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Enhancing Biodiversity and Environmental Sustainability in Intermodal Transport: A GIS-Based Multi-Criteria Evaluation Framework

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Abstract: Biodiversity is essential for the health and stability of our planet, contributing to ecosystem services like pollination, nutrient cycling, and climate regulation. However, it faces significant threats from human activities, including habitat destruction and pollution. Transportation infrastructure, if not carefully managed, can fragment habitats and disrupt wildlife migration, exacerbating biodiversity loss. Thus, incorporating environmental and biodiversity considerations into transport planning is crucial for promoting long-term sustainability. Accordingly, the goal of this paper is to define a framework for evaluating and ranking intermodal transport routes based on their impact on the environment and biodiversity. The study employs a Geographic Information System (GIS)-based Multi-Criteria Decision-Making (MCDM) model, combining input from interactive GIS maps and stakeholders with a novel hybrid approach. The MCDM part of the model combines fuzzy Delphi and fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods for obtaining the criteria weights and the Axial Distance-based Aggregated Measurement (ADAM) method for obtaining the final ranking of the routes. This methodology application on several Trans-European Transport Network (TEN-T) routes revealed that the Hamburg/Bremerhaven–Wurzburg–Verona route had the least environmental and biodiversity impact. The study identified the Rotterdam–Milano route as the optimal choice, balancing sustainability, ecological preservation, and transport efficiency. The route minimizes ecological disruption, protects biodiversity, and aligns with European Union strategies to reduce environmental impact in infrastructure projects. The study established a framework for evaluating intermodal transport routes based on environmental and biodiversity impacts, balancing efficiency with ecological responsibility. It makes significant contributions by integrating biodiversity criteria into transport planning and introducing a novel combination of GIS and MCDM techniques for route assessment.

Keywords: biodiversity; sustainability; intermodal transport; geographic information system (GIS); Delphi; decision-making-trial and evaluation laboratory (DEMATEL); axial distance-based aggregated measurement (ADAM)

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Academic Editor: Giovanni Leonardi

Received: 15 January 2025
Revised: 29 January 2025
Accepted: 6 February 2025
Published: 8 February 2025

Citation: Krstić, M.; Tadić, S.; Miglietta, P.P.; Porrini, D. Enhancing Biodiversity and Environmental Sustainability in Intermodal Transport: A GIS-Based Multi-Criteria Evaluation Framework. *Sustainability* **2025**, *17*, 1391. https://doi.org/10.3390/su17041391

1. Introduction

Biodiversity, encompassing the variety of life from genes to ecosystems, is essential for planetary health, contributing to vital ecosystem services like pollination, nutrient cycling, and climate regulation. However, human activities such as habitat destruction, pollution, climate change, overexploitation, and invasive species introduction severely threaten biodiversity. Transportation infrastructure, including roads, railways, and urban expansion, increases habitat fragmentation, restricting species migration and reproduction. Additionally, vehicles contribute to pollution and the spread of invasive species, further destabilizing ecosystems. Addressing the impact of transportation on biodiversity is crucial for conservation and sustainable development.

Intermodal transportation, which integrates multiple transport modes like rail, road, and sea, plays a pivotal role in modern logistics [1]. It is defined as "*the transport of goods in one and the same loading unit or vehicle using multiple modes of transport, where there is no transshipment of goods when changing modes*" [2]. Beyond enhancing freight movement efficiency, intermodal transport significantly reduces the environmental footprint of logistics networks [3]. By alleviating road congestion and reducing greenhouse gas emissions, it supports sustainable economic growth. As trade volumes rise alongside environmental concerns, optimizing intermodal transport routes becomes essential for achieving sustainability goals.

Beyond reducing emissions, intermodal transportation can mitigate biodiversity loss by integrating ecological considerations into transport planning. Poorly managed transport infrastructure can fragment habitats, disrupt wildlife migration, and accelerate ecosystem degradation. Therefore, incorporating biodiversity-sensitive planning ensures that infrastructure development aligns with ecological balance, preserving vital ecosystems and promoting long-term sustainability.

European policies advocate for intermodal freight transport to minimize environmental impacts, recognizing it as key to sustainable development. The European Green Deal [4] calls for a modal shift to rail and inland waterways to decarbonize transport and achieve net-zero emissions by 2050. Likewise, the EU's Sustainable and Smart Mobility Strategy [5] highlights intermodal transport as essential for reducing greenhouse gas emissions, alleviating congestion, and minimizing freight transport's ecological footprint. These policies have promoted intermodal solutions within the Trans-European Transport Network (TEN-T) corridors.

However, transitioning to intermodal transport alone does not eliminate environmental impacts. Intermodal terminals, critical to these networks, can contribute to habitat fragmentation and local emissions if not carefully designed [6]. Addressing this requires integrating energy-efficient technologies, renewable energy, and biodiversity-sensitive infrastructure planning. Further research is needed to refine intermodal transport systems to align with broader European environmental objectives.

This study develops a methodology for ranking and selecting intermodal transport routes with the least negative impact on biodiversity and the environment for specific transport requests. The approach involves aggregating the total environmental impact of each route based on multiple indicators (criteria). The proposed framework integrates a Geographic Information System (GIS)-based Multi-Criteria Decision-Making (MCDM) model, combining spatial data analysis with expert input. The model applies fuzzy Delphi and fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods to determine criteria weights and employs the Axial Distance-based Aggregated Measurement (ADAM) method for final route ranking.

The methodology is tested on intermodal routes within the TEN-T corridors, specifically the North Sea–Mediterranean and Scandinavian–Mediterranean corridors. Results based on real-world data indicate that the Hamburg/Bremerhaven–Würzburg–Verona route in the Scandinavian–Mediterranean corridor has the least environmental and biodiversity impact.

The paper is structured as follows. Section 2 provides background and methodology with relevant literature, followed by Section 3, a detailed problem description. Section 4 outlines the methodology and application steps, while Section 5 presents input values, results, sensitivity analysis, and validation. Section 6 discusses key contributions, implications, and limitations. Section 7 provides concluding remarks and directions for future research.

2. Background and Related Papers

Intermodal transport is essential for efficient freight movement, reducing congestion, and minimizing environmental impact [7]. Optimizing intermodal routes improves logistics efficiency, lowers costs, and shortens transit times. Key research topics include terminal location selection [8], transshipment technologies [9], network resilience [10], information needs [11], and modern technologies [12]. Environmental studies focus on carbon footprint evaluation [13], stakeholder awareness [14], and emission impacts [15]. With growing environmental concerns [16], sustainable intermodal transport reduces emissions, alleviates congestion, and minimizes ecological footprints, balancing economic efficiency with sustainability [17].

The Trans-European Transport Network (TEN-T) is crucial in enhancing connectivity and promoting sustainable transport in Europe. Its Core Network Corridors improve intermodal efficiency and environmental performance, aligning with the European Green Deal [18]. However, integrating physical and digital infrastructures, particularly in Southeast Europe, poses challenges requiring strategic solutions [19]. The Belt and Road Initiative (BRI) adds complexity, influencing TEN-T and necessitating adaptations for logistical and environmental efficiency [20]. Multimodal transport technologies within TEN-T highlight the need for synchronized, eco-friendly solutions [21]. Studies measuring TEN-T's impact on urban accessibility emphasize connectivity improvements while stressing sustainability [22]. Green corridors and network design focus on minimizing environmental impact and supporting biodiversity and ecological sustainability [23]. Collectively, these efforts advance resilient, environmentally responsible transport networks by bridging research gaps in TEN-T integration.

Biodiversity protection is increasingly vital in environmental and transport studies, as infrastructure can disrupt habitats and wildlife corridors, leading to biodiversity loss [24]. Integrating biodiversity into transport planning helps mitigate these impacts and supports long-term ecological sustainability [25]. Most studies focus on transport's general environmental effects [26,27], but research has shown intermodal transport's potential benefits. Rail-based freight corridors reduce greenhouse gas emissions and urban congestion compared to road transport [6], with Life Cycle Assessments (LCAs) indicating CO_2 reductions of up to 70% when shifting from road to rail [17]. High-speed rail consolidates freight, reducing habitat fragmentation [26], yet poorly planned routes can disrupt wildlife corridors [28], necessitating GIS-based assessments [29]. Despite these insights, no studies specifically assess intermodal transport's impact on biodiversity or rank transport routes by biodiversity protection criteria. This research aims to address these gaps.

Previous studies on intermodal transport route optimization and environmental assessment have used MCDM [30], GIS [31], Environmental Impact Assessment (EIA) [6], LCA [32], and Strategic Environmental Assessment (SEA) [33]. While some combine GIS with MCDM [34], no research applies this to intermodal transport optimization considering biodiversity, a gap this study addresses.

GIS is crucial for integrating biodiversity conservation into transport planning [35], enabling spatial analysis of ecological and logistical factors [36]. It assesses habitat fragmentation and supports mitigation measures like green corridors [37,38]. In intermodal transport, GIS optimizes routes by balancing environmental and operational criteria [39]. However, few studies fully integrate biodiversity-specific criteria into intermodal transport planning, highlighting a critical research gap this paper addresses.

The proposed methodology integrates Delphi, DEMATEL, and ADAM. The Delphi method [40] is a structured, iterative forecasting technique using expert panels to reach a consensus. Experts anonymously refine their responses over multiple rounds, reducing bias and uncertainty. This method is particularly useful for complex decisions with uncertainty or limited data [41]. Delphi is often combined with other MCDM methods to systematically evaluate multiple criteria. Its advantages include iterative expert input, reduced bias, and structured decision-making. Recent applications include assessing artificial intelligence (AI) in construction [42], identifying AI implementation barriers in Information Technology (IT) industry [43], ranking resilient supply chains [44], and evaluating social resilience in water protection areas [45]. By integrating Delphi with DEMATEL and ADAM, the methodology ensures a comprehensive, consensus-driven approach to intermodal transport optimization, addressing key environmental and logistical challenges while improving decision-making reliability.

The DEMATEL method [46] analyzes complex causal relationships by identifying cause-and-effect chains and visualizing decision structures [47]. It effectively handles interrelated factors, enhancing prioritization by considering both direct and indirect influences between criteria [48]. Often combined with other MCDM methods, DEMATEL helps structure criteria and assign weights based on causal strength [49]. Recent applications include maximizing sustainability in renewable systems [50], assessing urban resilience [51], evaluating construction risks [52], and prioritizing ecosystem indicators [53]. By incorporating DEMATEL, transport planning can systematically evaluate environmental and logistical factors, leading to more informed and effective decision-making.

The ADAM method [54] ranks alternatives by calculating volumes of complex polyhedra in a 3D coordinate system, with points representing origins, reference points indicating alternative values, and weighted points incorporating criterion weights. Known for its simplicity, scalability, and ease of use [55], ADAM involves intuitive geometric calculations that are easy to interpret visually. It offers stability with minimal risk of rank reversal, as changes in criteria weights have little impact on outcomes. Although new, it has been applied in various fields, including entrepreneurial ecosystems [56], distribution channel selection [57], digitalization in the agro-industry [58], and railway infrastructure performance [59].

Another research gap addressed in this paper is the fact that the previously described MCDM methods have never been combined, providing a novel approach to multi-criteria decision-making.

3. Problem Statement

Despite Italy having numerous ports, northern European ports like Rotterdam, Antwerp, and Hamburg hold a substantial share of freight flows, especially for northern Italy's intermodal terminals. The observed ports are among the busiest ports in Europe. Annually, the observed four ports serve over 35% of the total container traffic in Europe. These ports benefit from superior capacity, efficiency, and connectivity, making them key entry points for goods destined for Europe. The robust rail and road networks from these ports and the established Trans-European Transport Network (TEN-T) corridors facilitate direct and efficient transport to northern Italian regions, such as Milan and Verona, which are crucial industrial hubs. This logistical advantage ensures that these northern ports remain pivotal for Italian imports.

There are various routes connecting northern European ports to intermodal terminals in northern Italian cities. These routes differ in their economic, social, and environmental impacts. Economically, routes leveraging high-speed rail systems can reduce transit times and costs, enhancing efficiency and competitiveness for businesses in northern Italy. Socially, the development and maintenance of these routes can create jobs and stimulate economic growth in local communities. However, infrastructure projects can also lead to displacement and other social disruptions. Environmentally, rail transport is generally more sustainable than road transport, emitting fewer greenhouse gases and reducing road congestion. Conversely, road transport routes may contribute to higher emissions and environmental degradation, particularly in urban areas.

This paper addresses the environmental aspects of these routes, more precisely the evaluation of the routes based on their impact on biodiversity. Transport routes vary significantly in their effects on local ecosystems. Rail routes, while more sustainable in terms of emissions, can still disrupt wildlife habitats and migration patterns, leading to biodiversity loss if not carefully managed. On the other hand, road transport can contribute to higher pollution levels and habitat fragmentation, further threatening local flora and fauna. Comprehensive environmental assessments are needed to identify and mitigate these impacts, ensuring that the chosen routes minimize harm to biodiversity. This approach addresses immediate environmental concerns and promotes long-term ecological sustainability in the regions affected by these transport corridors.

3.1. Intermodal Transport Routes

Northern European ports are connected to a large number of Italian intermodal terminals. Most of these connections are established through two TEN-T corridors, the North Sea–Mediterranean corridor and Scandinavian–Mediterranean corridor. In this paper, four particular routes are analyzed in detail, each of which belongs to one of the two mentioned corridors (Figure 1). These are the routes between the intermodal terminal Melzo (Milan) and the ports of Antwerpen (R1) and Rotterdam (R2), and between the intermodal terminal Verona Quadrante Europa and the ports of Hamburg (R3) and Rostock (R4). These routes were chosen because they connect the largest and most important northern European ports on the mentioned corridors with the largest and most important intermodal terminals in the north of Italy.

The routes are very similar in terms of applicable transport technology, although they differ in terms of time and distance. R1 is 955 km long, R2 is 1081 km long, R3 is 1200 km long, and finally R4 is 1352 km long. Besides this, the routes differ significantly in terms of impact on the environment, that is, in terms of criteria that take into account different aspects of the impact of the transport flow performance on biodiversity. These criteria are explained in more detail below.

3.2. GIS-Based Biodiversity-Oriented Criteria

In developing sustainable intermodal transport routes, it is crucial to incorporate GIS-based biodiversity-oriented criteria. These criteria ensure that transportation planning not only addresses efficiency and connectivity but also prioritizes the preservation of ecological systems. By leveraging advanced GIS data, planners can identify and protect sensitive areas, maintain habitat connectivity, and mitigate impacts on critical habitats and biodiversity hotspots.

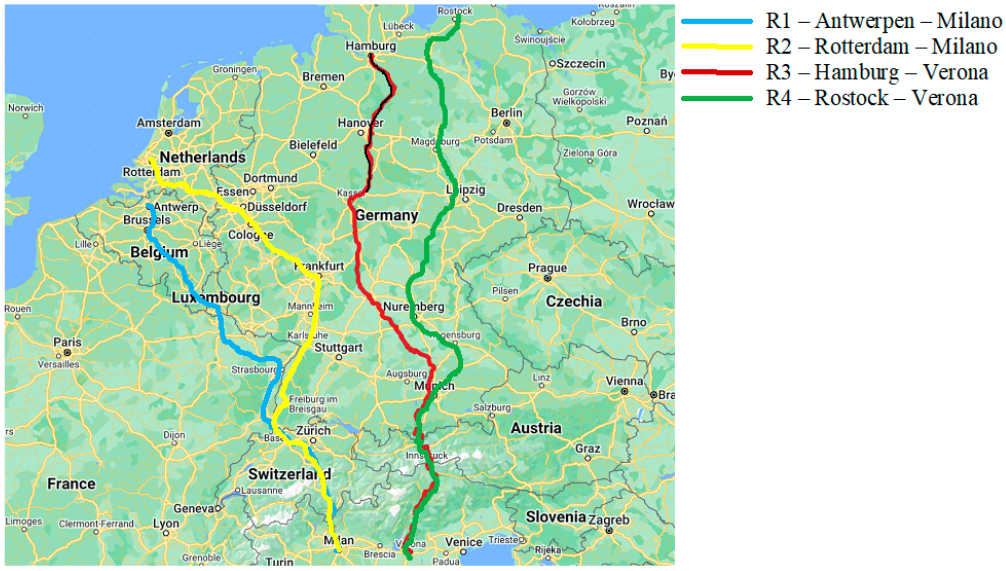

Figure 1. Considered intermodal transport routes.

The Land Use and Land Cover (C1) criterion specifically evaluates how different land types, such as urban areas, agricultural lands, and forests, interact with proposed intermodal transport routes. For urban sprawl, the purpose is to identify and avoid highly urbanized regions to prevent conflicts with residential and commercial areas using Weighted Urban Proliferation (WUP) metrics, which assess the percentage of built-up areas, dispersion, and land uptake per person. In agricultural areas, the goal is to protect productive lands and biodiversity, utilizing Corine Land Cover (CLC) 2018 data to map and prioritize routes that minimize impacts on high-value agricultural zones and avoid fragmentation. For forests, the objective is to prevent deforestation and habitat loss by applying High-Resolution Layer (HRL) Forest 2018 data to identify forest types and tree cover density and select routes that preserve dense and ecologically sensitive forested areas. This integrated approach ensures transport routes are environmentally sustainable, economically viable, and politically feasible.

The Protected Areas and Conservation Zones (C2) criterion evaluates intermodal transport routes to prevent disruption of regions designated for biodiversity preservation. Utilizing GIS data, including Natura 2000 sites covering SPAs, SCIs, and SACs, planners access detailed ecological descriptions for informed decision-making [60]. The Emerald Network, comprising Areas of Special Conservation Interest, extends protection to non-EU member states. Nationally designated areas (CDDAs) provide a comprehensive inventory of protected sites across Europe. By overlaying GIS layers and conducting spatial analyses, planners identify and mitigate potential impacts on these critical zones. This integrated approach ensures routes avoid or minimize crossing protected areas, supporting sustainable, ecologically responsible planning aligned with international and national conservation efforts.

The Biodiversity Hotspots and Critical Habitats (C3) criterion evaluates intermodal transport routes with areas of significant ecological importance and critical habitats for species preservation. It aims to identify and protect regions that serve as biodiversity hotspots, harboring high levels of species diversity and unique ecosystems. Additionally, it seeks to safeguard critical habitats essential for the survival of endangered species and the maintenance of ecosystem functions. Utilizing GIS data collected under the Habitats Directive (92/43/EEC) [60] which monitors habitat types and species populations across Member States, the criterion assesses the distribution and conservation status of habitats and species within grid cells. By integrating this spatial data, route planning can account for areas of conservation concern, minimizing disruptions to biodiversity while ensuring the long-term sustainability of transport infrastructure development.

The Habitat Connectivity and Wildlife Corridors (C4) criterion assesses how intermodal transport routes intersect with and impact wildlife habitats and movement corridors. Utilizing the Effective Mesh Density metric, it assesses landscape fragmentation caused by Fragmentation Geometries (FGs), including impervious surfaces and traffic infrastructure like medium-sized roads. GIS data covering EEA39 map FGs [60], highlighting areas of pronounced landscape fragmentation hindering wildlife corridors. It aims to identify and preserve areas that facilitate the movement of wildlife between habitats, ensuring genetic diversity and access to essential resources. By evaluating landscape connectivity, this criterion helps minimize disruptions to natural ecosystems caused by infrastructure development. It considers the implications of route planning on wildlife populations, ecosystem resilience, and the provision of ecosystem services. By integrating considerations of habitat connectivity into route planning, it supports sustainable development practices that balance transportation needs with ecological conservation objectives.

The Environmental Sensitivity and Vulnerability (C5) criterion evaluates intermodal transport routes to identify and avoid areas highly susceptible to environmental damage. It helps preserve delicate ecosystems and supports sustainable infrastructure development. The criterion uses data from the European Nature Information System [60], which provides information on various terrestrial and marine habitats across Europe. These data combine information on land features with habitat details to improve understanding of ecosystem types and their locations. Produced by the European Environment Agency, this information supports the EU Biodiversity Strategy and efforts to meet international biodiversity targets. By using these maps, planners can ensure that transport routes minimize impacts on sensitive and vulnerable areas, promoting environmentally responsible development.

The Topography and Elevation (C6)criterion assesses intermodal transport routes based on terrain features, aiming to minimize environmental impact and optimize route efficiency by considering height, slope, and proximity to the sea. This criterion uses GIS data to categorize landscapes into five relief typologies: low coasts, high coasts, inland, uplands, and mountains. This Elevation Breakdown helps allocate land cover changes according to these typologies, offering a clear understanding of the landscape's structure. Derived from high-resolution datasets like the EU-DEM [60], the data provide accurate, up-to-date information. The delineation of European mountain areas uses digital elevation models considering altitude, climate, and topography variables. Covering the entire European continent, this dataset serves as a reference for recognizing the ecological and strategic value of mountain areas. By integrating these data, transport planners can design routes that respect natural terrain features, enhancing sustainability and reducing construction challenges, ensuring that infrastructure development is both efficient and environmentally responsible.

The Hydrology and Watersheds (C7) criterion evaluates intermodal transport routes based on the characteristics of water bodies and watersheds to protect surface water resources and ensure sustainable water management. It uses GIS data from the European surface water bodies delineated for the First River Basin Management Plans under the Water Framework Directive, which includes detailed information on rivers, lakes, reservoirs, and coastal waters. These data help avoid critical water resources by identifying significant surface water elements. Additionally, the EEA's potential flood-prone area extent delineates areas susceptible to flooding, such as river channels and floodplains, providing essential information to prevent infrastructure placement in high-risk zones. The Copernicus High-Resolution Layer Water and Wetness (WAW) shows the occurrence of water and wet surfaces from 2012 to 2018 [60], indicating degrees of wetness and the presence of permanent and temporary water bodies. By integrating these data, transport planners can design routes that respect hydrological features, promoting sustainable and environmentally responsible development while minimizing flooding risks and protecting vital water resources.

3.3. Stakeholders

For addressing the defined problem, four main stakeholder groups are involved: government and regulatory bodies, industry and transport operators, local and affected communities, and environmental and conservation organizations.

The Government and Regulatory Bodies (S1) stakeholder group includes environmental agencies, transport and infrastructure authorities, and urban and regional planners. Environmental agencies aim to protect ecosystems and biodiversity by implementing regulations that minimize environmental impacts. Transport and infrastructure authorities focus on developing efficient, safe, and sustainable transportation networks that support economic growth and enhance connectivity. Urban and regional planners work to create balanced regional development and sustainable urban environments by aligning transportation infrastructure with land-use planning. Common goals and interests of this group include ensuring sustainable development, regulatory compliance, public health and safety, stakeholder engagement, and long-term planning. These bodies strive to balance the need for transportation infrastructure with environmental and biodiversity conservation, fostering transparent decision-making processes and supporting resilient transport systems that address environmental challenges like climate change.

The Industry and Transport Operators (S2) stakeholder group encompasses logistics and freight forwarding companies, transportation service providers, and economic and policy analysts. These stakeholders focus on ensuring efficient and cost-effective transport operations while minimizing environmental impacts. Logistics and freight companies aim to optimize supply chain processes and enhance connectivity across different modes of transport. Transportation service providers prioritize safety, reliability, and sustainability in their operations. Economic and policy analysts evaluate the economic implications and policy aspects of transportation routes to ensure they align with broader economic goals. Common goals and interests include improving operational efficiency, reducing environmental footprints, complying with regulations, enhancing economic benefits, and fostering innovation in transport technologies. This group plays a critical role in balancing operational needs with environmental and economic considerations, contributing to the development of sustainable and effective intermodal transport systems.

The Local and Affected Communities (S3) stakeholder group includes residents, community leaders, and Indigenous groups (where applicable). These stakeholders are directly impacted by transport routes and focus on protecting their living environments, health, and cultural heritage. Residents and community leaders aim to ensure that transportation projects do not harm their quality of life, seeking measures to reduce noise, pollution, and disruption. Indigenous groups are concerned with preserving their land rights, cultural sites, and natural resources. Common goals and interests include maintaining environmental quality, safeguarding public health, preserving cultural and natural heritage, and ensuring meaningful community engagement in decision-making processes. This group plays a vital role in highlighting the social and environmental impacts of transport routes and advocating for sustainable and community-friendly transportation solutions that respect local needs and rights.

The Environmental and Conservation Organizations (S4) stakeholder group includes conservation NGOs, advocacy groups, and academic and research institutions specializing in environmental science and ecology. These stakeholders are dedicated to protecting natural habitats, preserving biodiversity, and promoting sustainable practices. Conservation NGOs and advocacy groups focus on safeguarding wildlife, advocating for stringent environmental regulations, and raising public awareness about conservation issues. Academic and research institutions provide scientific insights and data to inform decision-making and develop innovative solutions for environmental challenges. Common goals and interests include preserving ecosystems, mitigating the impact of transportation on biodiversity, advancing environmental research, and influencing policy to foster sustainability. This group is crucial for ensuring that transportation projects consider environmental impacts and incorporate strategies to protect and enhance natural resources, contributing to the long-term health of the planet.

4. Hybrid GIS-Based Fuzzy D-DEMATEL-ADAM Model

The complexity of evaluating intermodal transport routes based on biodiversity and environmental sustainability requires the use of MCDM methods. Traditional decision-making approaches often rely on single-criterion optimization, such as cost minimization or transit time reduction. However, in transport planning, particularly when integrating environmental and biodiversity concerns, trade-offs between conflicting objectives must be carefully managed. The inclusion of multiple criteria ensures a more holistic and balanced decision-making process.

By combining GIS with the MCDM model, this study enhances traditional MCDM applications in transport sustainability assessment. The integration of spatial data, stakeholder representatives weight assignment, and advanced ranking methodologies ensures that transport route selection is both methodologically sound and environmentally responsible.

GIS data expressed in the form of criteria are used as values for evaluating and ranking the alternatives by applying the ADAM method. This method was chosen because of its advantages described in Section 2. However, the defined criteria are interdependent, and when determining their importance, i.e., weights, it is necessary to take these connections into account. Having in mind this and the advantages of the DEMATEL method compared to some other methods, it was selected to perform this procedure. Since the evaluations are performed by different stakeholder representatives who favor different criteria, it was necessary to apply the Delphi method that enabled the unification of different evaluations. The structure of the proposed model is shown in Figure 2 and the steps of its application are described below.

Step 1: Define the sets of alternatives and criteria for their evaluation. Identify the stakeholders interested in solving the problem.

Step 2: Obtain the input values of the alternatives according to the criteria.

Step 2.1: Extract the GIS maps and related data.

Step 2.2: Express the GIS data into numerical values.

Step 3: Obtain the criteria weights using the fuzzy Delphi-based DEMATEL method (fuzzy D-DEMATEL).

Step 3.1: Establish a scale for criteria evaluation (Table 1).

Table 1. Fuzzy scale for criteria evaluation.

Linguistic Term	Abbreviation	Fuzzy Scale
None	N	(1, 1, 2)
Very low	VL	(1, 2, 3)
Low	L	(2, 3, 4)
Fairly low	FL	(3, 4, 5)
Medium	M	(4, 5, 6)
Fairly high	FH	(5, 6, 7)
High	H	(6, 7, 8)
Extremely high	EH	(8, 9, 10)

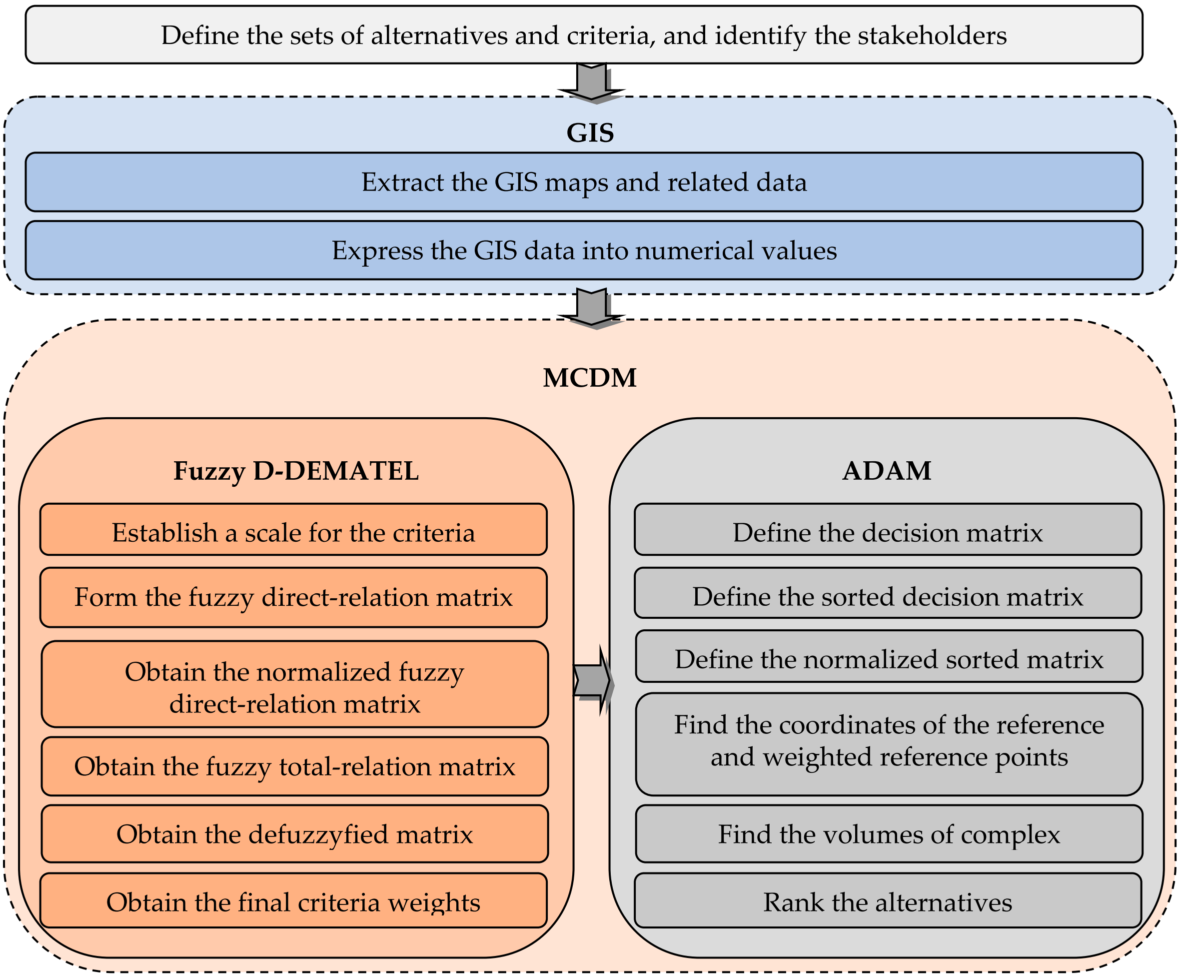

Figure 2. The structure of the proposed model.

Step 3.2: Form the fuzzy direct-relation matrix $\widetilde{\Delta}$:
This is Example 1 of an equation:

$$\widetilde{\Delta} = \begin{bmatrix} / & \widetilde{\delta}_{12} & \cdots & \widetilde{\delta}_{1n} \\ \widetilde{\delta}_{21} & / & \cdots & \widetilde{\delta}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \widetilde{\delta}_{n1} & \widetilde{\delta}_{n2} & \cdots & \widetilde{\delta}_{nn} \end{bmatrix}, \tag{1}$$

in which δ_{ij} represents the unified degree to which criterion affects the i affects criterion j, obtained using the following equations, which are part of the fuzzy Delphi method (adapted from [61]):

$$\widetilde{\delta}_{ij} = \left(\alpha_{ij}, \beta_{ij}, \gamma_{ij}\right), \tag{2}$$

$$\alpha_{ij} = Min\left(l_{hij}\right), \ \ h = 1, \ldots, o, \tag{3}$$

$$\beta_{ij} = \left(\prod_{l=1}^{o} m_{hij}\right)^{1/o}, \ \ h = 1, \ldots, o, \tag{4}$$

$$\gamma_{ij} = Max\left(u_{hij}\right), \ \ h = 1, \ldots, o, \tag{5}$$

where α_{ij}, β_{ij} and γ_{ij} are the lower, middle, and upper values of the δ_{ij}, respectively, and $\alpha_{ij} \leq \beta_{ij} \leq \gamma_{ij}$. l_{hij}, m_{hij}, and u_{hij} are the lower, middle, and upper values of the representative evaluation of the degree to which criterion affects the i affects criterion

j according to stakeholder h. n is the total number of criteria and o is the number of stakeholders.

Step 3.3: Obtain the normalized fuzzy direct-relation matrix $\widetilde{X}$ from matrix $\widetilde{\Delta}$:

$$S = \left[s_{jk}\right]_{n\times m}, \tag{6}$$

where

$$s = 1/\max_{1\leq j\leq n}\sum_{j=1}^{n}\gamma_{ij}. \tag{7}$$

Step 3.4: Obtain the fuzzy total-relation matrix $\widetilde{T}$ using the following equation:

$$\widetilde{T} = \widetilde{X}\left(I - \widetilde{X}\right)^{-1}, \tag{8}$$

where I is the identity matrix.

Step 3.5: Obtain the defuzzyfied matrix [62]:

$$Crisp\left(\widetilde{T}\right) = \frac{l_{ij}^{t} + 4m_{ij}^{t} + u_{ij}^{t}}{6}, \tag{9}$$

where $\widetilde{t}_{ij} = \left(l_{ij}^{t}, m_{ij}^{t}, u_{ij}^{t},\right)$ are the elements of matrix $\widetilde{T}$.

Step 3.6: Obtain the final criteria weights:

$$w_j = \sum_{i=1}^{n}\widetilde{t}_{ij},\ \forall j = 1,\ldots,n. \tag{10}$$

Step 4: Rank the alternatives using the ADAM method [54].

Step 4.1: Define the decision matrix:

$$E = \left[e_{jk}\right]_{n\times m}, \tag{11}$$

where e_{jk} are the evaluations of the alternatives k in relation to criteria j, and m is the total number of alternatives.

Step 4.2: Define the sorted decision matrix:

$$S = \left[s_{jk}\right]_{n\times m}, \tag{12}$$

where s_{jk} indicates the sorted e_{jk} evaluations by descending values of criteria weights.

Step 4.3: Define the normalized sorted matrix:

$$n_{jk} = \begin{cases} \frac{s_{jk}}{\max\limits_{k} s_{jk}}, & for\ j \in B \\ \frac{\min\limits_{k} s_{jk}}{s_{jk}}, & for\ j \in C \end{cases}, \tag{13}$$

where n_{jk} are the normalized evaluations, B is the set of benefit, and C is the set of cost criteria.

Step 4.4: Find the coordinates (x, y, z) of the reference (R_{jk}) and weighted reference (P_{jk}) points:

$$x_{jk} = n_{jk} \times \sin\alpha_j,\ \forall j = 1,\ldots,n;\ \forall k = 1,\ldots,m, \tag{14}$$

$$y_{jk} = n_{jk} \times \cos\alpha_j,\ \forall j = 1,\ldots,n;\ \forall k = 1,\ldots,m \tag{15}$$

$$z_{jk} = \begin{cases} 0, & for\ R_{jk} \\ w_j, & for\ P_{jk} \end{cases},\ \forall j = 1,\ldots,n;\ \forall k = 1,\ldots,m \tag{16}$$

where α_j is

$$\alpha_j = (j-1)\frac{90^\circ}{n-1},\ \forall j = 1,\ldots,n. \tag{17}$$

Step 4.5: Find the volumes of complex polyhedra:

$$V_k^C = \sum_{p=1}^{n-1} V_p,\ \forall k = 1,\ldots,m, \tag{18}$$

where V_p is

$$V_p = \frac{1}{3}B_p \times h_p,\ \forall p = 1,\ldots,n-1, \tag{19}$$

where B_p is

$$B_p = c_p \times a_p + \frac{a_p \times (b_p - c_p)}{2}, \tag{20}$$

where a_p is

$$a_p = \sqrt{(x_{j+1} - x_j)^2 + (y_{j+1} - y_j)^2}, \tag{21}$$

b_p and c_p are

$$b_p = z_j, \tag{22}$$

$$c_p = z_{j+1} \tag{23}$$

h_p is

$$h_p = \frac{2\sqrt{s_p(s_p - a_p)(s_p - d_p)(s_p - e_p)}}{a_p} \tag{24}$$

where s_p is

$$s_p = \frac{a_p + d_p + e_p}{2} \tag{25}$$

where d_p and e_p are

$$d_p = \sqrt{x_j^2 + y_j^2} \tag{26}$$

$$e_p = \sqrt{x_{j+1}^2 + y_{j+1}^2} \tag{27}$$

Step 4.6: Rank the alternatives according to the decreasing values of V_k^C $(i = 1,\ldots,m)$. The best alternative is the one with the highest value.

5. Results of the Intermodal Transport Route Evaluation

The process of intermodal transport route evaluation and ranking begins with the collection of input data. Data for the criteria weights are collected through the questionnaires with the stakeholders' representatives, while the data for the alternatives (routes) evaluation are extracted from the available GIS data. The following describes the input data, the results obtained by applying the proposed methodology, and the sensitivity analysis and validation of the results.

5.1. Input Data

The input data for the application of the proposed methodology are the evaluations of the criteria's importance and alternatives (routes) according to the criteria. Criteria importance was evaluated by the stakeholder representatives of different experience. One of the objectives of the research was to avoid discrimination of stakeholders based on their experience, as can be seen from the structure of stakeholder representatives presented in Table 2. However, previous research has shown that work experience at entry level and intermediate level last up to 5 years, and that the level of seniority begins after that period [63,64]. Furthermore, ref. [65] indicated that individuals with more than 15 years of experience have higher levels of agreement, suggesting a significant difference in perspectives beyond the 15-year mark. Accordingly, the aim was to have the majority of respondents belong to these levels of experience. More than 70% of stakeholder representatives whose contributions depend on experience (all except local and affected communities) have more than 5 years of experience, which gives credibility to the evaluations. Their responses were statistically processed to extract the representative evaluations shown in Table 3.

Table 2. Stakeholder representatives' structure.

Stakeholder	Number of Representatives	Experience (Years)
Government and Regulatory Bodies	1	<5
	2	5–15
	1	>15
Industry and Transport Operators	2	<5
	3	5–15
	3	>15
Local and Affected Communities	1	/
	2	/
	2	/
Environmental and Conservation Organizations	2	<5
	1	5–15
	3	>15

Table 3. Stakeholder representatives' evaluations of criteria.

	C1	C2	C3	C4	C5	C6	C7
C1	(/, /, /, /)	(EH, VH, VH, VH)	(VH, H, H, H)	(EH, H, H, H)	(M, FL, L, L)	(VL, VL, L, L)	(L, L, L, L)
C2	(H, M, FH, H)	(/, /, /, /)	(H, FL, M, FH)	(FH, FH, FH, FH)	(M, FL, FH, FH)	(VL, VL, VL, L)	(L, L, L, L)
C3	(H, M, M, FH)	(FH, M, M, FH)	(/, /, /, /)	(FH, FH, FH, H)	(FL, L, FL, M)	(N, N, VL, VL)	(VL, VL, VL, VL)
C4	(FH, M, H, H)	(FL, FL, FH, FH)	(FH, M, M, M)	(/, /, /, /)	(H, FH, FH, FH)	(N, N, VL, VL)	(VL, VL, L, L)
C5	(FL, M, H, H)	(VH, VH, EH, EH)	(VH, VH, VH, VH)	(FL, M, H, H)	(/, /, /, /)	(N, VL, VL, L)	(N, N, VL, VL)
C6	(FH, H, FL, FL)	(L, M, FL, M)	(L, FL, L, L)	(M, M, M, M)	(VL, L, L, L)	(/, /, /, /)	(M, FH, FH, FH)
C7	(M, M, M, FL)	(L, FL, FL, FL)	(VL, L, L, L)	(FL, M, M, FL)	(L, FL, FL, FL)	(M, FH, FH, FH)	(/, /, /, /)

The evaluations of the alternatives according to the criteria are based on GIS data of the European Environment Agency [60]. GIS data are transformed into numerical values suitable for the application of MCDM methods in different ways. To ensure consistency and accuracy in the evaluation of transportation routes, a methodology for spatial analysis was adopted. A uniform buffer distance was applied on both sides of all routes when assessing a specific indicator. This approach allowed for consistent spatial coverage, ensuring that areas of influence along each route were evaluated on an equal basis. Furthermore, recognizing that the impact of routes varies depending on the characteristics of the areas they traverse, the segments of the routes based on the extent of their interaction with specific spatial features were weighted. For example, sections passing through environmentally sensitive or protected areas were assigned higher weights to reflect their greater potential for impact.

Given that the routes under consideration vary in length, it was essential to normalize the impact assessments to enable fair comparisons. This was achieved by calculating the cumulative impact of each route for all indicators, taking into account both the weighted contributions of individual route sections and the overall length of the route. All routes were divided into smaller segments based on their interactions with different spatial features (e.g., protected areas, biodiversity habitats, etc.). This approach allowed each segment to be scored separately, and the final score was calculated as a weighted sum of effects across segments, transformed into a value on a scale of 1 to 10 in proportion to the relative value in relation to other routes. By focusing on cumulative impacts, the methodology captured the total influence of each route across all relevant criteria.

For C1, the proportion of the route length passing through urban areas (Figure 3a,b) and agricultural areas (Figure 3c) was observed. A route that has more kilometers travelled not disturbing these areas has a better rating. For example, on an entire distance, R1 does not disturb these areas for a length of 264 km, R2 on a distance of 528 km, R3 on a distance of 396 km, and R4 on a distance of 462 km. The considered width of the influence zone (the space on either side of the affected route) for this criterion was 25 km. These values were normalized by dividing each of them with their sum, and multiplying by the influence zone width. In this way the following evaluations were obtained: R1-4, R2-8, R3-6, and R4-7.

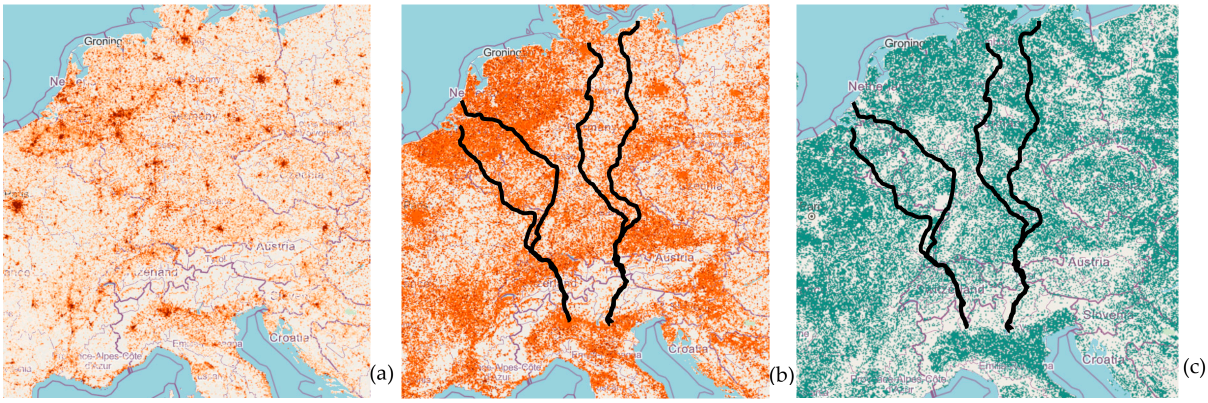

Figure 3. Overview of routes passing through urban areas (**a**,**b**) and over agricultural areas (**c**).

For C2, in addition to the number of kilometers of routes passing through protected areas, the degree of protection of those areas was taken into account (Figure 4a). A route on which less kilometers travelled through the protected areas with varying degree of protection not disturbing these areas has a better rating. For example, on an entire distance, R1 does not disturb these areas for a length of 264 km, R2 on a distance or around 528 km, R3 on a distance of 396 km, and R4 on a distance of462 km. The considered width of the influence zone (the space on either side of the affected route) for this criterion was 25 km. These values were normalized by dividing each of them with the sum of them all and multiplying by the influence zone width. In this way, the following evaluations were obtained: R1-4, R2-8, R3-6, and R4-7.

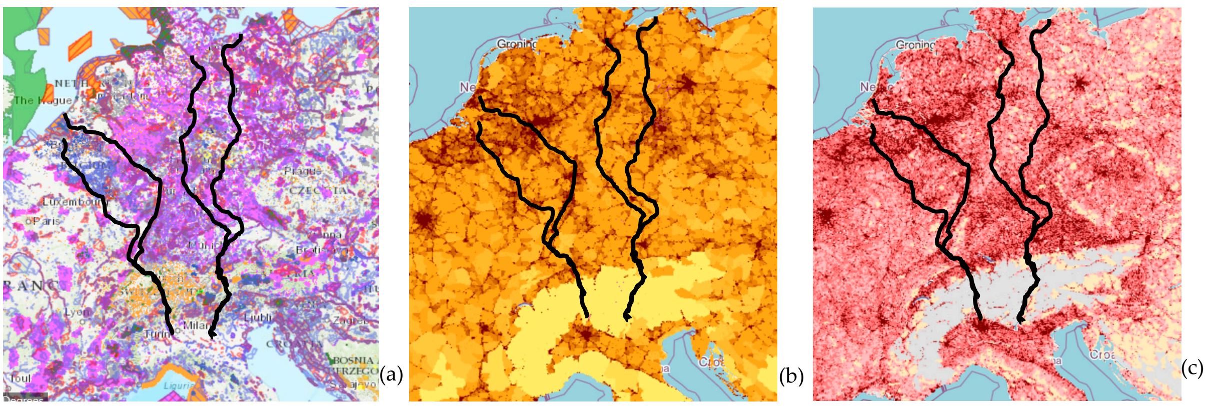

Figure 4. Overview of routes passing through protected (**a**) and fragmented areas (**b**,**c**).

Criterion C3 considered the extent to which the route disturbs un-fragmented areas (Figure 4b,c). More precisely, if the route passes through areas that are already fragmented and do not contribute to further fragmentation, it is rated as better. The values for the route evaluation were obtained by considering the number of un-fragmented areas it passes through, weighted by the normalized surface of these areas, expressed in square kilometers. For example, R1 passes through around 180 surfaces, R2 through more than 230, R3 through a little less than 200, and R4 through more than 250. However, the area of these surfaces differs significantly, ranging from a few dozen square kilometers to more than a thousand square kilometers. When calculating the final evaluations, they were considered as an index obtained by normalizing all surfaces (ranging from the smallest to the biggest) on a scale of 0–1. After weighting and normalizing the values, the following criterion values were obtained: R1-4, R2-9, R3-7, and R4-2.

Criterion C4 took into account the number of kilometers of the route passing through natural habitats, the number of natural habitats it disrupts, as well as the degree of endangerment of plant and animal species in those habitats (Figure 5). A route that damages habitats and endangers species to a lesser extent is rated better. The evaluations were obtained by summarizing the number of kilometers of the route passing through the natural habitats, weighted by the number of different habitats it disrupts and the number of endangered species in each of these habitats. The four routes pass through the habitats for 295 km, 187 km, 373 km, and 490 km, respectively. The number of habitats and species was considered in calculations similarly to the surface areas for the previous criterion. After the normalization, the following values were obtained: R1-6, R2-7, R3-5, and R4-3.

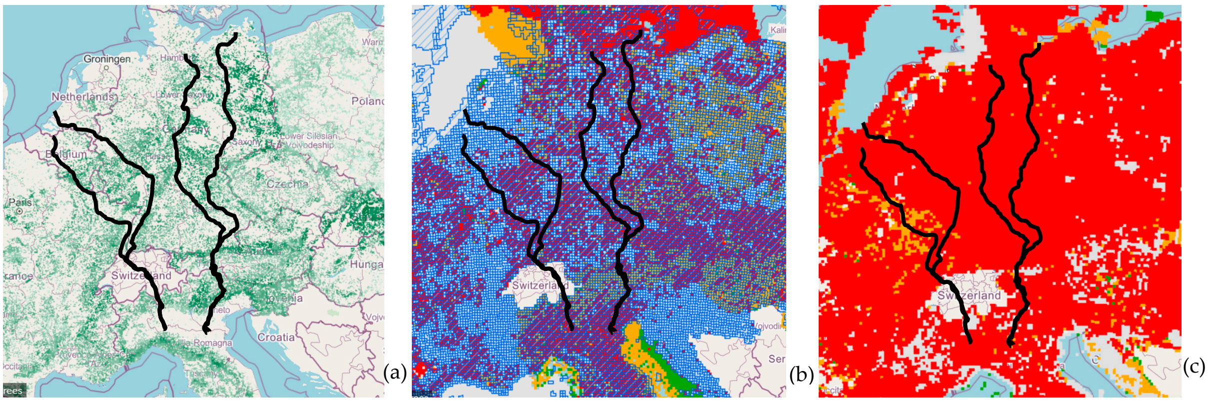

Figure 5. Overview of routes passing through forest areas (**a**) and protected plant and animal habitats (**b**,**c**).

When evaluating the routes in relation to criterion C5, it was taken into account how many different types of ecosystems the route damages and to what extent (which part of the route passes through threatened ecosystems) (Figure 6a). A route that is more dangerous is rated lower. The routes were evaluated according to this criterion by weighting the number of kilometers the route passes through the threatened ecosystem by the number of different ecosystems and their area expressed in square kilometers. For example, it cannot be the same if two routes pass through the threatened ecosystems the same number of kilometers, but one disrupts only one ecosystem and the other disrupts several. For example, the total length of R1 passing through ecosystems is about 440 km, R2—220 km, R3—400 km, and R4—330 km. These values were weighted and normalized and the following values were obtained: R1-4, R2-7, R3-4, and R4-5.

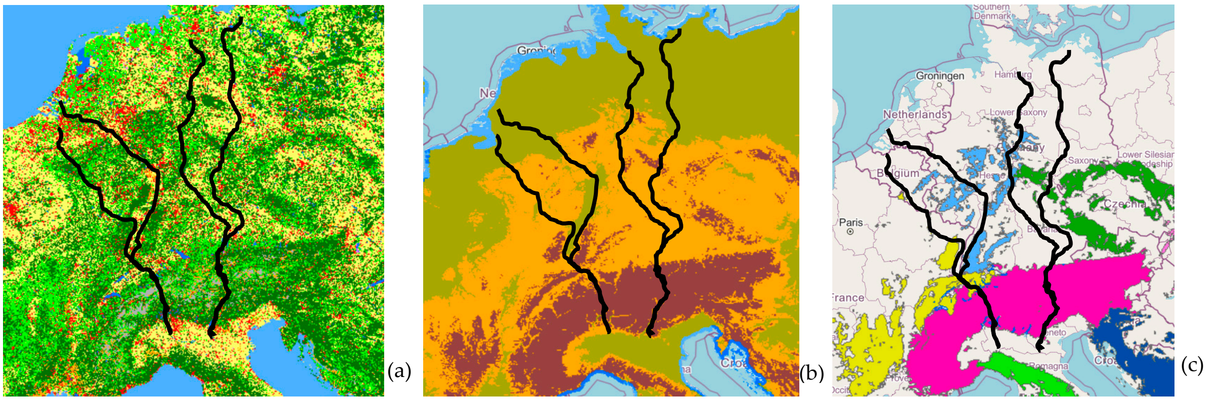

Figure 6. Overview of routes passing through protected ecosystems (**a**), elevations (**b**) and mountainous areas (**c**).

In relation to criterion C6, the topography of the terrain through which the routes are implemented was observed, that is, to what extent they pass through areas of high elevation and mountain areas (Figure 6b,c). A route with more kilometers travelled outside of elevated or mountainous areas has a better rating. For example, R1 does not pass through such areas for a length of 678 km, R2 on a distance of 452 km, R3 on a distance of 678 km, and R4 on a distance of 226 km. The considered width of the influence zone for this criterion was 18 km. The methodology for obtaining the routes evaluations was the same as for C1, and the values were R1-6, R2-4, R3-6, and R4-2.

With criterion C7, it was observed in what proportion the routes pass through floodplains (Figure 7a), areas with a high degree of surface water (Figure 7b) and wetlands (Figure 7c). A route that passes through these areas to a lesser extent is rated better. Similar to the previous criterion, a route with more kilometers travelled outside of mentioned areas has a better rating. The defined four routes do not pass through these areas for a length of 522 km, 870 km, 348 km, and 174 km, respectively. The considered width of the influence zone for this criterion was 22 km. The methodology for obtaining the routes evaluations was the same as for C1, and the values were R1-6, R2-10, R3-4, and R4-2.

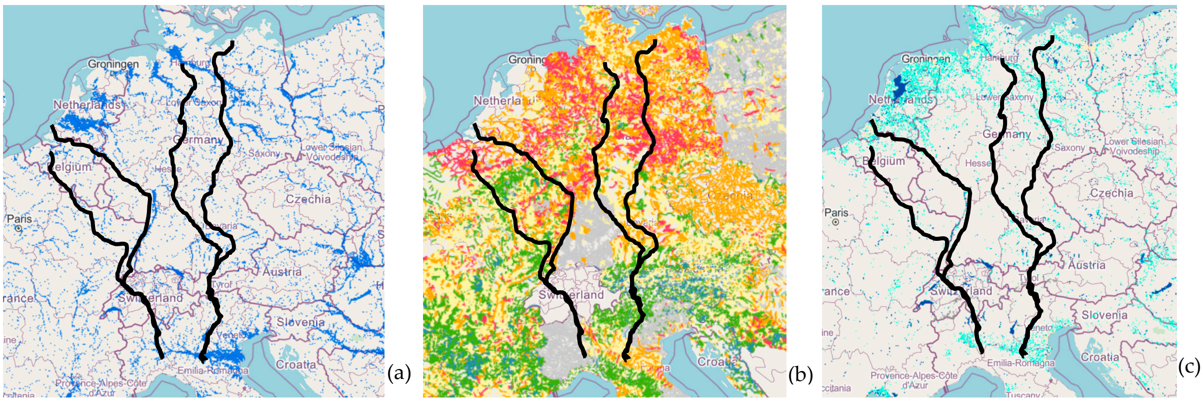

Figure 7. Overview of routes passing through floodplains (**a**), surface waters (**b**) and wetlands (**c**).

The GIS datasets used in this study vary slightly in grid cell resolution depending on the specific indicator; however, these differences are minimal and do not significantly affect the analysis. More importantly, for each indicator, the same grid resolution was consistently applied across all routes, ensuring full comparability. Despite these variations, the consistent application of each resolution within a given criterion ensures that the assessment reflects the true differences between routes rather than inconsistencies in spatial resolution. This methodological consistency guarantees that the analysis reliably reflects the relative impacts of each route while maintaining a high level of comparability across indicators and criteria.

Based on this GIS information, the experts assigned scores to the alternatives on a scale from 1 to 10, where 1 typically represented the least favorable option and 10 represented the most optimal or preferred alternative. These ratings reflected the experts' judgments about how well each alternative performed according to the established criteria, considering the spatial context and environmental factors provided by the GIS data.

The use of GIS data allowed the experts to make well-informed, data-driven evaluations, ensuring that the assessments were grounded in real-world geographical and environmental considerations. This approach introduced an additional layer of precision to the decision-making process, helping to ensure that the final ranking of alternatives was both objective and relevant to the specific planning context. Numerical values of route ratings according to the criteria obtained based on the presented GIS data are presented in Table 4.

Table 4. Route ratings according to the criteria.

	C1	C5	C2	C4	C6	C3	C7
R1	4	4	7	6	6	4	6
R2	8	7	5	7	4	9	10
R3	6	4	6	5	6	7	4
R4	7	5	5	3	2	2	2

5.2. Results

The numerical counterparts of the linguistic evaluations presented in Table 3 were used to form the direct-relation matrix (1) by applying Equations (2)–(5). The values from this matrix were further processed by applying Equations (6) and (7) to obtain the normalized fuzzy direct-relation matrix, and afterward, Equation (8) was used to obtain the fuzzy total-relation matrix. The values from this matrix were then defuzzified using Equation (9), while the final criteria weights were obtained using Equation (10). The defuzzified (crisp) total-relation matrix and the final criterion weights are presented in Table 5.

Table 5. The crisp total-relation matrix and final criterion weights.

	C1	C2	C3	C4	C5	C6	C7	Sum	w_j
C1	0.40	0.57	0.53	0.56	0.40	0.25	0.27	2.98	0.162
C2	0.48	0.37	0.46	0.48	0.39	0.22	0.25	2.65	0.145
C3	0.44	0.45	0.32	0.46	0.35	0.20	0.22	2.44	0.133
C4	0.47	0.46	0.45	0.35	0.41	0.21	0.23	2.58	0.140
C5	0.50	0.57	0.54	0.51	0.32	0.23	0.24	2.91	0.158
C6	0.43	0.42	0.39	0.44	0.33	0.17	0.30	2.47	0.134
C7	0.41	0.40	0.36	0.41	0.33	0.27	0.17	2.34	0.128

The values presented in Table 4 represent the decision matrix (11). These values from this matrix were sorted using Equation (12) to form the sorted decision matrix and then normalized using Equation (13), thus forming the normalized sorted matrix. By applying Equations (14)–(17), the coordinates of the reference and weighted reference points were obtained. They were used in Equations (18)–(27) to obtain the volumes of complex polyhedra. The final ranking of the alternatives was obtained by arranging the volume values in decreasing order. The following volumes were obtained: $V_1^C = 0.0402$, $V_2^C = 0.0587$, $V_3^C = 0.0408$, and $V_4^C = 0.0221$. The graphical representations of the polyhedra are presented in Figure 8. Based on the obtained results, it can be concluded that the best-ranked alternative is R2—Rotterdam–Milano.

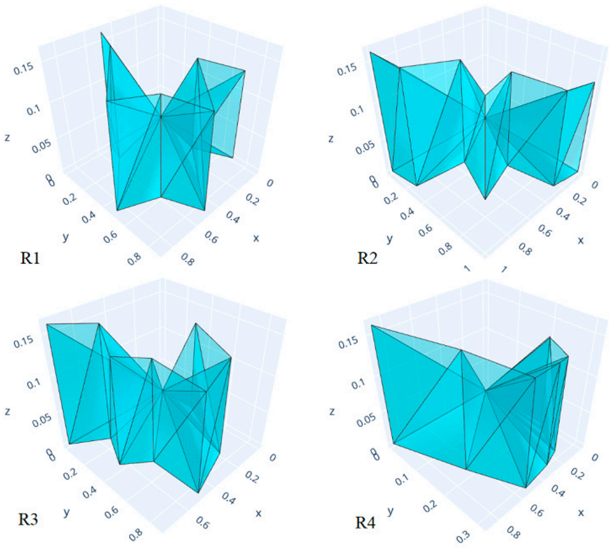

Figure 8. Complex polyhedra obtained by the ADAM method.

5.3. Sensitivity Analysis

The criteria weights are the result of the subjective evaluations of stakeholders' representatives. Regardless of the fact that all respondents were told that it is very important to be impartial, it is impossible to avoid a certain level of subjectivity when evaluating criterion importance. Therefore, it is necessary to carry out a sensitivity analysis, the aim of which is to examine the stability of the solution when certain parameters of the model are changed. In this case, a sensitivity analysis was conducted by creating an additional 12 scenarios. The scenarios were created by systematically reducing the importance of the three most important criteria—Land Use and Land Cover (C1), Environmental Sensitivity and Vulnerability (C5), and Protected Areas and Conservation Zones (C2). These criteria were chosen for the sensitivity analysis because they had the highest influence on the final ranking of the routes, as determined in the initial MCDM analysis. In the first four scenarios (Sc.1–Sc.4), the weight of C1 was reduced by 25, 50, 75 and 100%, respectively, while retaining the weights of the other criteria. The same was performed for C5 in the following four scenarios (Sc.5–Sc.8) and for C2 in the final four scenarios (Sc.9–Sc.12). To further test the sensitivity and robustness of the model, additional scenarios were developed. One set of scenarios involved the simultaneous reduction in the weights of two or all three of the most important criteria (C1, C5, C2) by 25%, 50%, 75%, and 100%. For example, Scenarios 13–16 reduced the weights of C1 and C5 simultaneously, Scenarios 17–20 applied the same reductions to C5 and C2, Scenarios 21–24 reduced the weights of C1 and C2, and Scenarios 25–28 reduced the weights of all three criteria simultaneously. To assess the consistency between the initial rankings and those obtained under different scenarios, the Spearman correlation coefficient (SCC) was calculated, providing a quantitative measure of the rank-order stability across all sensitivity analyses. The average SCC value of 0.991 indicates an extremely high level of consistency between the rankings. The obtained results are shown in Table 6, and the comparative presentation of the final ranks of the alternatives by scenarios is shown in Figure 9.

Table 6. Sensitivity analysis results.

	R1		R2		R3		R4		SCC
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	
Sc.0	0.0402219	3	0.058745	1	0.040767	2	0.022116	4	1
Sc.1	0.0406343	3	0.060189	1	0.041385	2	0.023018	4	1
Sc.2	0.0411335	3	0.061936	1	0.042134	2	0.02411	4	1
Sc.3	0.0416327	3	0.063683	1	0.042883	2	0.025202	4	1
Sc.4	0.0421319	3	0.06543	1	0.043631	2	0.026294	4	1
Sc.5	0.0400212	3	0.057396	1	0.040281	2	0.021305	4	1
Sc.6	0.0405096	2	0.056907	1	0.040385	3	0.021108	4	0.98333
Sc.7	0.0409979	2	0.056419	1	0.04049	3	0.020912	4	0.98333
Sc.8	0.0414862	2	0.055931	1	0.040595	3	0.020716	4	0.98333
Sc.9	0.0403593	3	0.058489	1	0.040737	2	0.021688	4	1
Sc.10	0.0408046	3	0.058489	1	0.040928	2	0.02137	4	1
Sc.11	0.0412499	2	0.058489	1	0.041119	3	0.021052	4	0.98333
Sc.12	0.0416951	2	0.058489	1	0.04131	3	0.020734	4	0.98333
Sc.13	0.0395221	3	0.055649	1	0.039532	2	0.020213	4	1
Sc.14	0.0395112	2	0.053413	1	0.038888	3	0.018925	4	0.98333
Sc.15	0.0395004	2	0.051178	1	0.038244	3	0.017636	4	0.98333
Sc.16	0.0394895	2	0.048942	1	0.037599	3	0.016348	4	0.98333
Sc.17	0.0388943	3	0.055559	1	0.039168	2	0.019748	4	1
Sc.18	0.0378746	2	0.052629	1	0.037789	3	0.017489	4	0.98333
Sc.19	0.0368549	2	0.049699	1	0.03641	3	0.015231	4	0.98333
Sc.20	0.0358351	2	0.046769	1	0.035031	3	0.012973	4	0.98333
Sc.21	0.0407717	3	0.059932	1	0.041356	2	0.02259	4	1
Sc.22	0.0417162	3	0.061679	1	0.042296	2	0.023364	4	1
Sc.23	0.0426606	3	0.063426	1	0.043235	2	0.024138	4	1
Sc.24	0.0436051	3	0.065174	1	0.044175	2	0.024912	4	1
Sc.25	0.0383952	3	0.053812	1	0.038419	2	0.018656	4	1
Sc.26	0.0368762	2	0.049135	1	0.036292	3	0.015306	4	0.98333
Sc.27	0.0353573	2	0.044457	1	0.034164	3	0.011955	4	0.98333
Sc.28	0.0338384	2	0.03978	1	0.032036	3	0.008605	4	0.98333

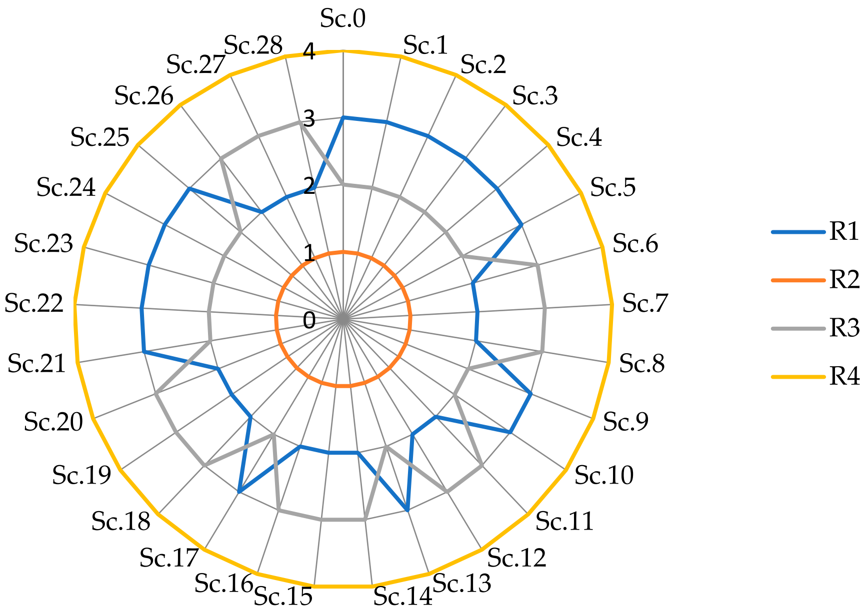

Figure 9. Sensitivity analysis results.

5.4. Validation

The results obtained by the proposed methodology were validated by comparing them with the results obtained by other relevant, widely used MCDM methods such as TOPSIS, VIKOR, SAW, COPRAS, AHP, COBRA, ELECTRE, PROMETHEE, and MARCOS. Changes in the final ranking of alternatives when using the mentioned methods are shown in Figure 10. To additionally confirm the validity of the obtained results, for each pair of comparisons of the results obtained by the ADAM method and each of the mentioned validation methods, SCC values were calculated. The mean SCC value of 0.937 indicates a particularly high degree of correlation of the obtained results. Based on all the above, it is clear that the obtained results are valid.

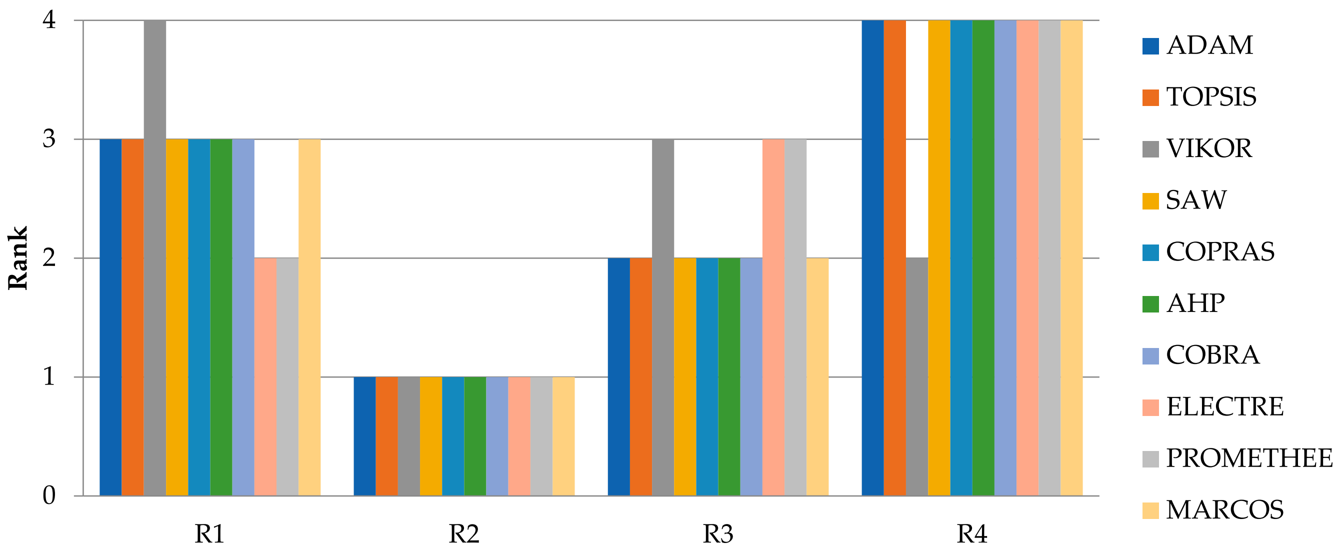

Figure 10. Result validation.

6. Discussion

This section provides a detailed exploration of the study, outlining the solution overview, key contributions, limitations, and broader implications of the research.

6.1. Solution Overview

The study comparing several intermodal transport routes highlights the Rotterdam–Milano (R2) route as the optimal choice, considering both environmental and operational criteria. This route effectively balances sustainability, ecological preservation, and transport efficiency, making it an excellent solution within the North Sea–Mediterranean corridor. One of the key factors in selecting this route is its minimal impact on land use and land cover. The route avoids heavily urbanized areas, which helps reduce conflicts with residential and commercial zones, particularly in densely populated regions like Rotterdam. By utilizing existing infrastructure and carefully planning around high-value agricultural lands and ecologically sensitive forests, the route mitigates potential environmental and economic disruptions. In terms of protected areas, R2 demonstrates excellent ability to circumvent key conservation zones. The route avoids significant disruption to biodiversity hotspots and critical habitats. Wildlife corridors and habitat connectivity are also highly preserved along the route. The application of the Effective Mesh Density metric implies that the route avoids areas prone to landscape fragmentation. By minimizing interference with wildlife movement, the route supports ecological resilience and biodiversity, which is critical for maintaining genetic diversity and the overall health of ecosystems. The route's environmental sensitivity and vulnerability were also carefully assessed. By using data from the European Nature Information System, planners were able to identify and avoid areas highly susceptible to ecological damage. This not only protects vulnerable ecosystems but also aligns with European Union biodiversity strategies aimed at reducing environmental impact in infrastructure projects. The relatively flat terrain between Rotterdam and Milan further supports the route's selection. It minimizes construction challenges and reduces the need for environmentally harmful alterations to the landscape. The absence of significant elevation changes also improves transport efficiency, cutting down fuel consumption and emissions, which further enhances the sustainability profile of the route. Finally, hydrological considerations play a vital role in the selection of this route. The R2 path avoids key surface water bodies and flood-prone areas, ensuring that critical water resources are protected. This helps reduce the risk of flooding and supports sustainable water management practices, critical in light of increasing climate change impacts. Overall, the Rotterdam–Milano (R2) route stands out as the best solution by harmonizing environmental responsibility with transport efficiency. Its minimal ecological disruption, protection of biodiversity, and adaptation to natural landscapes make it an exemplary choice for future sustainable transport development.

6.2. Contributions

This study makes several important contributions to the fields of biodiversity, intermodal transport planning, and MCDM, particularly by addressing aspects that previous research has not fully explored. While earlier studies have examined the environmental and logistical impacts of transport routes, they have generally not focused on how intermodal transport affects biodiversity [13–15]. This study stands out by incorporating specific biodiversity criteria, such as land use, habitat connectivity, and critical habitats, into the evaluation of transport routes. By doing so, it offers a deeper understanding of the ecological consequences of transport infrastructure, ensuring that biodiversity protection is considered alongside transport efficiency. Additionally, most existing studies have focused on ranking transport routes based on factors like cost, time, or general environmental impact without integrating criteria that prioritize biodiversity protection [26,27]. This research goes a step further by developing a ranking system that highlights ecological responsibility, demonstrating how sustainable transport planning can simultaneously meet logistical needs and safeguard ecosystems. Another key contribution is the innovative combination of GIS and MCDM techniques. Although both GIS and MCDM have been used in various fields (e.g., [66,67]), their joint application in the context of transport route evaluation, especially with a focus on biodiversity, is unique. By leveraging the spatial analysis capabilities of GIS, integrating multiple weighted factors into a decision-making process, and using the structured MCDM framework, this study provides a comprehensive and systematic approach to evaluating transport routes. GIS data play a crucial role by offering spatial insights into these factors, enhancing the overall analysis. This study also introduces a novel approach to multi-criteria decision-making by combining MCDM methods that have not been integrated into previous research. Unlike conventional weighting techniques that assume independence among criteria, the fuzzy DEMATEL method accounts for interdependencies, improving the accuracy of weight assignment, particularly for factors like habitat connectivity and protected area conservation. The Delphi method further enhances decision-making by incorporating expert knowledge from key stakeholders, ensuring that environmental criteria reflect real-world priorities rather than arbitrary assignments. Finally, the ADAM method offers a robust, geometry-based ranking approach that minimizes rank reversal issues, integrating spatial data to ensure that the most sustainable transport route is selected based on a comprehensive evaluation rather than a single dominant factor. This combination allows for a more subtle evaluation of transport routes, taking into account a broader range of criteria and offering a more comprehensive analysis. By integrating these decision-making tools, the study enhances the robustness and reliability of the results, providing a more effective way to weigh complex and often competing factors.

6.3. Limitations

This study provides valuable insights into sustainable transport planning but has limitations. Reliance on GIS data may introduce inaccuracies due to resolution, timeliness, and variability across sources. Small-scale features like fragmented habitats may be overlooked, and outdated datasets might not reflect recent environmental changes, highlighting the need for continuous updates and validation.

While the GIS-MCDM approach is effective, its accuracy depends on the relevance of selected criteria. This study prioritizes ecological and efficiency factors but does not fully address social or economic impacts. Static evaluation weights may not capture changing stakeholder priorities, and interdependencies between criteria—such as environmental and economic effects—are treated in isolation, oversimplifying relationships. Aggregating stakeholder inputs assumes uniform perspectives, potentially overlooking conflicts.

The study's focus on European routes limits its applicability to regions with different environmental and regulatory conditions. Data inconsistencies may also hinder scalability. These factors could lead to overconfidence in route rankings, masking risks or opportunities.

Future research should expand the framework to diverse geographies and integrate dynamic criteria to enhance adaptability. Despite these limitations, the study provides a solid foundation for data-driven sustainable transport planning.

6.4. Implications

The study has significant theoretical and practical implications in the fields of biodiversity, sustainable transport planning, and MCDM. Theoretically, the research enhances the understanding of how biodiversity considerations can be systematically integrated into transport planning. By applying a framework that evaluates routes based on their impact on habitat connectivity, biodiversity hotspots, and protected areas, the study contributes to a more nuanced theoretical model of sustainable transport. This integration challenges traditional transport planning models, which often overlook detailed ecological impacts, and introduces a new paradigm where biodiversity is a central criterion in route assessment. This theoretical advancement provides a foundation for future research to further explore and refine methods for incorporating ecological factors into transport infrastructure planning.

Practically, the study offers actionable strategies for transport planners and decision-makers. The successful identification of the Rotterdam–Milano (R2) route as the best choice underscores how incorporating biodiversity-focused criteria can lead to more environmentally responsible infrastructure development. This practical approach provides a blueprint for designing intermodal transport systems that minimize ecological disruption while optimizing operational efficiency. Managers can use the study's methodology to ensure that new transport routes align with conservation goals and regulatory requirements, ultimately supporting more sustainable and biodiversity-friendly infrastructure projects.

7. Conclusions

The goal of this paper was to establish a framework for evaluating and ranking intermodal transport routes based on their environmental and biodiversity impacts. By integrating ecological considerations into transport planning, the study aims to provide a comprehensive assessment approach that balances operational efficiency with the need to protect critical habitats, wildlife corridors, and sensitive ecosystems. This framework is designed to ensure that transport routes are not only efficient but also environmentally responsible, contributing to sustainable development and biodiversity conservation.

This paper makes several key contributions to the fields of biodiversity, intermodal transport planning, and MCDM by addressing previously unexplored aspects. Unlike earlier studies, which primarily focused on logistical and general environmental impacts, this research integrates specific biodiversity criteria—such as land use, habitat connectivity, and critical habitats—into transport route evaluation. By doing so, it provides a more comprehensive understanding of the ecological consequences of intermodal transport, ensuring biodiversity protection alongside operational efficiency. Additionally, the study introduces an innovative approach by combining GIS and MCDM techniques to create a balanced, systematic framework for route assessment. This integration allows for a more nuanced evaluation of transport routes, offering a practical model for sustainable and ecologically responsible infrastructure development.

Future research could build on this study by addressing its limitations and expanding its scope. One key area for improvement is the incorporation of higher-resolution and more up-to-date GIS data to enhance the accuracy of evaluations, especially in rapidly changing urban and ecological areas. Additionally, future studies could explore a broader set of criteria, incorporating social and economic impacts into transport route evaluations that would enhance the framework's comprehensiveness by addressing community well-being, economic development, and equity alongside environmental considerations. This more holistic approach would support balanced decision-making, stakeholder engagement, and alignment with broader policy goals for sustainable and inclusive development. Expanding the geographical scope beyond European routes would also allow for the framework to be applied and validated in different environmental, legal, and logistical contexts, making the approach more versatile and globally applicable. Future research could also use the developed framework and the GIS-MCDM model, or some of its parts, solely or in combination with some other methods, for solving other problems from various fields.

Author Contributions: Conceptualization, M.K. and D.P.; methodology, M.K.; software, M.K.; validation, M.K., S.T. and P.P.M.; formal analysis, M.K.; investigation, M.K., S.T., P.P.M. and D.P.; resources, D.P.; data curation, M.K.; writing—original draft preparation, M.K.; writing—review and editing, M.K., P.P.M. and D.P.; visualization, M.K.; supervision, D.P.; project administration, D.P.; funding acquisition, D.P. All authors have read and agreed to the published version of the manuscript.

Funding: Project funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4—Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of Italian Ministry of University and Research funded by the European Union—Next Generation EU [Project code CN_00000033, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research, CUP F87G22000290001, Project title "National Biodiversity Future Center—NBFC"].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data used in the study are disclosed within the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

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