
CR05_w	0.039984021	0.027109096
CR06_w	0.069894115	0.060384772
CR07_w	0.118449354	0.074039930
CR08_w	0.055588609	0.040244054
CR09_w	0.241252526	0.107307620
CR10_w	0.000147781	0.000000000
CR11_w	0.062523893	0.054839271

The next step is to measure the Euclidean distance from both the ideal best (D_i^+) and ideal worst (D_i^-) values (Liu, 2009). The following equations were used in the QGIS, in the resource Field Calculator, one pair of distances for every site, as shown in Table 17.

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (\nu_{ij} - A_j^+)^2} \quad , \quad D_i^- = \sqrt{\sum_{j=1}^{n} (\nu_{ij} - A_j^-)^2}$$

And to calculate the **closeness coefficient** (C_i):

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}$$ (Higher C_i (closer to 1) = better suitability)

This ratio represents how close a site is to the ideal solution.

As the final step, sites were sorted by their TOPSIS scores in **descending order**, sorting the values from the most suitable (**1st place**) to the least suitable (**20th**).

Table 17 presents the final TOPSIS results for the 20 candidate sites and Stage 6. This technique is the MCDA approach, a way to **differentiate and rank** the candidates on more than just that single pixel-based score, as was performed at Stage 5 (Figure 29).

Table 17. Final TOPSIS scores and ranking of candidate sites.
Source: by the author.

Dist_PIS	Dist_NIS	TOPSIS Scores	TOPSIS Rank	Site ID
0.322823	0.128529	0.284765	**1st**	**S10**
0.322728	0.128376	0.284582	**2nd**	**S5**
0.322728	0.128376	0.284582	**3rd**	**S18**
0.322606	0.128177	0.284343	**4th**	**S16**
0.322392	0.127828	0.283923	**5th**	**S13**
0.321904	0.127223	0.283267	**6th**	**S4**
0.321438	0.12665	0.282646	**7th**	**S12**
0.321032	0.126098	0.282017	**8th**	**S17**
0.320964	0.125985	0.281877	**9th**	**S8**
0.320362	0.125153	0.280918	**10th**	**S14**
0.320244	0.124959	0.280678	**11th**	**S1**
0.319929	0.124486	0.280111	**12th**	**S11**
0.319843	0.124331	0.279916	**13th**	**S7**
0.319715	0.124133	0.279675	**14th**	**S2**
0.319308	0.123562	0.279003	**15th**	**S20**
0.3186	0.122593	0.277867	**16th**	**S19**
0.318368	0.122228	0.277415	**17th**	**S6**
0.317812	0.121487	0.276548	**18th**	**S15**
0.317481	0.121018	0.275982	**19th**	**S3**
0.316904	0.120282	0.275128	**20th**	**S9**

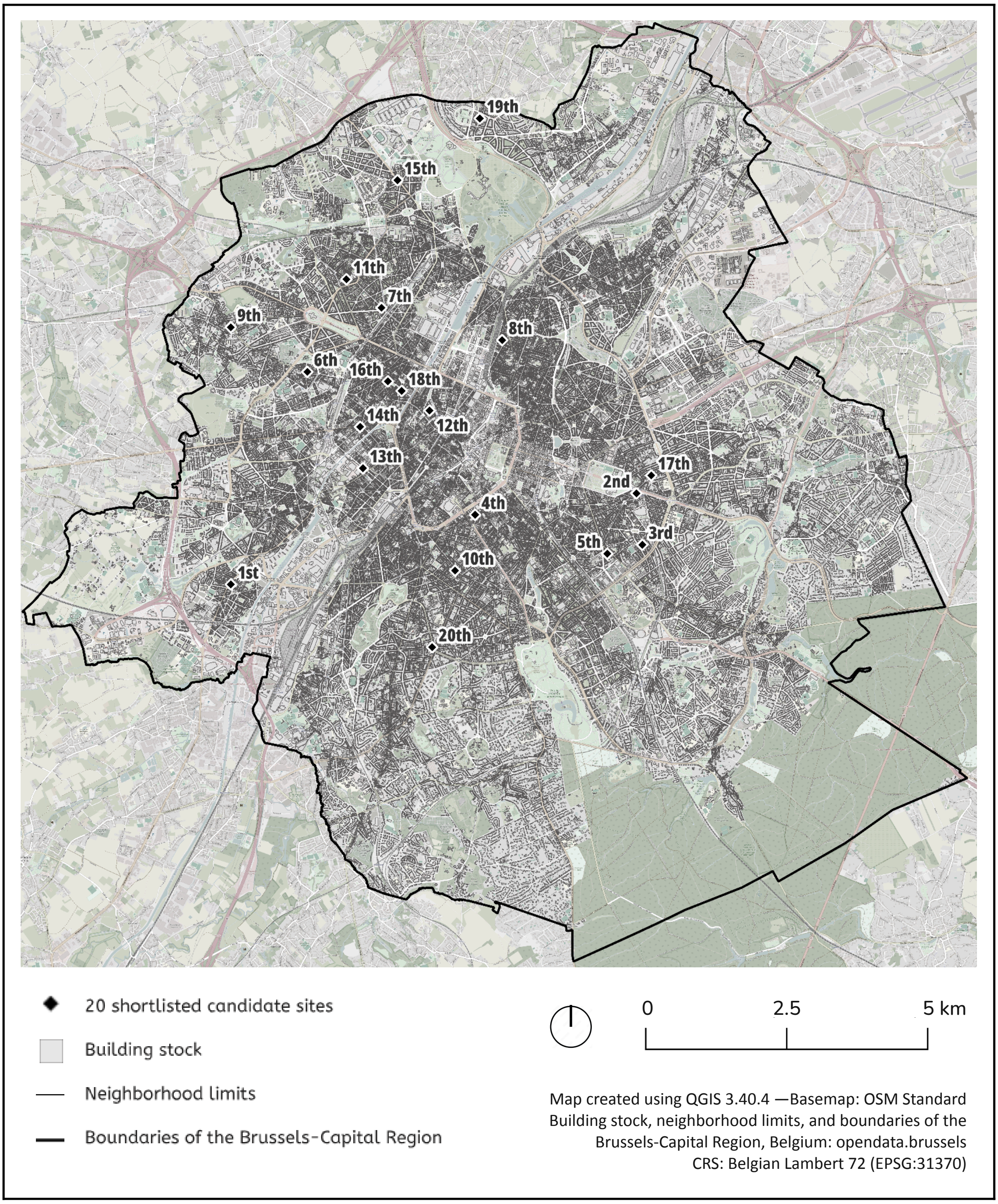


Figure 29. TOPSIS rank for the 20 shortlisted candidate sites.
Source: by the author based on opendata.brussels, 2025.

The analysis showed a relatively narrow spread in closeness scores (TOPSIS), ranging from 0.2751 to 0.2848, yet enough to differentiate between alternatives. The TOPSIS scores were calculated using weighted criteria derived from the Fuzzy AHP procedure, which emphasized, particularly for this study, the **demographic attributes (CR03)**, **proximity to goods receivers (CR09)**, and **access restrictions (CR07)**. These three factors together accounted for over 65% of the total weight, significantly influencing the final ranking.

Although the original GIS-MCDM framework by Aljohani and Thompson (2020) includes a sensitivity analysis in Stage 6 to test how site rankings change with different weight combinations, it does not consider how accessible the sites are in practice or whether they are well-positioned to be shared by multiple logistics operators. For this reason, this master's thesis introduces a new Stage 7 focused on shared-use potential. This additional step helps validate the TOPSIS ranking by examining how many operators can reach each site by cargo bike, using cycling isochrones. It brings an operational perspective that responds to cargo bike use, cycling accessibility, and a way to support collaboration between operators.

Stage 7: Nano-hub accessibility and shared-use potential

Stage 7 was introduced as a proposed methodological improvement to the Aljohani and Thompson (2020) framework. This stage aims to **analyze the potential for shared use of the 20 shortlisted candidate sites for nano-hub location**. To perform this assessment, this stage introduces a candidate site-centric analysis based on real cycling isochrones. The objective is to assess how accessible each shortlisted nano-hub is to existing cycle logistics operators within a realistic travel time, thereby identifying which hubs are best positioned for multi-operator use.

For this stage, the GOAT (Geo Open Accessibility Tool) was applied. GOAT is an open-source web-based platform for multimodal accessibility analysis based on OpenStreetMap (OSM)[22] data that allows users to visualize and calculate catchment areas based on travel time, transport mode, and real transport infrastructure. With this tool, the results, which are isochrone polygons, can be exported as vector layers to be integrated on QGIS. These isochrones represent the **maximum area reachable by bike** from each hub under realistic conditions (Plan4Better, 2025b). These isochrones visualize the extent to which each hub is accessible from its surroundings, which illustrates how the reachable area grows as travel time increases. Such time-based accessibility analysis is a common tool in transport planning, including transit system design, logistics coordination, and accessibility assessment, helping to explore how travel patterns relate to time constraints (O'Sullivan et al., 2000; Dovey et al., 2017; BedİRoğlu, 2021; Śleszyński et al., 2023; Russo et al., 2024).

As a first step, using the GOAT platform, **cycling catchment areas were generated for 5, 10, and 15 minutes** of travel time (Figure 30), assuming an average cycling speed of 15 km/h and incorporating real-world cycling infrastructure (Plan4Better, 2025a). The analysis was applied with

[22] OpenStreetMap (OSM) is a collaborative, open-source geospatial database providing detailed and frequently updated information on features like roads, buildings, land use, and points of interest. Its accuracy and completeness, particularly in urban areas, benefit from active local contributions (OSMF, 2025).

emphasis on the **top 20 sites** identified through the TOPSIS multi-criteria ranking. These travel-time polygons were then imported into QGIS for further analysis. For shared-use evaluation, the **15-minute isochrone** was selected as the primary analytical boundary. This threshold reflects the urban proximity principle promoted by the 15-minute city framework (Moreno et al., 2021). Using the GIS spatial join tool "Join attributes by location," the number of existing cycle logistics operators located within each hub’s 15-minute cycling catchment was counted. The corresponding total map showing 5, 10, and 15-minute isochrones and the maps per hub (Figure 31) for the top 20 sites act as visual tools to support interpretation.

The numerical results are detailed in Table 18. This table shows the number of reachable operators per site and a corresponding ranking. Sites with greater operator proximity are considered to offer higher potential for collaborative or multi-actor use, which is generally associated with more efficient, cost-effective, and sustainable logistics operations (Muñoz-Villamizar et al., 2015).

Table 18. Shared-Use Ranking of Shortlisted Sites Based on 15-Minute Cycling Reach Catchments. Source: by the author.

Shared-Use Rank	Site ID	Number of Operators within 15 min
1st	S16	7
2nd	S11	6
3rd	S5	5
4th	S7	5
5th	S14	5
6th	S2	4
7th	S6	4
8th	S10	4
9th	S15	4
10th	S18	4
11th	S19	4
12th	S9	3
13th	S13	3
14th	S17	3
15th	S4	2
16th	S12	1
17th	S1	0
18th	S3	0
19th	S8	0
20th	S20	0

The shared-use potential analysis reveals significant variation in how well each shortlisted nano-hub is positioned to serve multiple cycle logistics operators within a 15-minute cycling distance. As shown in Table 18, Site S16 ranked highest, with 7 operators reachable, followed by S11 and S5, each within reach of 6 and 5 operators, respectively. These sites demonstrate strong spatial alignment with operator locations and are therefore well-suited for collaborative or multi-actor use.

In contrast, sites like S1, S3, S8, and S20 fall outside the operational range of any identified operator, suggesting limited shared-use potential under current conditions.

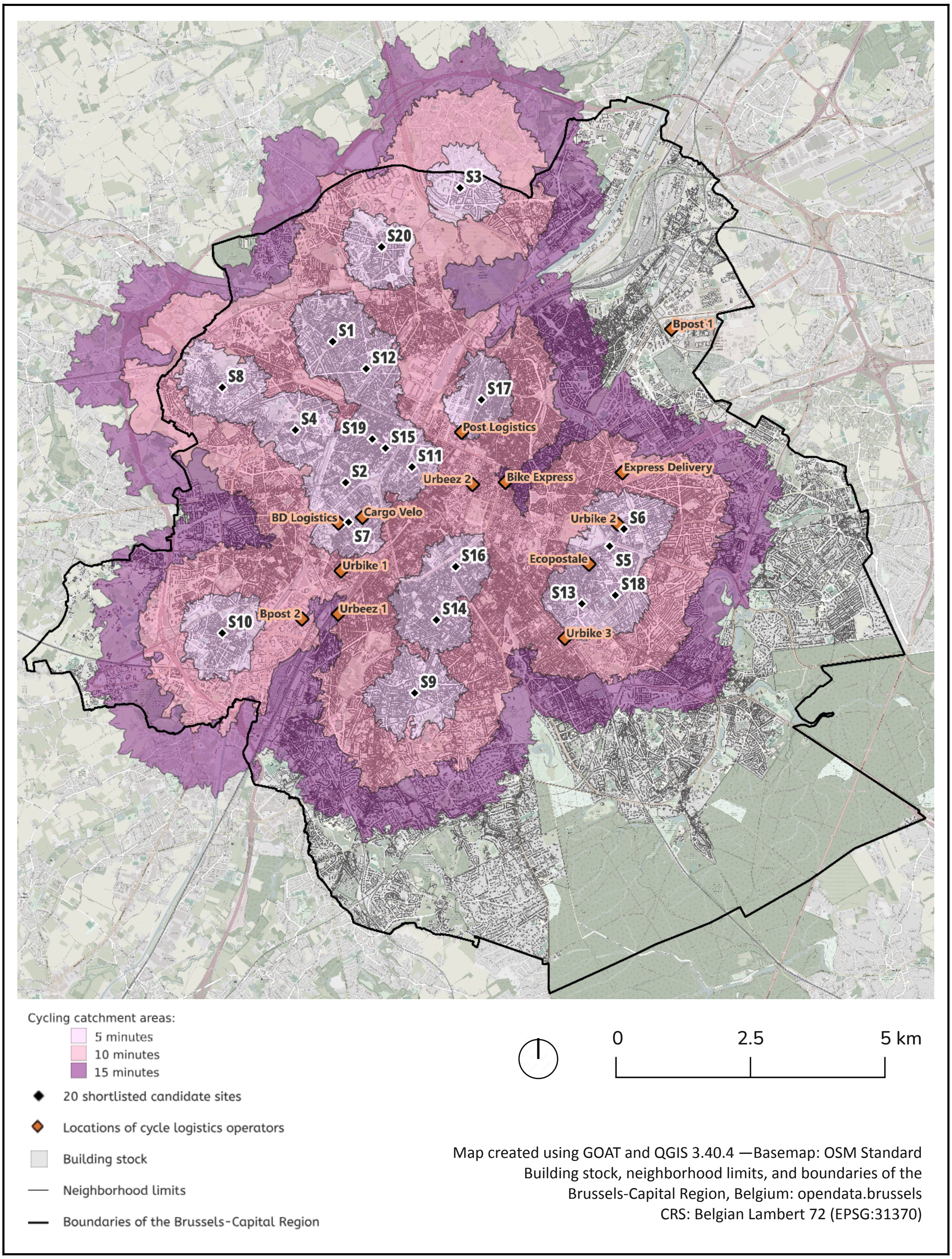
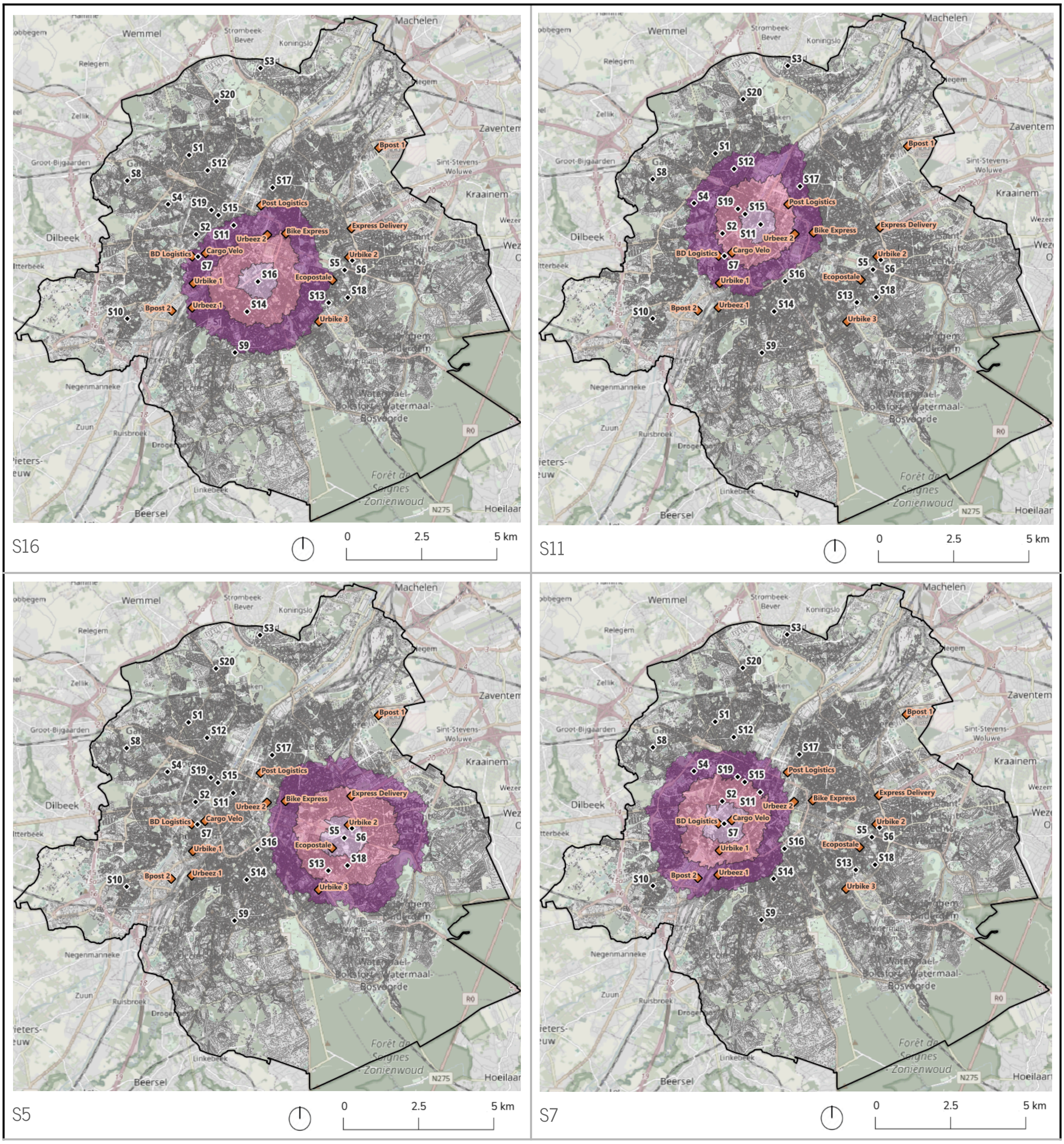
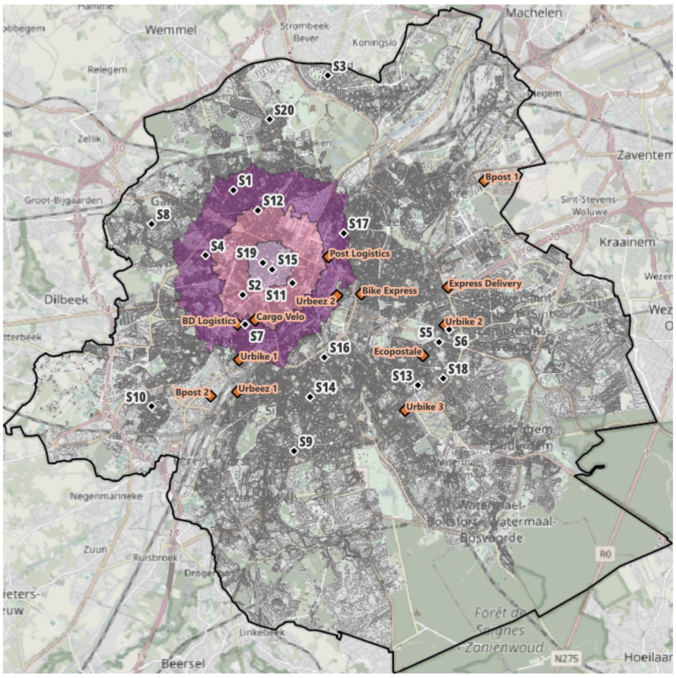


Figure 30. Total cycling catchment areas (5, 10, 15 min) from 20 shortlisted sites with operators' locations. Source: by the author based on opendata.brussels, 2025; OSMF, 2025.

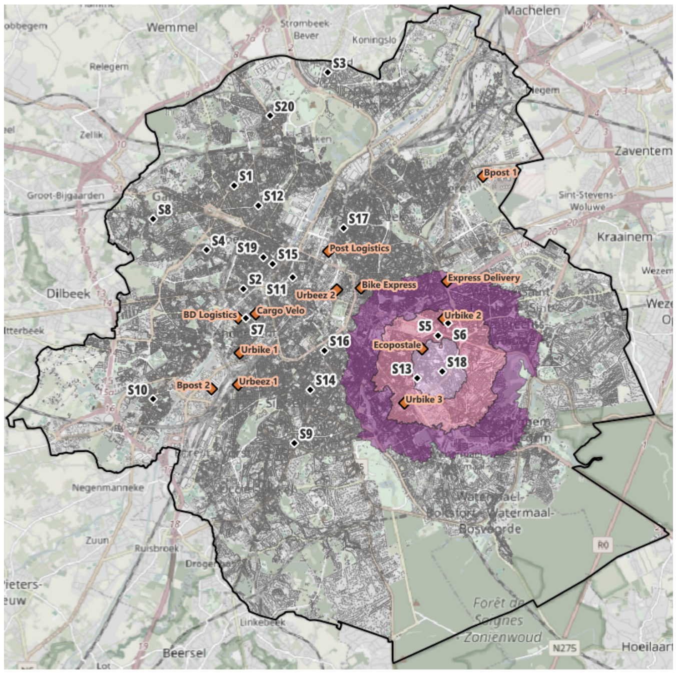

S16
S11
S5
S7
0
2.5
5 km
Wemmel
Machelen
Strombeek Bever
Koningslo
Relegem
Zellik
Groot-Bijgaarden
Zaventem
Sint-Stevens-Woluwe
Kraainem
Dilbeek
Negenmanneke
Zuun
Ruisbroek
Drogen
Linkebeek
Beersel
Hoeilaart
Watermael-Boitsfort
Forêt de Soignes
Zonienwoud
N275
R0
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
S14
S15
S16
S17
S18
S19
S20
Bpost 1
Bpost 2
Post Logistics
Bike Express
Express Delivery
Urbeez 1
Urbeez 2
BD Logistics
Cargo Velo
Urbike 1
Urbike 2
Urbike 3
Ecopostale


S14
S2
S6
S10
0
2.5
5 km
Wemmel
Machelen
Strombeek Bever
Koningslo
Relegem
Zellik
Groot-Bijgaarden
Zaventem
Sint-Stevens-Woluwe
Kraainem
Dilbeek
Negenmanneke
Zuun
Ruisbroek
Drogenbos
Linkebeek
Beersel
Watermael-Boitsfort - Watermaal-Bosvoorde
Forêt de Soignes - Zonienwoud
Hoeilaart
N275
R0
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
S14
S15
S16
S17
S18
S19
S20
Bpost 1
Bpost 2
Post Logistics
Bike Express
Express Delivery
Urbeez 1
Urbeez 2
Urbike 1
Urbike 2
Urbike 3
BD Logistics
Cargo Velo
Ecopostale



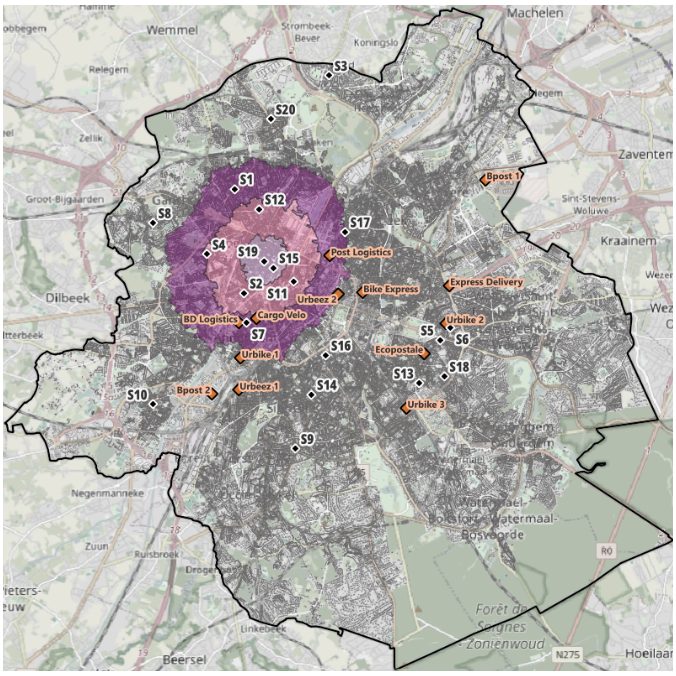
S15

0 2.5 5 km



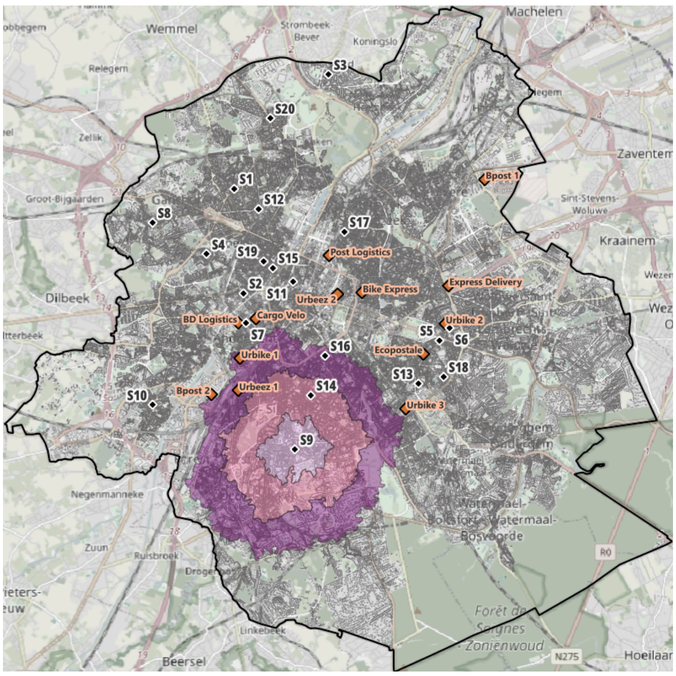
S18

0 2.5 5 km



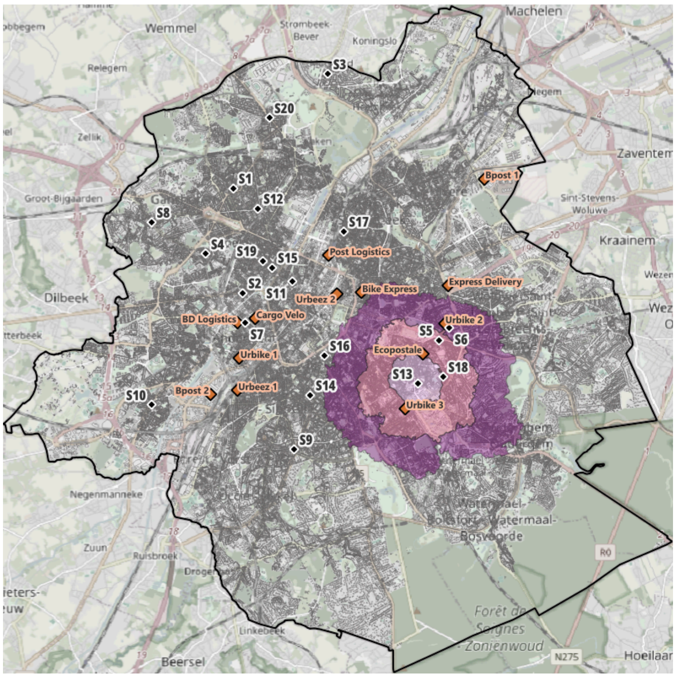
S19

0 2.5 5 km



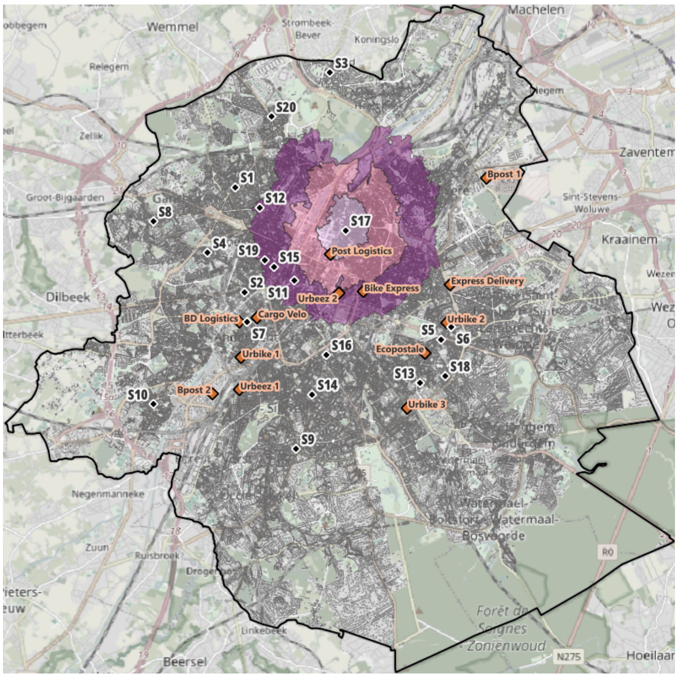
S9

0 2.5 5 km



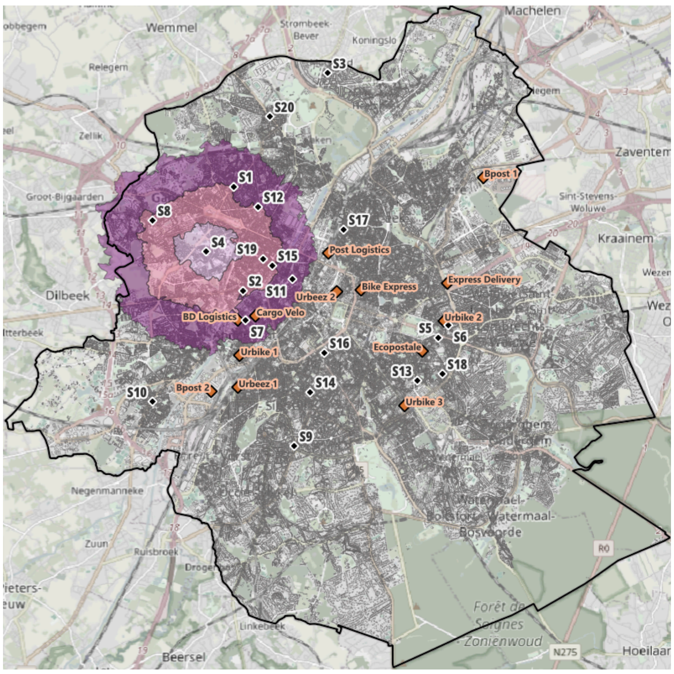
S13

0 2.5 5 km



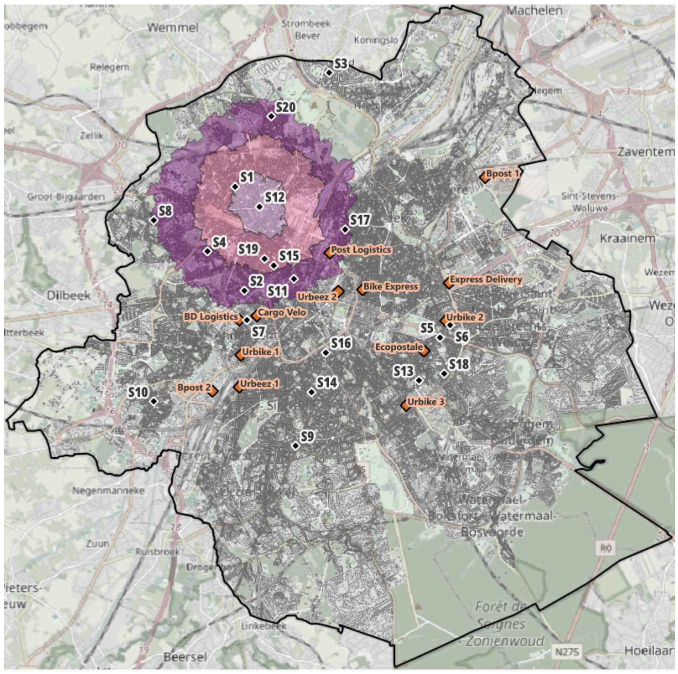
S17

0 2.5 5 km



S4

0 2.5 5 km



S12

0 2.5 5 km

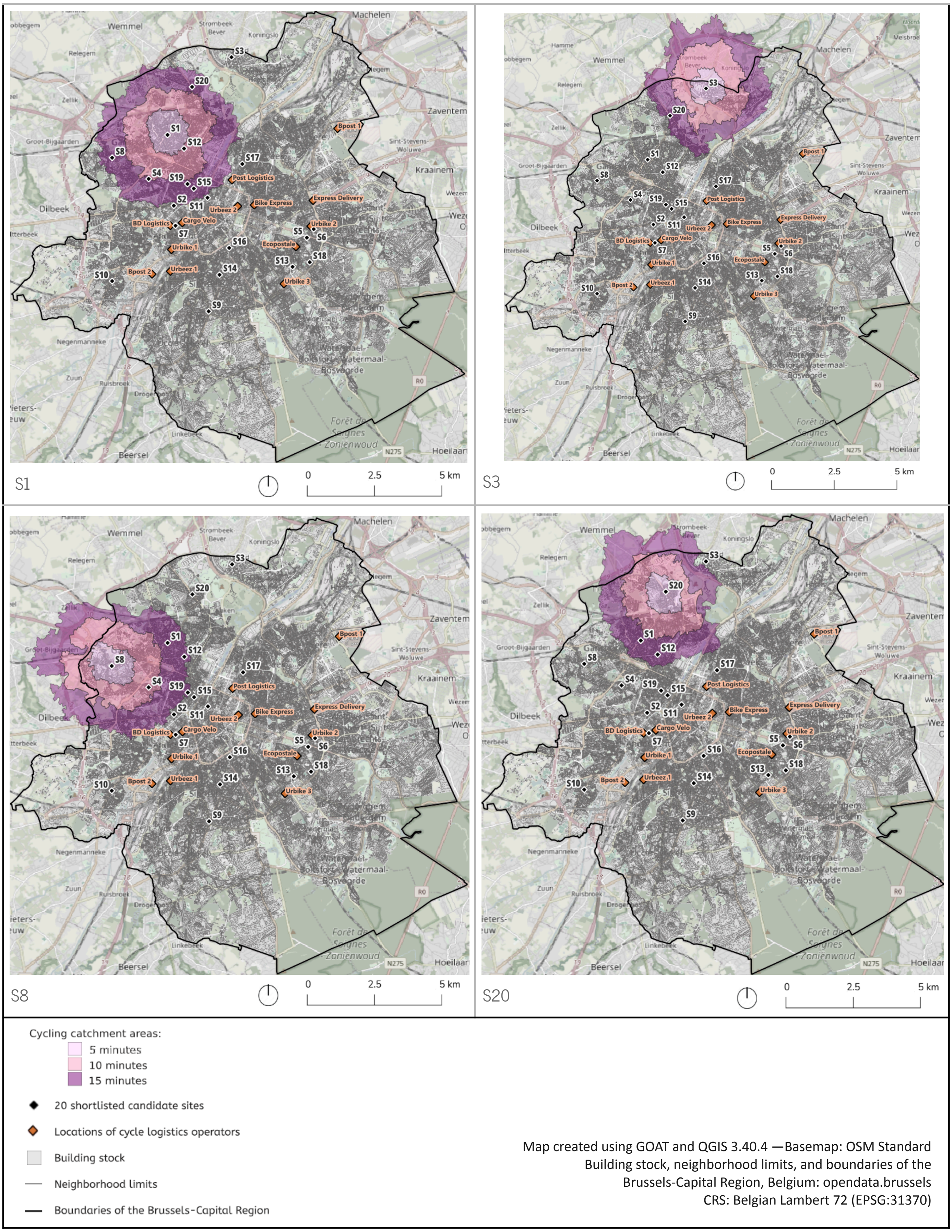


Figure 31. Cycling catchment areas (5, 10, 15 min) per hub from 20 shortlisted sites with operators' locations.
Source: by the author based on opendata.brussels, 2025; OSMF, 2025.

6. Discussion

6.1. Key findings from the spatial analysis

A comparison between the final stages, the Stage 6 TOPSIS ranking, and the Stage 7 shared-use ranking reveals differences in how the candidate sites perform depending on the evaluation lens. While TOPSIS assessed site suitability based on multi-criteria performance (Liu, 2009), Stage 7 introduced a more functional perspective, focusing on how many cycle logistics operators are accessible within a 15-minute cycling catchment area (Plan4Better, 2025a). This contrast highlights the value of combining technical evaluation with real-world accessibility analysis when planning urban logistics infrastructure.

Some sites performed consistently well in both stages. Site S16 ranked 4th in the TOPSIS analysis and 1st in shared-use potential, indicating it combines strong multi-criteria performance with excellent proximity to multiple operators. Sites S5 and S14 also maintained strong positions across both stages, suggesting they are robust choices for further development. These consistent performers represent low-risk options, as they align well with both strategic planning objectives and the operational realities of cycle logistics.

On the other hand, some sites showed significant discrepancies between the two rankings. Site S10, for instance, was the top-ranked location in TOPSIS but only 8th in terms of shared-use potential. Similarly, S18 and S12 ranked highly in suitability (3rd and 7th, respectively) but dropped to 10th and 16th when accessibility to logistics operators was considered. In contrast, some sites that were ranked lower in the TOPSIS framework stood out in the shared-use analysis. Site S11, which was only 12th in TOPSIS, emerged as 2nd in terms of operator proximity, and S7, ranked 13th in TOPSIS, reached 4th in shared use. These results suggest that some sites with modest multi-criteria scores may be more promising in operational terms, especially when considering the opportunity for shared infrastructure and co-location with multiple operators, which is aligned with horizontal collaboration frameworks (Hribernik et al., 2020; ITF, 2024b).

In both cases, whether sites score consistently well or display contrasting performances, each location should be further analyzed in detail. This includes investigating their specific urban context to identify potential implementation challenges, particularly if sites are selected without fully accounting for their integration into the existing urban fabric and consulting stakeholders, which Kania et al. (2022) identify as critical for large-scale integration.

The divergence between rankings reinforces the importance of considering both strategic suitability and practical accessibility. For Brussels, where the nano-hub project is still in its early stages, proximity to cycle logistics operators might serve as a promising starting point for implementation. **Sites like S16, S11, and S5, which combine proximity with relatively strong suitability scores, could offer low-barrier, high-impact pilot opportunities**.

The methodological framework applied in this study shows its relevance by combining spatial and functional dimensions to guide the selection of nano-hub locations for cycle logistics. By integrating a multi-criteria decision analysis (MCDA) with an accessibility layer, the approach moves beyond static site suitability and introduces a more context-sensitive evaluation process. This multi-layered method captures not only how suitable a site is based on policy, infrastructure, and spatial data (via the MCDA framework), but also how well it is positioned to support shared use and operational synergies (via catchment analysis), while responding to calls for planning tools that bridge logistics efficiency and sustainability with urban integration, as well as better alignment between urban planning and urban logistics (Assmann et al., 2019; Cowie & Fisken, 2023; Schachenhofer et al., 2023; Comi et al., 2024).

6.2. Practical recommendations for integrating nano-hubs in Brussels

One promising approach for Brussels is to draw inspiration from New York City's pilot programs, which have successfully repurposed underused urban spaces—such as curbside parking, parking areas, and areas annexed to buildings or road infrastructure—into microhub facilities (NYC DOT, 2023; Brendlen, 2024). These sleeping assets have the potential to provide flexible, low-cost entry points for testing and scaling logistics infrastructure without the high capital investment typically associated with permanent facilities. In the New York case, microhubs were often set up in areas with high delivery demand but limited space, using modular structures that could be relocated or adapted as needed. This strategy minimized disruption to existing urban functions while enabling fast implementation, which is highly desirable, especially for Brussels, where public space competition is high (Bjørgen et al., 2019).

Brussels could benefit from adopting a similar model, with a particular focus on sleeping assets (Schachenhofer et al., 2023) like **parking spaces and temporarily vacant buildings** that can host small-scale hubs without claiming additional public space. It could also combine logistics functions with parcel counter services, cargo bike garages, cafes, or rental stations for cargo bike use, further enhancing their contribution to urban livability and making better use of space (Assmann et al., 2019).

A complementary recommendation is to prioritize nano-hub locations that maximize **shared-use potential** across multiple cycle logistics operators. The Stage 7 analysis in this study demonstrated that hubs accessible to several operators within short cycling times are more likely to achieve consistent utilization and operational viability. In practice, this means giving preference to sites with strong connectivity to the existing cycle logistics operators and proximity to delivery demand clusters. This approach supports more efficient use of limited space, fosters horizontal collaboration, and aligns with the goals of the Urban Logistics Green Deal (Mobilise, 2019).

A third recommendation is to adapt existing **policy and regulatory frameworks** to facilitate the integration of the nano-hubs while safeguarding and enhancing **urban livability**. Current land-use zoning, permitting processes, and building codes can limit the flexibility needed to establish small-scale logistics facilities, particularly in unconventional locations such as temporarily vacant buildings or residual spaces. Drawing from New York City's example, Brussels could introduce targeted regulatory tools, such as a permit system for microhub operators, clear siting and design standards for on-street and off-street hubs, and data-sharing requirements to monitor performance and guide policy adjustments (NYC DOT 2023; 2024d). Importantly, and as demonstrated in NYC, citizen and stakeholder engagement should be implemented from the earliest stages of planning and site selection (NYC DOT 2024e), supporting reframing urban logistics as an essential urban service, rather than an industrial activity that threatens livability (Assmann et al., 2019; Buldeo Rai, 2024). Public consultations, participatory design workshops, and transparent communication about benefits and trade-offs can help build trust, reduce opposition, and ensure that hubs are integrated in ways that reflect community needs and protect neighborhood quality of life.

Together, these recommendations reinforce the adapted GIS-MCDA framework developed in this study, ensuring that spatial planning, operational efficiency, policy reform, and diverse stakeholder participation work together and support each other to deliver a nano-hub integration that is both sustainable and aligned with Brussels' livability objectives.

6.3. Limitations of the study

(1) Data availability and resolution: Some spatial layers used in the analysis were only available at coarse resolutions or as proxies, which may limit the accuracy of site-level comparisons. Potential omissions or biases in the datasets—such as incomplete coverage of logistics operators—may also affect results.

(2) Limited stakeholder sample size: The number of stakeholders who participated in the survey used to derive the AHP weights was relatively small. As such, the weightings may not fully reflect the diversity of priorities across the logistics ecosystem.

(3) Difficulty in reaching stakeholders: The survey and interviews did not fully capture perspectives from all relevant actors; particularly those representing public agencies and civil society are scarce or missing. This limited the representativeness of the multi-criteria weighting.

(4) Exclusion of sensitivity analysis: Although sensitivity analysis is part of the original GIS-MCDA framework by Aljohani and Thompson (2020), it was not applied in this study. While the GIS-MCDA process produced a ranked list of suitable sites, the emphasis was on interpreting these results in terms of territorial coverage and accessibility across the Brussels-Capital Region. Within this approach, variations in criteria weights were considered unlikely to provide additional insight. Instead, a catchment area analysis (Stage 7) was introduced to offer a more operational and context-specific validation of the results, making variations in criteria weights less relevant to the study's objectives. As a result, the potential influence of weighting uncertainty on the rankings remains an avenue for future exploration.

6.4. Suggestions for future research

This study offers a foundation that future research could build upon and refine. First, criterion **CR11 (Sustainable Integration with Urban Environment)** could be expanded and redefined as a broader category**,** such as **D. Social-environmental Indicators**, incorporating more diverse and detailed datasets. In the present study, this expansion was not necessary, as the data available shared the same format (point layers), allowing for a straightforward merge. However, given the growing importance of social equity, environmental justice, and livability in urban planning and logistics (Assmann et al., 2019; Cowie & Fisken, 2023; Buldeo Rai, 2024), future research could benefit from disaggregating this criterion into more specific indicators—such as other types of air pollution (from vehicle emissions), noise pollution (from vehicles and infrastructure), greenhouse gas emissions contributing to climate change, or a criterion to represent the negative impact on ecosystems and natural habitats due to transportation infrastructure and activities—to better capture the multidimensional impacts of logistics activities and infrastructure.

Secondly, due to the early stages of implementation in the case study of Brussels, this study relies on **unstructured interviews** to collect qualitative insights from stakeholders. While this approach proves valuable for exploratory understanding, future studies could **transform these interactions into structured or semi-structured interviews** based on survey instruments. Doing so would allow for more systematic comparison across stakeholder groups and enable quantification of responses.

Finally, the current workflow for the spatial analysis was conducted in a big part manually in QGIS. To improve **scalability and reproducibility**, future applications of this framework could focus on **automating the process through Python scripting in QGIS**. Automating steps such as raster normalization, criteria weighting, and site ranking reduces processing time, minimizes the risk of manual error, and enables replication in different urban contexts or with real-time data inputs.

7. Conclusion

This research developed and applied an adapted GIS-MCDA framework to assess and prioritize locations for nano-hub integration in Brussels, combining spatial analysis, multi-criteria decision-making, and accessibility assessment. Beyond its immediate findings, the strength of this framework lies in its versatility. The methodology is designed to remain operational even in contexts where data availability is limited, while also being capable of delivering more precise and robust outputs when higher-quality or more detailed datasets become available. Each stage—from the definition and weighting of criteria to the catchment area analysis—can be easily updated, refined, or expanded as new information emerges, allowing for iterative improvements without the need to redesign the entire process. This adaptability makes the framework not only a decision-support tool for early-stage projects but also a scalable model for long-term strategic planning, transferable to other cities or adapted to different logistics typologies. By applying this adaptable framework to Brussels, the study identified opportunities for nano-hub integration and outlined practical strategies, such as leveraging sleeping assets and maximizing shared-use potential, that can be refined as data and operational conditions evolve. In this way, the framework functions as a living instrument to guide future, data-enhanced decision-making in sustainable urban logistics.

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9. Appendices

Appendix A: Data preparation and adaptation procedures

This appendix provides explanations of the data content, limitations, and adaptations to generate the set of criteria included in the spatial analysis. It describes the aim of the criterion, how some of the datasets were adapted to fit the framework applied to this study and how missing information was generated or obtained through proxy indicators.

1. **Existing Distribution Centres/Warehouses in Area (CR01):** This criterion was adapted from Aljohani and Thompson (2020) but the same intention was kept. The approach was changed to focus on cycle logistics and nano-hubs. In this research, criterion CR01 aims to locate the nano-hub in an area with a high density of locations of cycle logistics operators/companies. The data used are the hub locations of cycle logistics carriers partnered with the BCLF (Table I).

ID	Company Name	Company Address
1	Cargo Velo	Bergensesteenweg 95, 1070, Anderlecht, Belgium
2	Urbike 1	Rue des Veterinaires 42, 1070, Anderlecht, Belgium
3	Urbike 2	Rue de Linthout 176, 1040, Etterbeek, Belgium
4	Urbike 3	Av. de la Couronne 227, 1050, Ixelles, Belgium
5	BD Logistics	Rue Ropsy Chaudron 24, 1070, Anderlecht, Belgium
6	Post Logistics	Rue du Progrès 56, 1210, Saint-Josse-ten-Noode, Belgium
7	Express Delivery	Boulevard Auguste Reyers 80, 1030, Schaerbeek, Belgium
8	Ecopostale	Rue Champ du Roi 127, 1040, Etterbeek, Belgium
9	Urbeez 1	Avenue Van Volxem 404, 1190, Forest, Belgium
10	Urbeez 2	Rue de ligne 27, 1000, Brussels, Belgium
11	Bike Express	Chaussée de Louvain 32, 1210, Saint-Josse-ten-Noode, Belgium
12	Bpost 1	Avenue de Schiphol 2, 1140, Evere, Belgium
13	Bpost 2	Bd Industriel 16, 1070, Anderlecht, Belgium

Table I. Cycle Logistics Carriers partners with BCLF.
Source: by the author

2. **'Sleeping Assets' Represented by Idle Real Estate in Area (CR02)**: This criterion was adapted and expanded from Aljohani and Thompson (2020). Criterion CR02 aims to locate nano-hubs in areas with available idle real estate infrastructure (within the available data, these are urban spaces and buildings that are vacant or not fully utilized). In this study, the data include:

   (1) parking infrastructure, represented by public car parks in the Brussels-Capital Region (BCR) obtained from official sources (Brussels Mobility, 2022b); and

(2) empty buildings or underutilized areas within occupied buildings, represented by documented temporary occupations of vacant buildings in Brussels. The second dataset (Table II) was extracted from Heydari's (2022) thesis, which catalogued vacant buildings intermittently used for public or creative purposes. However, its suitability for nano-hubs cannot be guaranteed, as the actual availability of these spaces and whether they meet the area requirements for such facilities remain uncertain.

ID	Vacant buildings in Brussels	Address	Building Typology
1	123 Rue Royale	Rue Royale 123, 1000 Bruxelles	Not informed
2	70-treize	Bd Guillaume Van Haelen 83, 1190 Forest	Not informed
3	Allee du Kaai	Havenlaan 53, 1000 Bruxelles	Industrial Building
4	Antidote AND Studio City Gate	Rue de la Petite Île 1A, 1070, Anderlecht	Not informed
5	Arlon 104	Rue d'Arlon 104, 1000 Bruxelles	Office Building
6	BAF (Brussels Art Factory)	Rue Coenraets 82, 1060 Saint-Gilles	Not informed
7	BiestebroekBis	Rue Gustaaf Vanden Berghe 24, 1070 Anderlecht	Not informed
8	Chassart	Av. Van Volxem 400, 1190 Forest	Not informed
9	Circularium	Chausée de Mons 95, 1070 Anderlecht	Industrial Building
10	Commons Josaphat	Bd Général Wahis 16, 1030 Schaerbeek	Not informed
11	Grand Hospice	Rue du Grand Hospice 7, 1000 Bruxelles	Not informed
12	In Limbo / ADK	Rue Brichaut 15, 1030 Schaerbeek	Not informed
13	Korenbeek	Rue du Korenbeek 133, 1080 Molenbeek-Saint-Jean	Not informed
14	L'Accroche	Av. du Pont de Luttre 72, 1190 Bruxelles	Industrial Building
15	L'Annexe	Rue du Métal 19, 1060 Saint-Gilles	School (l'annexe of the Van der Kelen School)
16	L'hôtel Tagawa	Av. Louise 323, 1050 Bruxelles	Not informed
17	L'itol Soleil	Rue des Chevaliers 11, 1050 Ixelles	Not informed
18	L'Uzinne	Quai de l'Industrie 79, 1080 Molenbeek-Saint-Jean	Industrial Building (Warehouse)
19	La Bougie	Rue de la Bougie 34, 1070 Anderlecht	Industrial Site
20	La Clef	Rue Fransman 118, 1020 Bruxelles	Industrial Building (mail sorting center building)
21	La Ferme du Chant des Cailles	Av. des Cailles 12, 1170 Watermael-Boitsfort	Not informed
22	La Serre	Rue gray 171, Ixelles	Industrial Building
23	La Vallée	Rue Adolphe Lavallée 39, 1080 Molenbeek	Industrial Building (laundry)
24	La Zinzinerie	Av. du Port 49, 1000 Bruxelles	Industrial Building
25	Lab North - WTC	Boulevard Simon Bolivar 30, 1000 Bruxelles	Office Building
26	Le Bunker	Rue des Plantes 66A, 1210 Saint-Josse-ten-Noode	Cinema-Theater
27	Le Lac	Av. de la Verrerie 23, 1190 Forest	School
28	Les Brasseries Atlas	Rue du Libre Examen 15, 1070 Anderlecht	Industrial Building (brewery)
29	LeTri Postal	Avenue Fonsny 48, 1060 Saint-Gilles	Not informed
30	Maxima	Rue du Monténégro 144, 1190 Forest	Industrial Building
31	Naast Monique	Quai de l'Industrie 230, 1070 Anderlecht	Industrial Building
32	Parckfarm	Bd Emile Bockstael 1, 1020 Bruxelles	Not informed
33	Pic nic the street	Bd Anspach 85, 1000 Bruxelles	Not informed
34	Pop up Canal	Quai de Mariemont 36, 1080 Molenbeek-Saint-Jean	Commercial Building
35	Pop-up Sablon	Rue Lebeau 18, 1000 Bruxelles	Not informed
36	Probité	Rue de la Probité, 1050 Ixelles (Etterbeek)	House
37	Rainbow House	Rue du Marché au Charbon Kolenmarkt 42, 1000 Bruxelles	Office Building

38	Recyclart	Rue de Manchester 13/15, 1080 Molenbeek-Saint-Jean	Bank
39	Reset	Rue de Ligne 8, 1000 Brussel	Industrial Building
40	See U	Av. de la Couronne 227, 1050 Ixelles	Industrial Building
41	Sorocité	Rue Fernand Léger 36, Evere Brussels	Appartment Complex
42	The Faculty	Rue des Vétérinaires 47, 1070 Anderlecht	School
43	The Production Hub	Chaussée de Vilvorde 11, 1120 Laeken	Not informed
44	Tiers-lieu ABC	Rue Abbé Cuylits 44, 1070 Anderlecht	Not informed
45	Woningen 123 logements	Rue du Progrès 214, 1030 Schaerbeek	Not informed
46	WoonBox	Rue Pierre van Humbeek 5, 1080 Molenbeek-Saint-Jean	Not informed
47	ZonneKlopper	Av. de la Verrerie 23, 1190 Forest	Industrial Building

Table II. Inventory of Temporary Occupations Representing Potential Idle Real Estate for Nano-Hubs. Source: adapted from Heydari (2022).

3. **Demographic Attributes (CR03)**: This criterion aims to locate nano-hubs in residential areas that are likely to generate high delivery demand. To identify relevant demographic determinants, this study draws on Buldeo Rai et al. (2024), who analyzed factors influencing frequent online shopping in the Brussels-Capital Region. Their results show that **gender is the only sociodemographic variable with a statistically significant effect**, with men more likely than women to purchase online frequently. Other traditional indicators, such as age, education, and employment status, were not significant in the final model, suggesting they have limited direct influence on shopping frequency. However, the authors highlight that **company car ownership** can act as a **proxy for both income and employment status**, meaning that socioeconomic conditions may still exert indirect influence. In this research, due to the lack of neighborhood-level disaggregated data on company cars, **car ownership per household** was used as a practical proxy. The dataset includes both privately owned and company-provided vehicles. A threshold of **0.55 cars per household** (the 2023 Brussels-Capital Region average reported by STATBEL) was adopted to classify areas as having favorable demographic attributes (STATBEL, 2023).

4. **Primary Land-Use Zones (CR04)**: This criterion aims to locate the nano-hubs in an area with specific land-use zones, established by the PRAS (Plan Régional d'Affectation du Sol), the regional land-use plan of the Brussels-Capital Region. The PRAS defines a detailed zoning system that regulates the function and development potential of each parcel in the region. These zones determine where certain activities are permitted or restricted, making them a fundamental reference for assessing the spatial compatibility of nano-hubs (perspective.brussels, 2025b). Based on this official land-use regulation, Table IV presents the details of each zone and its compatibility with the proposed facilities. The color code is as follows:

green = **compatible; yellow = conditionally compatible;** and **red = not compatible**.

For the purposes of this study, only zones classified as compatible are considered.

Table IV. PRAS Zoning Classification and Suitability for Nano-hub Integration. Source: By the author based on (perspective.brussels, 2025c).

ID No.	PRAS Zoning Classification (french)	Intended Function	Nano-hub Compatibility
Special requirements relating to housing areas			
1	Zones d'habitation à prédominance résidentielle	Predominantly residential housing	Urban logistics would likely disturb the quiet residential character.
2	Zones d'habitation	Residential with neighborhood-scale amenities	Conditionally compatible but not recommended, as urban logistics would likely disturb the quiet residential character.
Special requirements relating to mixed areas			
3	Zones mixtes	Mixed-use (residential and small business/ services)	Small, low-impact microhubs may be integrated into the urban fabric if carefully planned and accepted by the community.
4	Zones de forte mixité	High-intensity mixed-use zones	These areas are designed to support both housing and economic activity, making them well suited for small-scale microhubs.
Special requirements for industrial zones			
5	Zones d'industries urbaines	Urban industry (productive activities and logistics activities)	Microhubs are appropriate in these zones, as they can operate with fewer nuisance constraints.
6	Zones d'activités portuaires et de transport	Port and logistics activities	Suitable for nano-hubs, as they can operate with fewer nuisance constraints
Special requirements for other business zones			
7	Zones administratives	Offices and public administration	The zone's primary function is institutional, but microhubs could be viable where light logistics, service functions, or office-related delivery demand exists.
8	Zones d'équipements d'intérêt collectif ou de service public	Schools, hospitals, public facilities	Complementary businesses are allowed only under strict conditions, but primary function is not commercial or industrial but institutional and civic.
9	Zones de chemin de fer	Railway infrastructure	Primarily railway zones; but could host hubs through agreements with SNCB (rail operator) or Infrabel (infrastructure manager), particularly for last-mile logistics close to stations or tracks.
9bis.	Zones d'entreprises en milieu urbain	Urban enterprise zones (light industry and services)	Compatible for small microhubs integrated into mixed-use urban settings with economic activity.
Special requirements for green areas and agricultural zones			
10	Zones vertes	Urban green areas	Protected areas; unsuitable for van/truck access or logistics activity.
11	Zones vertes de haute valeur biologique	High ecological value green areas	Strong environmental protection prohibits any form of logistical or commercial use.

12	Zones de parc	Parks and landscaped open spaces	Microhubs are not permitted in recreational parks.
13	Zones de sports ou de loisirs de plein air	Outdoor sports and leisure areas	Conflicts with recreational use.
14	Zones de cimetières	Cemeteries	Inappropriate and strictly prohibited.
15	Zones forestières	Forest areas	Protected, natural conservation areas.
16	Zones de servitudes au pourtour des bois et forêts	Buffer zones around forests	Highly regulated for environmental protection; logistics use is not allowed.
17	Zones agricoles	Agricultural land	Inappropriate and too remote.
Special requirements for certain parts of the territory			
18	Zones d'intérêt régional	Strategic zones for urban redevelopment	High potential for microhubs, especially during (re)development. For these zones land uses are defined by special detailed planning documents (PPAS). When these are not yet established, the area follows strong mixed-use rules (similar to Zone 4).
19	Zone d'intérêt régional à aménagement différé	Strategic zones awaiting development	Primarily railway zones; microhubs may not be allowed unless re-zoned through formal government action.
20	Zone de réserve foncière	Reserved land for future urbanization	Integrating microhubs would be possible only if the area is formally re-designated for logistics or mixed use.
Requirements for overlay zones			
21	Zones d'intérêt culturel, historique, esthétique ou d'embellissement	Protected cultural/historic areas	Use highly restricted, with conflict with preservation goals, facade protections, and heritage regulations.
22	Liseré de noyau commercial	Commercial core edges	These are prime retail areas with strong commercial activity, ideal for microhubs supporting deliveries to shops and customers nearby.
23	Point de variation de mixité	Mixity variation points	As these are transitional areas from residential to mixed-use, microhubs are suitable. Mix variation points areas are intended to support a greater degree of functional diversity within residential blocks by integrating local shops, offices, and service activities into a residential context.
24	Espaces structurants	Structuring urban spaces	Public spaces requiring preservation and enhancement of landscape quality. Hubs would interfere with the public, aesthetic, and green character of these spaces.

5. **Proximity to Major Freight Corridors (CR05)**: This criterion aims to minimize the distance between nano-hubs and major freight routes. For this study, the regional road network of the Brussels-Capital Region (BCR) was considered. Public agencies have indicated that sites located near these corridors are regarded as feasible and often preferable for potential hub locations.

6. **Traffic Intensity of Major Roads in Area (CR06)**: This criterion was adapted to fit into a cycle-logistics system. CR06 aims to locate nano-hubs in areas with low traffic intensity, as high congestion on major roads could discourage cargo bike operators from using the facility. The analysis considers 30 km/h zones, which, following the Brussels Regional Sustainable Development Plan (Plan Régional de Développement Durable—PRDD), became the default speed limit across the BCR on 1 January 2021, with exceptions for major axes where the limits remain 50 km/h or 70 km/h (Lhuillier, 2020).

7. **Access Restrictions in the Area (CR07)**: This criterion aims at locating nano-hubs in areas with minimal access restrictions or land-use conflicts to ensure smooth operations and reduce potential disruptions. Priority is given to locations without:
    a. **Sensitive uses** (BCR green space areas): zones intended mainly for the development of nature and bodies of water, with limitations on construction.
    b. **Conflicting uses** (BCR-protected goods): Heritage, protection areas, and UNESCO protection areas.

8. **Facility Rental Costs (CR08)**: This criterion aims to locate the facility in an area where rental prices are competitive, helping to minimize overall expenses. Priority is given to areas with lower rental costs to optimize the affordability of the proposed facility, in case the nano-hubs are located inside or annexed to buildings. In the absence of detailed data on commercial or logistics facility rental prices in the Brussels-Capital Region, this study uses a proxy indicator: the **average rental price of a common Brussels apartment (2023)** (Table V), based on the *Baromètre des Locations* published by Federia (2024). While residential rental prices do not directly reflect commercial rents, they provide a spatially consistent and up-to-date measure of local property market conditions, allowing relative cost differences between neighborhoods to be assessed.

Table V. Average apartment rental prices by commune in the BCR.
Source: Federia (2024).

ID	Commune	Average Rental Price (€/month, 2023)
1	Saint-Gilles	1179
2	Jette	976
3	Uccle	1387
4	Forest	1201
5	Woluwe-Saint-Lambert	1353
6	Auderghem	1255
7	Saint-Josse-ten-Noode	1169
8	Evere	1167
9	Bruxelles	1289
10	Woluwe-Saint-Pierre	1486
11	Anderlecht	973
12	Koekelberg	1184
13	Ganshoren	956
14	Etterbeek	1218
15	Ixelles	1368
16	Molenbeek-Saint-Jean	1015
17	Watermael-Boitsfort	1203
18	Schaerbeek	1068
19	Berchem-Sainte-Agathe	1041

9. **Existing Goods Receivers in Area (CR09)**: This criterion aims to position nano-hubs in areas with a high density of commercial goods receivers to reduce the distance between the proposed hubs and the main freight destinations within the city.

10. **Proximity to Cycling Infrastructure (CR10):** This criterion was adapted to fit into a cycle-logistics system. CR10 favors hub locations close to cycling infrastructure in the BCR, facilitating safe and direct access for cargo bike operations.

11. **Integration with Urban Environment (CR11**)[23]: This criterion aims to move towards the sustainable integration of the nano-hub operations into BCR by minimizing socio-environmental disruptions. It prioritizes areas that harmonize compatibility between livability standards and minimal environmental externalities, mitigating disruptions such as air pollutants (represented as black carbon exposure) and road accidents (by avoiding zones with high occurrence).
    a. **Black Carbon exposure**: Black Carbon is not a single compound but a component of fine particulate matter (PM2.5), mainly emitted from diesel

[23] For this criterion, sustainability indicators in urban logistics related to social and environmental dimensions are being considered. According to Comi & Russo (2012), social sustainability can be evaluated through metrics such as (1) reduced interference between urban mobility segments (e.g., freight vehicles, private cars, and pedestrians), (2) decreased reliance on motorized transport, (3) lower road accident rates, and (4) enhanced urban livability. Environmental sustainability, meanwhile, is assessed via: (1) lower pollutant emissions (e.g., particulate matter, CO_2), (2) noise mitigation, and (3) minimized habitat disruption. These criteria align with the holistic approach advocated in sustainable urban freight literature, ensuring systemic compatibility between logistics operations and broader urban well-being (Janjevic & Ndiaye, 2012).

engines, biomass burning, and other incomplete combustion processes. Although the World Health Organization (WHO) has not set a specific safe limit for Black Carbon (µg/m³), it is recognized as a harmful pollutant with both health and climate impacts. In its 2021 *Global Air Quality Guidelines*, the WHO recommends an annual average limit of 5 µg/m³ for PM2.5 (WHO, 2021). In this study, the average daytime concentration of black carbon in Brussels was used as a proxy for assessing exposure in areas considered for nano-hub implementation. Applying the precautionary principle, 5 µg/m³ was adopted as the acceptable upper limit, based on the WHO guideline for PM2.5. Values above this threshold indicate potential risks to environmental and urban quality.

b. **Road accidents**: This georeferenced dataset contains records of all Belgian road accidents involving fatalities or injuries from 2017 to 2022, as reported by the federal police. Each record specifies the accident's precise location (point coordinates), date and time, road and weather conditions, and key road-safety indicators. For the purposes of this study, only the most recent year—2022—is analyzed, ensuring that the spatial patterns reflect the latest available accident data for neighborhoods in the Brussels-Capital Region.

Appendix B: Survey applied to stakeholders

VRIJE UNIVERSITEIT BRUSSEL

English

Dear stakeholder,

My name is Tiffany Nicoli, and I am a Master's student in Urban Studies at Vrije Universiteit Brussel and Université Libre de Bruxelles. Under the supervision of Professor Philippe Bouillard and the co-supervision of Professor Heleen Buldeo Rai, my research focuses on the integration of nano-hubs in Brussels to support cycle logistics, to optimize the use of urban space and promote environmental and social sustainability in the city.

Why do nano-hubs matter and what they are for?

Small delivery hubs have the potential to improve urban logistics. They help:

- Shorten delivery distances, making last-mile logistics more efficient.
- Increase delivery capacity, enabling more deliveries per hour.
- Reduce CO2 emissions and traffic congestion by minimizing the need for large delivery vehicles in urban areas.
- Optimize the use of cargo bikes, which are most effective for short-distance, eco-friendly deliveries.

By integrating these hubs into the urban landscape, Brussels can enhance the efficiency of cycle logistics, reduce environmental impacts, and make better use of limited urban space.

Thank you for participating!

By completing this survey, you consent to the use of your responses for research purposes. All data collected will remain confidential and will be used solely for academic and research-related objectives.

○ I agree

Participant Information:

Your Name:

Profession/Role:

Institution/Organization:

Introduction

This survey aims to understand how important different factors are when choosing the optimal locations for small delivery hubs in the Brussels-Capital Region. Your input will help us prioritize these factors and make informed decisions. You will be asked to compare pairs of factors and indicate which one is more important and by how much. Please use the scale below to make your comparisons.

Instructions

1. For each pair of factors, indicate which one is more important for locating small delivery hubs.
2. Use the following scale to rate the importance:
   - **1** Equally important
   - **3** Slightly more important
   - **5** Moderately more important
   - **7** Much more important
   - **9** Extremely more important.

If you think the second factor is more important, use the reciprocal values (**1/3**, **1/5**, **1/7**,**1/9**).

Block 1 of 4

Logistics Land-Use and Attributes

- **Factor A**: **Existing Distribution Centres/Warehouses in Area** (Nanohubs should be located in areas with a high density of cycle logistics operators' hubs—from where the deliveries are made by cargo bikes
- **Factor B**: **'Sleeping Assets' (Idle Real Estate in Area)** (Nanohubs should be located in these "residual areas"—urban spaces and buildings that are vacant, underutilized, or have unused capacity during specific times (e.g., parking garages, empty buildings, or areas in occupied buildings that are only used part-time).
- **Factor C: Demographic Attributes** (Nanohubs should be located close to residential areas with high demand for deliveries, considering online shopping behavior)
- **Factor D: Primary Land-Use Zones** (Nanohubs should be located in areas with Mixed-use zones, industrial zones, port zones, and administrative zones)

Which is more important?

	1 Equally important	3 1st Factor is slightly more important	5 1st Factor is moderately more important	7 1st Factor is much more important	9 1st Factor is extremely more important	1/3 2nd Factor is slightly more important	1/5 2nd Factor is moderately more important	1/7 2nd Factor is much more important	1/9 2nd Factor is extremely more important
Factor A: Existing Distribution Centers/Warehouses in Area **vs.** **Factor B**: 'Sleeping Assets' (Idle Real Estate in Area)	○	○	○	○	○	○	○	○	○
Factor A: Existing Distribution Centers/Warehouses in Area **vs.** **Factor C**: Demographic Attributes	○	○	○	○	○	○	○	○	○
Factor A: Existing Distribution Centers/Warehouses in Area **vs.** **Factor D**: Primary Land-Use Zones	○	○	○	○	○	○	○	○	○
Factor B: 'Sleeping Assets' (Idle Real Estate in Area) **vs.** **Factor C**: Demographic Attributes	○	○	○	○	○	○	○	○	○
Factor B: 'Sleeping Assets' (Idle Real Estate in Area) **vs.** **Factor D**: Primary Land-Use Zones	○	○	○	○	○	○	○	○	○
Factor C: Demographic Attributes **vs.** **Factor D**: Primary Land-Use Zones	○	○	○	○	○	○	○	○	○

Block 2 of 4

Transport Accessibility Indicators

- **Factor E: Proximity to Major Freight Corridors** (Nanohubs should be located close to important regional roads for freight transport)
- **Factor F: Traffic Intensity of Major Roads in Area** (Nanohubs should be located close to areas with low traffic intensity, preferably in 30 km/h zones)
- **Factor G: Access Restrictions in the Area** (Nanohubs should be located in areas with fewer restrictions for truck access)

Which is more important?

	1 Equally important	3 1st Factor is slightly more important	5 1st Factor is moderately more important	7 1st Factor is much more important	9 1st Factor is extremely more important	1/3 2nd Factor is slightly more important	1/5 2nd Factor is moderately more important	1/7 2nd Factor is much more important	1/9 2nd Factor is extremely more important
Factor E: Proximity to Major Freight Corridors **vs.** **Factor F:** Traffic Intensity of Major Roads in Area	○	○	○	○	○	○	○	○	○
Factor E: Proximity to Major Freight Corridors **vs.** **Factor G:** Access Restrictions in the Area	○	○	○	○	○	○	○	○	○
Factor F: Traffic Intensity of Major Roads in Area **vs.** **Factor G:** Access Restrictions in the Area	○	○	○	○	○	○	○	○	○

Block 3 of 4

Suitability Indicators

- **Factor H: Facility Rental Costs** (Nanohubs should be located in areas with lower rental costs)
- **Factor I: Existing Goods Receivers in Area** (Nanohubs should be located in areas with a high density of commercial establishments that receive goods)
- **Factor J: Proximity to Cycling Infrastructure** (Nanohubs should be located in areas close to bike lanes or safe cycling routes)
- **Factor K: Integration with Urban Environment** (Nanohubs should be located in areas that minimize negative impacts on residents and the environment)

Which is more important?

	1 Equally important	**3** 1st Factor is slightly more important	**5** 1st Factor is moderately more important	**7** 1st Factor is much more important	**9** 1st Factor is extremely more important	**1/3** 2nd Factor is slightly more important	**1/5** 2nd Factor is moderately more important	**1/7** 2nd Factor is much more important	**1/9** 2nd Factor is extremely more important
Factor H: Facility Rental Costs vs. **Factor I**: Existing Goods Receivers in Area	○	○	○	○	○	○	○	○	○
Factor H: Facility Rental Costs vs. **Factor J**: Proximity to Cycling Infrastructure	○	○	○	○	○	○	○	○	○
Factor H: Facility Rental Costs vs. **Factor K**: Integration with Urban Environment	○	○	○	○	○	○	○	○	○
Factor I: Existing Goods Receivers in Area vs. **Factor J**: Proximity to Cycling Infrastructure	○	○	○	○	○	○	○	○	○
Factor I: Existing Goods Receivers in Area vs. **Factor K**: Integration with Urban Environment	○	○	○	○	○	○	○	○	○
Factor J: Proximity to Cycling Infrastructure vs. **Factor K**: Integration with Urban Environment	○	○	○	○	○	○	○	○	○

Block 4 of 4

Cross-Group Comparisons

- **Factor A: Existing Distribution Centers/Warehouses in Area** (Nanohubs should be located in areas with a high density of cycle logistics operators' hubs—from where the deliveries are made by cargo bikes)
- **Factor E: Proximity to Major Freight Corridors** (Nanohubs should be located close to important regional roads for freight transport)
- **Factor G: Access Restrictions in the Area** (Nanohubs should be located in areas with fewer restrictions for truck access)
- **Factor J: Proximity to Cycling Infrastructure** (Nanohubs should be located in areas close to bike lanes or safe cycling routes)
- **Factor B: 'Sleeping Assets' (Idle Real Estate in Area)** (Nanohubs should be located in these "residual areas"—urban spaces and buildings that are vacant, underutilized, or have unused capacity during specific times (e.g., parking garages, empty buildings, or areas in occupied buildings that are only used part-time)
- **Factor I: Existing Goods Receivers in Area** (Nanohubs should be located in areas with a high density of commercial establishments that receive goods)
- **Factor C: Demographic Attributes** (Nanohubs should be located close to residential areas with high demand for deliveries, considering online shopping behavior)
- **Factor K: Integration with Urban Environment** (Nanohubs should be located in areas that minimize negative impacts on residents and the environment)

Which is more important?

	1 Equally important	**3** 1st Factor is slightly more important	**5** 1st Factor is moderately more important	**7** 1st Factor is much more important	**9** 1st Factor is extremely more important	**1/3** 2nd Factor is slightly more important	**1/5** 2nd Factor is moderately more important	**1/7** 2nd Factor is much more important	**1/9** 2nd Factor is extremely more important
Factor A: Existing Distribution Centers/Warehouses in Area **vs.** **Factor E:** Proximity to Major Freight Corridors	○	○	○	○	○	○	○	○	○
Factor G: Access Restrictions in the Area **vs.** **Factor J:** Proximity to Cycling Infrastructure	○	○	○	○	○	○	○	○	○
Factor B: 'Sleeping Assets' (Idle Real Estate in Area) **vs.** **Factor I:** Existing Goods Receivers in Area	○	○	○	○	○	○	○	○	○
Factor C: Demographic Attributes **vs.** **Factor K:** Integration with Urban Environment	○	○	○	○	○	○	○	○	○

Appendix C: R script for Fuzzy AHP and criteria weight calculation

```
# ==========================================================================================
# FUZZY AHP FOR SMALL DELIVERY HUB LOCATION SELECTION
# ==========================================================================================

# Load required libraries
library(readr)
library(knitr)
library(RColorBrewer)

# ==========================================================================================
# STEP 1: IMPORT DATA
# ==========================================================================================
raw_data <- read.delim("data.tsv", sep = "\t", header = FALSE, stringsAsFactors = FALSE, skip = 1)
colnames(raw_data) <- c("Stakeholder_ID", "Criterion_1", "Criterion_2", "Crisp_Value")

cat("Data summary:\n")
cat("Number of judgments:", nrow(raw_data), "\n")
cat("Number of stakeholders:", length(unique(raw_data$Stakeholder_ID)), "\n")
cat("Number of criteria:", length(unique(c(raw_data$Criterion_1, raw_data$Criterion_2))), "\n\n")

# ==========================================================================================
# STEP 2: CONVERT CRISP VALUES TO TFNs
# ==========================================================================================
crisp_to_tfn <- function(crisp) {
  if(crisp == 0.11) return(c(1/9, 1/9, 1/7))
  else if(crisp == 0.14) return(c(1/7, 1/5, 1/3))
  else if(crisp == 0.20) return(c(1/5, 1/3, 1))
  else if(crisp == 0.33) return(c(1/3, 1, 1))
  else if(crisp == 1) return(c(1, 1, 1))
  else if(crisp == 3) return(c(1, 3, 5))
  else if(crisp == 5) return(c(3, 5, 7))
  else if(crisp == 7) return(c(5, 7, 9))
  else if(crisp == 9) return(c(7, 9, 9))
  else return(c(NA, NA, NA))
}

data <- raw_data
data$TFN_l <- NA_real_
data$TFN_m <- NA_real_
data$TFN_u <- NA_real_

for (i in 1:nrow(data)) {
  tfn <- crisp_to_tfn(data$Crisp_Value[i])
  data$TFN_l[i] <- tfn[1]
  data$TFN_m[i] <- tfn[2]
  data$TFN_u[i] <- tfn[3]
}

cat("Sample of converted TFN values:\n")
print(head(data[, c("Stakeholder_ID", "Criterion_1", "Criterion_2", "Crisp_Value", "TFN_l", "TFN_m", "TFN_u")]))
cat("\n")

# ==========================================================================================
# STEP 3: IDENTIFY UNIQUE CRITERIA
# ==========================================================================================
all_criteria <- sort(unique(c(data$Criterion_1, data$Criterion_2)))
n_criteria <- length(all_criteria)

cat("All criteria being analyzed:", paste(all_criteria, collapse = ", "), "\n\n")

# ==========================================================================================
# STEP 4: AGGREGATE STAKEHOLDER JUDGMENTS
# ==========================================================================================
get_pair_comparisons <- function(c1, c2) {
  direct <- data[data$Criterion_1 == c1 & data$Criterion_2 == c2, ]
  inverse <- data[data$Criterion_1 == c2 & data$Criterion_2 == c1, ]
  if(nrow(inverse) > 0) {
```

```
    inverse$TFN_l <- 1/inverse$TFN_u
    inverse$TFN_m <- 1/inverse$TFN_m
    inverse$TFN_u <- 1/inverse$TFN_l
  }
  return(rbind(direct, inverse[, colnames(direct)]))
}

l_matrix <- m_matrix <- u_matrix <- matrix(1, nrow = n_criteria, ncol = n_criteria)
rownames(l_matrix) <- colnames(l_matrix) <- all_criteria
rownames(m_matrix) <- colnames(m_matrix) <- all_criteria
rownames(u_matrix) <- colnames(u_matrix) <- all_criteria

for(i in 1:n_criteria) {
  for(j in 1:n_criteria) {
    if(i == j) next
    c1 <- all_criteria[i]
    c2 <- all_criteria[j]
    pair_data <- get_pair_comparisons(c1, c2)
    if(nrow(pair_data) > 0) {
      l_matrix[i, j] <- exp(mean(log(pair_data$TFN_l), na.rm = TRUE))
      m_matrix[i, j] <- exp(mean(log(pair_data$TFN_m), na.rm = TRUE))
      u_matrix[i, j] <- exp(mean(log(pair_data$TFN_u), na.rm = TRUE))
      l_matrix[j, i] <- 1/u_matrix[i, j]
      m_matrix[j, i] <- 1/m_matrix[i, j]
      u_matrix[j, i] <- 1/l_matrix[i, j]
    }
  }
}

cat("Sample of fuzzy comparison matrix (middle values):\n")
print(round(m_matrix[1:5, 1:5], 3))
cat("\n")

# ==========================================================================================
# STEP 5: CALCULATE FUZZY WEIGHTS
# ==========================================================================================
row_geo_mean_l <- apply(l_matrix, 1, function(x) prod(x)^(1/n_criteria))
row_geo_mean_m <- apply(m_matrix, 1, function(x) prod(x)^(1/n_criteria))
row_geo_mean_u <- apply(u_matrix, 1, function(x) prod(x)^(1/n_criteria))

sum_l <- sum(row_geo_mean_u)
sum_m <- sum(row_geo_mean_m)
sum_u <- sum(row_geo_mean_l)

fuzzy_weights_l <- row_geo_mean_l / sum_l
fuzzy_weights_m <- row_geo_mean_m / sum_m
fuzzy_weights_u <- row_geo_mean_u / sum_u

weights_df <- data.frame(
  Criterion = all_criteria,
  Weight_l = fuzzy_weights_l,
  Weight_m = fuzzy_weights_m,
  Weight_u = fuzzy_weights_u
)

# ==========================================================================================
# STEP 6: DEFUZZIFICATION
# ==========================================================================================
weights_df$Defuzzified <- (weights_df$Weight_l + weights_df$Weight_m + weights_df$Weight_u) / 3
weights_df$Normalized <- weights_df$Defuzzified / sum(weights_df$Defuzzified)
weights_df$Percentage <- weights_df$Normalized * 100

# ==========================================================================================
# STEP 7: ADD DESCRIPTIONS (Example for 11 criteria)
# ==========================================================================================
criterion_descriptions <- data.frame(
  Criterion = c("A", "B", "C", "D", "E", "F", "G", "H", "I", "J", "K"),
  Code = c("CR01", "CR02", "CR03", "CR04", "CR05", "CR06", "CR07", "CR08", "CR09", "CR10", "CR11"),
  Description = c(
    "Existing Distribution Centres/Warehouses in Area",
```

```
    "'Sleeping Assets' (Idle Real Estate in Area)",
    "Demographic Attributes",
    "Primary Land-Use Zones",
    "Proximity to Major Freight Corridors",
    "Traffic Intensity of Major Roads in Area",
    "Access Restrictions in the Area",
    "Facility Rental Costs",
    "Existing Goods Receivers in Area",
    "Proximity to Cycling Infrastructure",
    "Integration with Urban Environment"
  )
)

result_df <- merge(weights_df, criterion_descriptions, by = "Criterion")
result_df <- result_df[order(-result_df$Percentage), ]

# ==========================================================================================
# STEP 8: DISPLAY RESULTS
# ==========================================================================================
formatted_results <- data.frame(
  Rank = 1:nrow(result_df),
  Criterion = paste0(result_df$Criterion, " (", result_df$Code, ")"),
  Description = result_df$Description,
  Weight = sprintf("%.2f%%", result_df$Percentage)
)

cat("Criteria Weights for Small Delivery Hub Location\n\n")
print(knitr::kable(formatted_results, format = "markdown"))

# ==========================================================================================
# STEP 9: EXPORT RESULTS
# ==========================================================================================
export_df <- data.frame(
  Rank = 1:nrow(result_df),
  Criterion = result_df$Criterion,
  Code = result_df$Code,
  Description = result_df$Description,
  Weight_Percentage = result_df$Percentage
)

write.table(export_df, "criteria_weights_results.tsv", sep = "\t", row.names = FALSE, quote = FALSE)

fuzzy_weights_export <- data.frame(
  Rank = 1:nrow(result_df),
  Criterion = result_df$Criterion,
  Code = result_df$Code,
  Description = result_df$Description,
  Weight_Lower = result_df$Weight_l,
  Weight_Middle = result_df$Weight_m,
  Weight_Upper = result_df$Weight_u,
  Weight_Defuzzified = result_df$Defuzzified,
  Weight_Normalized = result_df$Normalized,
  Weight_Percentage = result_df$Percentage
)

write.table(fuzzy_weights_export, "fuzzy_weights_complete.tsv", sep = "\t", row.names = FALSE, quote = FALSE)

cat("\nResults have been exported to:\n")
cat("- 'criteria_weights_results.tsv' (simplified results)\n")
cat("- 'fuzzy_weights_complete.tsv' (complete fuzzy weights)\n")
# ==========================================================================================
# END OF SCRIPT
# ==========================================================================================
```

Appendix D: F-AHP crisp pairwise comparisons

For the survey, criterion IDs were simplified to single-letter labels to improve readability for stakeholders. The correspondence is as follows:

Criterion ID	Survey Label
CR01	A
CR02	B
CR03	C
CR04	D
CR05	E
CR06	F
CR07	G
CR08	H
CR09	I
CR10	J
CR11	K

Stakeholder_ID	Criterion_1	Criterion_2	Crisp_Value
1	A	B	0.14
1	A	C	0.2
1	A	D	0.2
1	A	E	0.33
1	B	C	0.2
1	B	D	1
1	B	I	0.2
1	C	D	0.2
1	C	K	1
1	E	F	0.2
1	E	G	0.2
1	F	G	5
1	G	J	0.2
1	H	I	0.33
1	H	J	0.2
1	H	K	0.14
1	I	J	0.14
1	I	K	0.14
1	J	K	1
2	A	B	0.14
2	A	C	0.11
2	A	D	0.14
2	A	E	0.2
2	B	C	0.2
2	B	D	1
2	B	I	0.11
2	C	D	7
2	C	K	5
2	E	F	7
2	E	G	5
2	F	G	3
2	G	J	3
2	H	I	0.14

2	H	J	5
2	H	K	3
2	I	J	7
2	I	K	5
2	J	K	0.33
3	A	B	0.33
3	A	C	0.2
3	A	D	0.2
3	A	E	0.33
3	B	C	0.33
3	B	D	0.2
3	B	I	0.2
3	C	D	0.33
3	C	K	0.14
3	E	F	5
3	E	G	0.2
3	F	G	3
3	G	J	5
3	H	I	0.33
3	H	J	0.2
3	H	K	0.14
3	I	J	5
3	I	K	1
3	J	K	0.2
4	A	B	3
4	A	C	1
4	A	D	7
4	A	E	1
4	B	C	0.14
4	B	D	5
4	B	I	0.2
4	C	D	5
4	C	K	3
4	E	F	1
4	E	G	5
4	F	G	0.33
4	G	J	3
4	H	I	5
4	H	J	5
4	H	K	3
4	I	J	1
4	I	K	3
4	J	K	1
5	A	B	5
5	A	C	5
5	A	D	5
5	A	E	1
5	B	C	1
5	B	D	1
5	B	I	0.14
5	C	D	5
5	C	K	3
5	E	F	0.14
5	E	G	0.2
5	F	G	5
5	G	J	5

5	H	I	1
5	H	J	3
5	H	K	3
5	I	J	5
5	I	K	5
5	J	K	0.14
6	A	B	0.11
6	A	C	0.11
6	A	D	7
6	A	E	0.2
6	B	C	0.33
6	B	D	9
6	B	I	0.14
6	C	D	9
6	C	K	9
6	E	F	0.14
6	E	G	1
6	F	G	9
6	G	J	5
6	H	I	0.33
6	H	J	3
6	H	K	0.14
6	I	J	9
6	I	K	0.33
6	J	K	0.11
7	A	B	0.11
7	A	C	0.11
7	A	D	0.11
7	A	E	1
7	B	C	1
7	B	D	7
7	B	I	7
7	C	D	5
7	C	K	7
7	E	F	1
7	E	G	0.11
7	F	G	0.11
7	G	J	9
7	H	I	1
7	H	J	7
7	H	K	9
7	I	J	7
7	I	K	5
7	J	K	3

Table VI. Crisp Pairwise Judgments Provided by Stakeholders.
Source: by the authors.

Appendix E: Processing and normalization of criteria layers (stages 3 and 4)

Indicator Criteria ID	Stage 3: Construct Map Layers for Criteria Using QGIS Software	Stage 4: Normalize Criteria Maps Using Fuzzy Logic
CR01	**Tool: Point Density (Kernel Density Estimation)** The point layer of cycle-logistics operators hub locations was converted to a kernel-density surface, where: Radius= 2000 m (catchment area[24]) Output value= Scaled (density pts·m^{-2}) (scaling ensures that units remain comparable) The resulting raster ranges from 0 to 8×10^{-7} pt m^{-2} , where: MIN density = 0 (no operator influence) MAX density = 8×10^{-7} pt m^{-2} (highest observed density) Output layer: **CR01_raster**	**Function: Linear (increasing)** As suitability increases linearly with density**,** a linear-increasing fuzzy membership was applied using the QGIS Raster Calculator: **CR01_raster** = x $\mu(x)$ =membership value[25] (normalized result between 0 and 1) $\mu(x) = \frac{x}{8\times10^{-7}}$ and Suitability = 255 $\mu(x)$ Locations with the highest observed operator density receive suitability = 255; cells with no operators remain 0. Output layer: **CR01_fuzzy**
CR02	**Tool: Point Density (KDE)** The point layer of “sleeping assets” locations was converted to a kernel-density surface, where: Output value= Scaled (density pts·m^{-2}) (scaling ensures that units remain comparable) The resulting raster ranges from 0 to 6.6 × 10^{-}6 pt m^{-2} , where: MIN density = 0 (no “sleeping assets available in the area”) MAX density = 6.6×10^{-6} pt m^{-2} (highest observed density of “Sleeping assets”) Output layer: **CR02_raster**	**Function: Linear (increasing)** As suitability increases linearly with density, a linear-increasing fuzzy membership was applied using the QGIS Raster Calculator: **CR02_raster** = x $\mu(x)$ = membership value $\mu(x) = \frac{x}{6.6\times10^{-7}}$ and Suitability = 255 $\mu(x)$ Areas with more idle space reach 255; zero-asset cells score 0. Output layer: **CR02_fuzzy**

[24] This radius was stipulated based on a potential service area, as customers (final destinations) should be located within a cyclable distance from hubs (Konrad, 2021).

[25] In classical (“crisp”) set fuzzy theory, an element is either in a set or not in it, so its membership is binary: 1 or 0. A membership function generalizes this idea by allowing partial membership, represented by any real number between 0 and 1 (Zadeh, 1965). In this study μ(x) gives the degree of membership of the element x in a fuzzy set. A value of 0 means “definitely not in the set,” 1 means “fully in the set,” and intermediate values indicate partial membership.

CR03	**Tool: Inverse Distance Weighting (IDW)** Neighbourhood polygons containing the attribute cars per household were converted to centroids and interpolated via IDW. Statistics from the data: 0.042 and 2.55 are the MIN and MAX values for neighborhoods car-ownership rate indicator. With a MEAN of 0.55[26]. Most of the city has between 0.5 and 0.9 cars per household, and values > 1.5 are rare. Output layer: **CR03_raster**	**Function: Sigmoid (increasing)** A bell-shaped fuzzy membership was built from two opposing sigmoids: **CR03_raster** = x $\mu(x) = \frac{1}{1 + exp(-(x-L)/\alpha)} \times \frac{1}{1 + exp(-(x-H)/\alpha)}$ and Suitability = 255 $\mu(x)$. Where: P10= 0.28 P50= 0.55 P90= 0.83 Spread α = (P90 − P10)/6 ≈ 0.055 (controls slope of the S-curves) Output layer: **CR03_fuzzy** Mid-range optimum: Suitability peaks (≈ 255) around 0.5–0.6 cars · hh^{-1} and drops toward 0 below 0.28 or above 0.83 (≤ 0.28 or ≥ 0.83 → low suitability (≈ 0)).
CR04	**Tool: Euclidean Distance** The polygon layer of favorable land-use zones was rasterized: 1 = inside favorable zones 0 = outside favorable zones. and converted to a Euclidean-distance surface (**CR04_raster**, 0m – 5805m) that was generated with GDAL Proximity. Where: MIN = 0 m → inside or on the edge of a favorable-land-use polygon. MAX ≈ 5800 m → farthest corner of the Brussels-Capital Region Grid from the nearest polygon.	**Function: Sigmoid (decreasing)** A decreasing sigmoid fuzzy function was parameterised with the 10th, 50th and 90th percentiles obtained via *GRASS r.univar* tool: P10 = 100 m P50 = 707 m (distance where suitability = 0.5) P90 = 2766 m α = (P90−P10)/6 ≈ 444 m → slope (controls how fast the curve drops) Using the QGIS Raster Calculator, the membership function **CR04_raster** = d $\mu(d) = \frac{1}{1+exp((d-707)/444.3)}$ was scaled to the fuzzy range 0–255, creating the output layer: **CR04_fuzzy** In this case suitability declines sigmoidally with distance. Suitability = 255 inside/next to a zone and falling smoothly toward 0 as distance grows.

[26] The Brussels-Capital Region has an average rate of 0.55 cars per household (STATBEL, 2023).

CR05	**Tool: Euclidean Distance** The regional-road line layer was rasterized: 1 = regional roads cells 0 = elsewhere (background) and converted to a Euclidean-distance surface (**CR05_raster**, 0m – 5688m) that was generated with GDAL Proximity. Where: Min = 0 m → cells whose center coincides with a regional road line (or is exactly on it) Max ≈ 5688 m → farthest corner of the Brussels-Capital Region Grid from the nearest regional road line	**Function: Sigmoid (decreasing)** A decreasing sigmoid fuzzy function was parameterised with the 10th, 50th and 90th percentiles obtained via GRASS r.univar tool: P10 = 0 (cells located on a road) P50 = 500 m (distance where suitability = 0.5) P90 = 2 500 α = (P90−P10)/6 ≈ 417 m → slope (controls how fast the curve drops) Using the QGIS Raster Calculator, the membership function **CR05_raster** = d $\mu(d) = \frac{1}{1+exp((d-500)/417)}$ was scaled to the fuzzy range 0–255, creating the output layer: **CR04_fuzzy** In this case suitability declines sigmoidally with distance. Suitability = 255 in cells on or immediately adjacent to regional roads, suitability halves at ~500 m and falls to ~0 beyond ~2.5 km.
CR06	**Tool: Inverse Distance Weighting (IDW)** Road-segment lines containing a speed-limit attribute were converted to point samples (by extracting vertices, it returns one point per road vertex with the same speed_km/h attribute). This result was then interpolated with IDW tool, producing the output layer **CR06_raster**, which contains a continuous surface of speed limits. Statistics from the data: MIN = 30 km h^{-1} MAX = 101.07 km h^{-1} MEAN = 30.35 (95 % of all cells cluster round 30 km h^{-1}) P10 = 30.06 P50 = 30.22 (= median) P90 = 30.56 The IDW surface is almost flat at ≈ 30 km h^{-1} because BCR is dominated by 30-km h^{-1} residential streets; higher-speed segments are too sparse to influence the 100 m grid.	**Function: Linear (decreasing)** Because I am adopting the value of 30 km h^{-1} as a safety threshold, a piece-wise linear decreasing membership was applied. Rules adopted were: $Suitability(s) = 255$ (high suitability) to $s \leq 30$ km h^{-1} $Suitability(s) = 255\left[1 - \frac{S-30}{50-30}\right]$ to 30 < s < 50 km h^{-1} → <u>score declines linearly</u> $Suitability(s) = 0$ $s \leq 50$ km h^{-1} or more where s is the posted speed limit (km h^{-1}) obtained from the IDW speed surface. Output layer: **CR06_fuzzy**

CR07	**Tool: Euclidean Distance** Access-restricted polygons were rasterized: 1 = Access-restricted polygons cells 0 = elsewhere (background) and converted to a Euclidean-distance surface (**CR07_raster**, 0m – 5510.89m), that was generated with the tool GDAL Proximity. Where: Min = 0 m ⟶ cells whose coincides with the access-restricted zones. Max = 5510.89 ⟶ farthest corner of the Brussels-Capital Region Grid from the nearest access-restricted polygon.	**Function: Sigmoid (increasing)** Suitability rises sigmoidally with distance. An increasing sigmoid fuzzy function (distance-based avoidance) was parameterized with the 10th, 50th and 90th percentiles obtained via GRASS r.univar tool: P10 = 0 (cells inside the restricted zones) P50 = 283 (distance where suitability = 0.5) P90 = 2343.07 α = (P90−Q1)/6= (2343.07–100)/6 ≈ 374 m where: (Q1 = first quartile = 100 m) Considering that the modes of transport used for deliveries are bikes and small trucks/vans, the value of Q1 was adopted. This would give a steeper slope (not a smooth transition) that starts increasing immediately outside the access-restricted zones. Using the QGIS Raster Calculator, the membership function **CR07_raster** = d $\mu(d) = \frac{1}{1+exp((d-283)/374)}$ was scaled to the fuzzy range 0–255, creating the output layer: **CR07_fuzzy** In this case, cells inside restricted areas remain at 0, while suitability approaches ≈255 beyond ~2.3 km from any conflict zone.
CR08	**Tool: Inverse Distance Weighting (IDW)** The commune-level rent layer (rent_avg, €/month) was rasterized, assigning each cell the average rent of its commune (cr08_rent_raster, 956 – 1 486 €/month). (every polygon becomes one point) and were interpolated with IDW tool, producing the output layer **CR08_raster**. Statistics from the data: MIN = 956 €/month MAX = 1486 €/month As the commune boundaries are not hard barriers for rent, I am assuming a short-range spatial spill-over of rental costs across commune boundaries, avoiding unrealistically sharp discontinuities in the cost surface.	**Function: Sigmoid (decreasing)** A decreasing sigmoid fuzzy function was parameterized with the 10th, 50th and 90th percentiles obtained via *GRASS r.univar* tool: P10 = 1068.13 € P50 = 1192.55 € (=rental cost where suitability = 0.5) P90 = 1292.59 € α = (P90−P10)/6 = 37.41 € Using the QGIS Raster Calculator, the membership function **CR08_raster** = x $\mu(x)$ = membership value $\mu(x) = \frac{1}{1+exp((x-1192.55)/37.41)}$ was scaled to the fuzzy range 0–255, creating the output layer: **CR08_fuzzy**

		where: 255 = highest suitability (ideal locations). 0 = lowest suitability (unsuitable). In this case, suitability declines sigmoidally with distance. Communes with rental costs values below ≈ 1 050 €/month attain suitability ≈ 255 whereas those above ≈ 1 300 €/month drop below 20 in the fuzzy range (≈ 20 = very low—only about 8 % of the maximum suitability (20÷255≈0.08).
CR09	**Tool: Line Density (kernel length per cell)** To calculate the density of linear features within the boundaries of the Brussels-Capital Region, the original line vector layer was first converted into a point layer using the "Points along geometry" tool in QGIS. This process generated equidistant points at 1-meter intervals along each line segment, ensuring that the spatial pattern of the linear infrastructure was accurately represented in a format suitable for raster-based analysis. Subsequently, the point layer of delivery-destination street segments representing goods receiver locations was converted to a kernel-density surface. Statistics from the data: MIN = 0 MAX= 0.0621996 $pt \cdot m^{-2}$ The distribution is extremely right-skewed: 75 % of cells hold ≤ 0.0016 $pt \cdot m^{-2}$. Output layer: **CR09_raster**	**Function: Sigmoid (increasing)** Because the distribution is extremely skewed: P10 =1.4×10^{-5} $pt \cdot m^{-2}$ P50 = 0.0025 $pt \cdot m^{-2}$ (median) P90 = 0.01356 $pt \cdot m^{-2}$ α = (P90−P10)/6 = 0.00226 $pt \cdot m^{-2}$ An increasing sigmoid membership was adopted to enhance contrast in the sparse mid-range. Using the QGIS Raster Calculator, the membership function below was scaled to the fuzzy range 0–255: **CR09_raster** = x $\mu(x)$ = membership value $\mu(x) = \frac{1}{1+exp(-(x-0.00252)/0.00226)}$ and Suitability=255μ(x) Finally creating the output layer: **CR09_fuzzy** Median-density areas score ≈ 128, top-10 % hotspots reach ≥ 220, whereas cells with virtually no receivers remain near zero.
CR10	**Tool: Euclidean Distance** Vector line layer of existing cycle tracks / bike lanes was rasterized: 1 = bike route cells 0 = elsewhere (background) and converted to a Euclidean-distance surface (**CR10_raster**, 0m – 5594.64m)	**Function: Sigmoid (decreasing)** A decreasing sigmoid fuzzy function was parameterised with the 10th, 50th and 90th percentiles obtained via GRASS r.univar tool: P10 = 0 (cells located on a bike route) P50 = 223.61 m (distance where suitability = 0.5) P90 = 2309.68 α = (P90−P10)/6 ≈ 385 m

	that was generated with GDAL Proximity. Where: Min = 0 m → 0 m on/inside the bike route Max = 5594.64 m → farthest corner of the Brussels-Capital Region Grid from the nearest bike route	Using the QGIS Raster Calculator, the membership function layer **CR10_raster** = d $\mu(d) \ = \ \frac{1}{1+exp((d-223.61)/385)}$ and Suitability=255μ(d) was scaled to the fuzzy range 0–255, creating the output layer: **CR10_fuzzy** Locations directly on a bike route reach suitability ≈ 255; suitability halves at ~224 m and falls below 20 beyond ~2.3 km.
CR11	**Layer1** Geolocated road-accidents records in the year 2022 → Geometry = points → **Tool: Point Density (KDE)** **Layer2** Black Carbon concentration during working hours (daytime) (µg m^{-3}) → Geometry = polygons → **Tool: Inverse Distance Weighting (IDW)** Each raster was min–max normalized to 0–1 risk and averaged, producing the output layer **CR11_combined** (mean risk). Then, using the QGIS Raster Calculator with the respective values: CR11_combined = $\frac{Layer1_{normalized} + Layer2_{normalized}}{2}$	**Function: Sigmoid (decreasing)** Because higher combined values represent greater environmental and safety risk, a sigmoid-decreasing membership was applied to the risk raster (CR11_combined). The function was parameterized with the 10th, 50th and 90th percentiles obtained via GRASS r.univar tool: P10 = 0.437073 P50 = 0.576408 (risk where suitability = 0.5) P90 = 0.921184 α = (P90−P10)/6 = 0.08068 Using the QGIS Raster Calculator, the membership function layer **CR11_combined** = r $\mu(r) \ = \ \frac{1}{1+exp((r-0.5764)/0.08068)}$ and Suitability = 255μ(r) This assigns suitability ≈ 255 to very safe cells (risk ≤ 0.05), 128 at the median risk, and values below 30 to the highest-risk decile, creating the output layer: **CR11_fuzzy**

Table VII. Detailed Criteria Processing and Normalization Procedures.
Source: by the author.