Multi-criteria decision analysis for prospective sustainability assessment of Arctic transport infrastructure projects

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Abstract. The construction of transport infrastructure in Arctic regions is increasingly important to support the development of critical mineral deposits, which are essential for the transition to green technologies. Route selection in these regions faces particular challenges due to high and unpredictable construction costs, strict environmental regulations, and the requirement to take indigenous land use into account. This paper presents a methodology for evaluating alternative route alignments that explicitly considers Arctic-specific factors. The methodology is based on an integrated multi-criteria decision analysis comprising 29 criteria across four categories: 14 technical, 8 environmental, 4 social, and 3 economic. Qualitative factors are converted using Harrington's desirability functions, all criteria are normalised based on the min-max method, and a hierarchical equal weighting approach is applied. This approach is demonstrated using a case study of a road project providing access to the Kolmozero lithium deposit. According to the findings, Route 3 is the most favourable option as it stays economically competitive while avoiding protected natural areas, minimising overlaps with traditional land-use areas and reindeer herding zones, and requiring no wildlife crossings. The stochastic resilience of this result is confirmed by sensitivity analysis across three weighting scenarios. This approach provides a transparent, repeatable tool for feasibility studies and evidence-based route selection in Arctic transportation engineering.

1 Introduction

Currently, the Arctic region plays a significant role in the transition to green technology, hosting key deposits of battery metals and rare earth elements. As global demand for lithium is projected to increase fourfold by 2030, driven by the electric vehicle and renewable energy markets [1], the development of these Arctic deposits is critical to the development of the global green economy. The development of transport infrastructure in the Arctic region, particularly in the area surrounding the Kolmozero lithium deposit in the Murmansk region

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(Russian Federation), is becoming increasingly significant to provide transport connections to new deposits in remote areas.

The main problems of developing in the Arctic region are cost-intensive mining and the transportation of mined raw materials to consumers, the lack of transport infrastructure, and limited availability of labour resources [2]. The location of potential mining deposits in areas with limited transport accessibility makes the construction of additional roads, railways, and port facilities a high-priority task, as this would facilitate the transportation of raw materials and ensure the economic efficiency of these new deposits [3].

In the Arctic region, the cost of infrastructure construction is high and difficult to predict due to challenging climatic conditions, permafrost-related engineering challenges [4], the need to implement environmental protection measures and protect the rights of indigenous peoples [5]. It is therefore vital to critically evaluate the risks associated with construction projects and to ensure the viability of the project for all relevant stakeholders.

The evaluation of options for the development of transport infrastructure has historically been dominated by a prioritisation of technical and economic factors. However, contemporary evaluation methodologies are shifting towards a more integrated consideration of the environmental and social dimensions of transport construction [6]. The territory adjacent to deposits in the Arctic zone is often associated with the traditional habitation and economic activities of indigenous peoples. In particular, the area surrounding the Kolmozero lithium deposit in the Murmansk region is inhabited by the Sami people, who are engaged in traditional fishing and reindeer herding. The infrastructure facilities that are frequently intersected by migratory routes of reindeer exert a substantial influence on the regional economy and give rise to conflicts with indigenous communities. Recent studies have demonstrated that transport infrastructure exerts a considerable impact on reindeer migration routes and traditional land use systems, with climate change serving to intensify these effects [7,8]. Consequently, a comprehensive evaluation of reindeer migratory patterns should be conducted prior to the initiation of construction projects.

To assess the cost of infrastructure construction, it is necessary to consider not only new construction, but also the need to comply with regulatory standards for existing infrastructure. The unsatisfactory condition of regional roads is an additional risk factor, and the possibility of financing these works by private investors should be considered as part of the deposit development project. Additionally, the potential for private investors to assume obligations for regional road maintenance and repair should be given due consideration.

A significant number of multi-criteria decision analysis (MCDA) methodologies are currently available, including approaches to criteria selection and weighting methods [9, 10]. However, the specific challenges of infrastructure development in the Arctic region, particularly with regard to environmental factors and indigenous territories, require further study. In particular, evaluating transportation projects in the Arctic necessitates assessing the cumulative impact on indigenous territories and wildlife migration corridors.

This research provides an integrated MCDA methodology for transport infrastructure options evaluation in Arctic regions that combines technical feasibility, environmental constraints, indigenous peoples' rights, and economic efficiency. The study uses a project of road construction in the Murmansk region with the aim of providing transport accessibility to the Kolmozero lithium deposit as an example to illustrate the proposed MCDA methodology of Arctic transportation infrastructure that combines sustainable development practices with long-term project viability assessment.

2 Materials and methods

2.1 Multi-Criteria Decision Analysis Framework

The MCDA methodology for comprehensive assessment of Arctic transportation infrastructure factors comprises six stages (see Figure 1).

At the initial stage, it is necessary to assess the existing infrastructure and offer options for route formation, considering the construction of new roads and the reconstruction of existing ones. Subsequently, based on the analysis of the points of origin and points of destination, the existing infrastructure of public and private roads, it is necessary to develop route options and determine the research area.

The second stage involves the creation of a database to calculate 29 route assessment criteria, utilising established frameworks for transportation sustainability assessment (see Table 1).

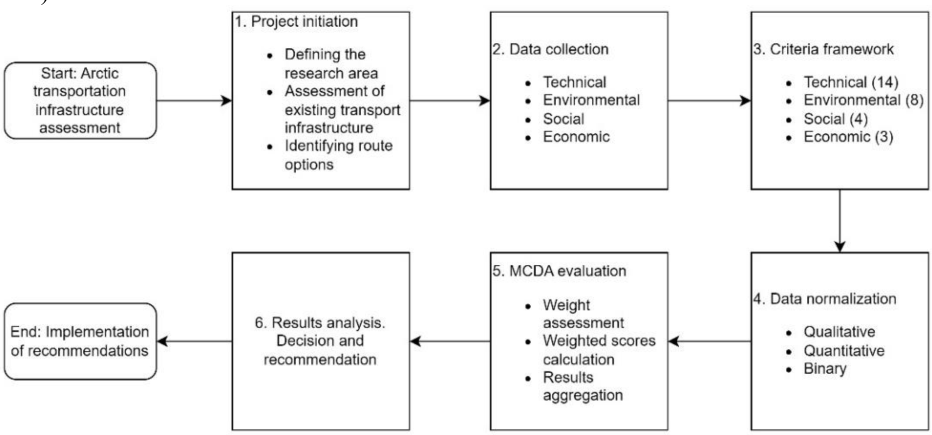

Fig. 1. The Multi-Criteria Decision Analysis methodology of Arctic transportation infrastructure.

Table 1. The Multi-Criteria Decision Analysis criteria categories.

Category	Criteria description	Code	Evaluation Scale
Technical (14 criteria)	Accessibility for conducting engineering geological surveys	T1	Low/Medium/High
	Engineering-geological complexity categories	T2	Simple I, Average II, Complex III
	Geological survey level of the territory	T3	Low/Medium/High
	Geomorphological conditions	T4	Simple I, Average II, Complex III
	Hydrogeological conditions	T5	Simple I, Average II, Complex III
	Hazardous geological and engineering-geological processes	T6	Simple I, Medium II, Complex III
	Specific soil conditions	T7	Simple I, Average II, Complex III
	Natural and technical working conditions	T8	Favourable I, Satisfactory II, Unsatisfactory III
	Water course intersections	T9	Count
	High-voltage power line intersections	T10	Count
	Engineering infrastructure intersections	T11	Count
	Absolute elevation differences	T12	Meters
	Presence of a ferry crossing	T13	Yes/No
	Water crossings with a width of over 5 m	T14	Count
Environmental (8 criteria)	Specially protected natural areas	En1	Yes/No
	Wetlands	En2	Yes/No
	Key ornithological territories	En3	Yes/No
	Specially protected forest areas and forest park zones	En4	Yes/No

Category	Criteria description	Code	Evaluation Scale
	Surface and groundwater abstraction points for the drinking water supply	En5	Yes/No
	Reclaimed lands and reclamation systems	En6	Yes/No
	Landfills and disposal sites for industrial and municipal solid waste	En7	Yes/No
	Sanitary protection zones	En8	Yes/No
Social (4 criteria)	Traditional territories of indigenous peoples	S1	Intersection %
	Tunnel-type wildlife crossings	S2	Count
	Location in relation to the Arctic zone	S3	Yes/No
	Traditional reindeer herding zones	S4	Yes/No
Economic (3 criteria)	Net Present Value (NPV)	E1	Million RUB
	Total route length	E2	Kilometres
	Regional road reconstruction length	E3	Kilometres

The technical criteria encompass risk factors associated with construction in remote, under-researched areas characterised by challenging climatic conditions, as well as risks associated with crossing existing infrastructure, which can have a substantial impact on construction costs. The evaluation scales for the qualitative criteria (T2, T4–T8) are defined in accordance with the Russian normative document, GOST 32868–2014. According to these scales, category I represents favourable conditions, including minor variability, a simple geological and geomorphological structure, single persistent aquifer, an absence of hazardous processes and specific soil conditions. Category II represents conditions with several geological and geomorphological elements, two or more persistent aquifers, and a limited distribution of hazardous processes or specific soils that do not influence design decisions. Category III represents unfavourable conditions with a significant number of engineering geological and geomorphological elements, a variable groundwater regime, and widely distributed, significant hazards and specific soil conditions that impact design decisions.

Criterion T1 assesses the accessibility of the area for conducting surveys. 'Low' indicates an absence of road infrastructure, 'Medium' indicates roads in the covered area with no year-round access, and 'High indicates full access to the location. Criterion T3 evaluates the availability of previous research. 'Low' indicates that no surveys are available, or that the available surveys are irrelevant and outdated. 'Medium' indicates that some surveys are available, but that they are partially irrelevant and require further investigation. 'High' indicates that recent, route-specific surveys can be used directly.

The environmental criteria encompass protected areas, water protection zones, and wildlife migration corridors.

The social criteria encompass Sami traditional territories, evaluating reindeer herding route intersections and traditional land use patterns, informed by recent research on indigenous peoples' planning frameworks. To ensure the preservation of animal migration routes, the construction of tunnel-type wildlife crossings may be recommended for selected routes. The availability and number of these elements significantly influence decision-making processes and are considered a distinct indicator.

The economic criteria to be considered are the costs of construction and operation of the new road, total route length, and regional road reconstruction length. Length indicators can enhance the importance of economic factors, as long distances increase risks and potential costs of road reconstruction and maintenance.

During the third stage of the methodology, it is necessary to evaluate the criteria for all four categories according to the evaluation scale.

The fourth stage is normalisation for binary, qualitative, and quantitative criteria. All binary indicators are converted into numerical format, with values of 1 and 0 assigned to yes and no constraints.

Qualitative factors are assessed using Harrington's desirability function, where the best approaches a value of 1 and the worst approaches a value of 0 (see Table 2). This approach has been successfully applied to multi-criteria evaluation problems in the mining and infrastructure domain [11].

All criteria were normalized using the widely adopted min-max method. This dimensionless normalization is one of the most frequently used approaches; it converts the minimum value of a criterion to 0, the maximum value to 1, and the rest to a decimal between 0 and 1 [12]:

$$q_j^0 \frac{q_j(x) - q_j^{min}}{q_j^{max} - q_j^{min}}, j = \overline{1,n} \tag{1}$$

$$q_j^0 \frac{q_j^{max} - q_j(x)}{q_j^{max} - q_j^{min}}, j = \overline{1,n} \tag{2}$$

where $q_j(x)$ is the absolute value of the j criterion,
q_j^{min} and q_j^{max} are the minimum and maximum values of the j criterion,
n is the number of criteria in the multi-criteria problem.

Table 2. Harrington's desirability function evaluation.

Criteria description	**Qualitative evaluation**	**Harrington's desirability function evaluation**
Assessment of accessibility and exploration of the territory	Low	0,285
	Medium	0,53
	High	0,78
Complexity of the engineering-geological conditions of the territory	Simple (I)	0,78
	Average (II)	0,53
	Complex (III)	0,285
Natural and technical working conditions	Favourable (I)	0,530
	Satisfactory (II)	0,285
	Unsatisfactory (III)	0,033

Considering the different orientation of the criteria, the values of the criteria tending to a maximum (accessibility and exploration of the territory) are evaluated with (1), while indicators tending to a minimum (route length, number of engineering facilities) are evaluated with (2).

To ensure balanced representation of all four criteria categories, a hierarchical equal weighting approach was adopted [13]. Each category received an equal weighting of 25%, and the criteria within each category also received equal weighting. This structure ensures democratic representation of all categories and prevents dominance by categories with more criteria. Consequently, the weights of the individual criteria are 1,79% (technical), 3,13% (environmental), 6,25% (social) and 8,33% (economic).

2.2 Study area and data collection

The study area encompasses the subarctic region of the Murmansk region, extending from the Kolmozero lithium deposit to existing regional road networks. Three alternative routes combining existing roads and new construction sections were evaluated, considering minimization of the distance between potential routes and existing regional roads (see Figure 2).

Due to the lack of materials from previously performed engineering surveys for the study area, office studies were carried out to produce overview plans and longitudinal profiles based on open-source data. The overview plan at a scale of 1:5000 and longitudinal profiles at a scale of 1:500 / 1:5000 (vertical/horizontal) were generated in the CREDO software.

To assess the degree of geological survey, archival and fund materials on mineral reserves and previously performed engineering-geological studies were collected. Engineeringhydrometeorological studies were based on a reconnaissance survey, published long-term observation data of the Federal Service for Hydrometeorology and Environmental Monitoring, and general information on water bodies and meteorological stations in the area.

To assess the ecological investigation of the territory, field data were collected, and official information from state executive authorities was obtained on zones of environmental constraints on land use along the three alternative road alignments.

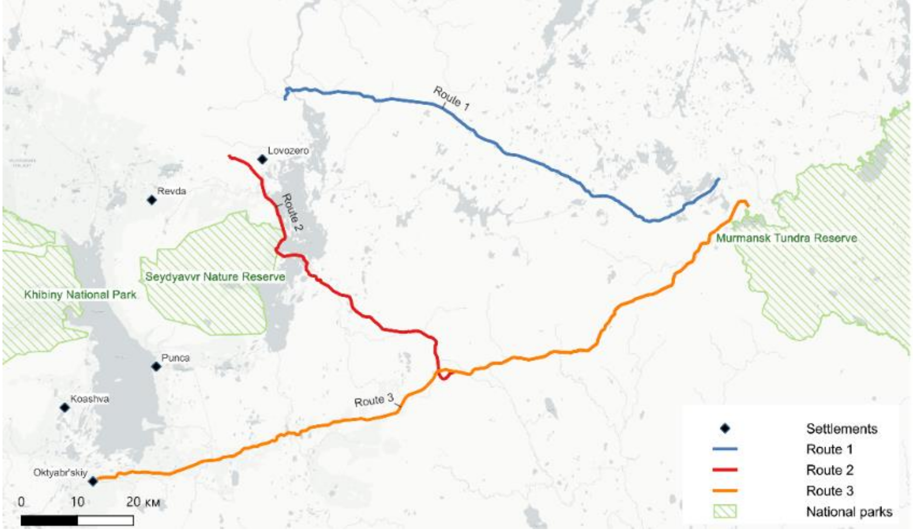

Fig. 2. Route alternatives considering the boundaries of national parks and nature reserves.

Capital expenditures for the construction of the new road were developed based on local cost estimate documentation. A high-level assessment of the costs for rehabilitation of existing regional roads, road maintenance, and repair was carried out using the regional standards of the Murmansk Region, assuming a 28-year road operating cycle. Transportation costs over 28 years were estimated using aggregated cost categories, based on data from vehicle manufacturers and transport operators. The costs of purchasing and maintaining vehicles, fuel, tyres, and labour were adjusted to reflect actual regional costs using information from open sources. The effectiveness of various routes was evaluated using the net present value (NPV) as a financial indicator. As there were no financial inflows, a comparison of negative NPV values was used instead (see Table 3).

Table 3. NPV calculation components.

Cost Category	Description
Rehabilitation of existing regional roads	Cost of bringing regional roads to standard condition. One-time (pre-construction stage)
Capital expenditures for road construction	Estimated construction cost. One-time (construction stage)
Maintenance of the new road	Cumulative annual expenditures for maintenance throughout the entire road operating cycle
Repair of the new road	Cumulative repair expenditures throughout the entire road operating cycle
Maintenance of bridges	Preventive and planned-preventive repair throughout the entire road operating cycle
Transportation costs	Cumulative expenditures throughout the entire road operating cycle (motor fuel, tire wear, technical maintenance and operational repair of motor vehicles, driver wages and contributions to social insurance, depreciation)

3 Results and discussion

3.1 Economic comparison of the routes

Following an economic comparison of the capital expenditure required to implement the project, it was concluded that Route 1 was the best in absolute terms. However, when assessed in terms of discounted costs, Route 3 was the preferred choice. This route is characterised by lower construction and maintenance costs, primarily due to the lower cost of construction and rehabilitation of existing regional roads throughout the 28-year operating cycle (see Figure 3).

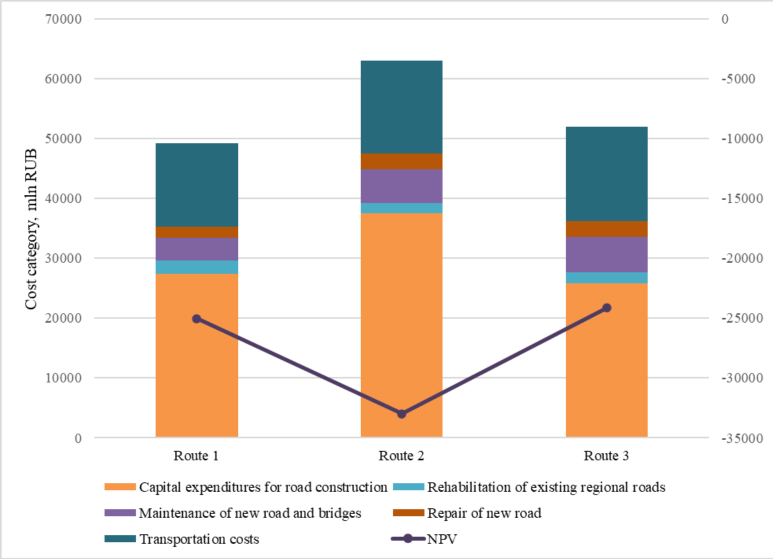

Fig. 3. Capital and operating costs for a 28-year operational cycle, expressed in absolute terms (in millions of roubles), and net present value (NPV).

3.2 The Multi-Criteria Decision Analysis of the routes

Data was collected and normalised within the framework of the analysis of 29 indicators. Based on a combination of criteria, considering construction risks and the project's implementation costs, Route 3 emerges as the most favourable choice by a significant margin (see Figure 4).

From the technical point of view, Route 3 is characterised by fewer overall restrictions and a more thorough study of the territory (see Figure 5). Meanwhile, Route 2 involves significant restrictions, such as the need to organise a ferry crossing and the crossing of high-voltage power lines. From an environmental perspective, Route 2 is the least favourable. It crosses the boundaries of the Seydyavr Nature Reserve and passes through the protection zones of power grid facilities and the water abstraction points on the Virma River.

From a social perspective, the studied areas encompass traditional Sami settlements and their traditional economic activity areas. While 95% of the planned routes for option 1 pass through areas inhabited by indigenous peoples, only 5% of the routes for options 2 and 3 affect these areas. At the same time, routes 1 and 2 cut through the grazing grounds of two reindeer herding cooperatives. This will not only have an extremely negative impact on the perception of the project and the price of its products, but also on the company's international reputation. Furthermore, tunnel-type wildlife crossings are planned for route options 1 and 2 to preserve animal migration routes, which will increase construction costs.

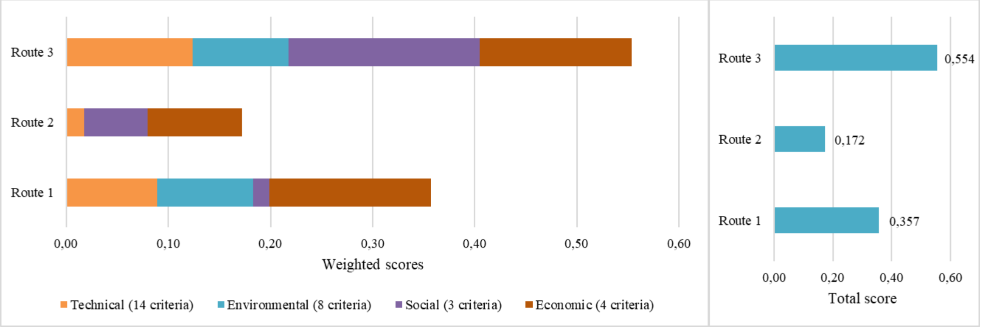

Fig. 4. Weighted scores for four categories of criteria and total scores for three routes.

Criterion description	Route 1	Route 2	Route 3
Technical criteria			
Accessibility for conducting engineering geological surveys	0,000	0,000	1,000
Engineering-geological complexity categories	0,000	0,000	0,000
Geological survey level of territory	0,000	0,000	1,000
Geomorphological conditions	0,000	0,000	0,000
Hydrogeological conditions	0,000	0,000	0,000
Hazardous geological and engineering-geological processes	0,000	0,000	0,000
Specific soil conditions	0,000	0,000	0,000
Natural and technical working conditions	0,000	0,000	1,000
Water course intersections	1,000	0,000	0,429
High-voltage power line intersections	1,000	0,000	1,000
Engineering infrastructure intersections	1,000	0,357	0,000
Absolute elevation differences	0,000	0,615	1,000
Presence of a ferry crossing	1,000	0,000	1,000
Water crossings with width over 5 m	1,000	0,000	0,500
Environmental criteria			
Specially protected natural areas	1,000	0,000	1,000
Wetlands	0,000	0,000	0,000
Key ornithological territories	0,000	0,000	0,000
Specially protected forest areas and forest park zones	0,000	0,000	0,000
Surface and groundwater abstraction points for drinking water supply	1,000	0,000	1,000
Reclaimed lands and reclamation systems	0,000	0,000	0,000
Landfills and disposal sites for industrial and municipal solid waste	0,000	0,000	0,000
Sanitary protection zones	1,000	0,000	1,000
Social criteria			
Traditional territories of indigenous peoples	0,000	1,000	1,000
Tunnel-type wildlife crossings	0,250	0,000	1,000
Location in relation to the Arctic zone	0,000	0,000	0,000
Traditional reindeer herding zones	0,000	0,000	1,000
Economic criteria			
Net Present Value (NPV)	0,902	0,000	1,000
Total route length	1,000	0,112	0,000
Regional road reconstruction length	0,000	1,000	0,784

Fig. 5. The normalised criteria for three routes.

3.3 Sensitivity Analysis of the routes

A sensitivity analysis was carried out to assess the resilience of the three alternative scenarios. Scenario 1 is the basic scenario with equal weighting; scenario 2 represents a dominance of environmental and social factors; and scenario 3 is a traditional option with a dominance of technical and economic factors. The sensitivity analysis shows that Route 3 achieves the highest total score in all scenarios, confirming that the result is not affected by reasonable variations in group weights (see Figure 6).

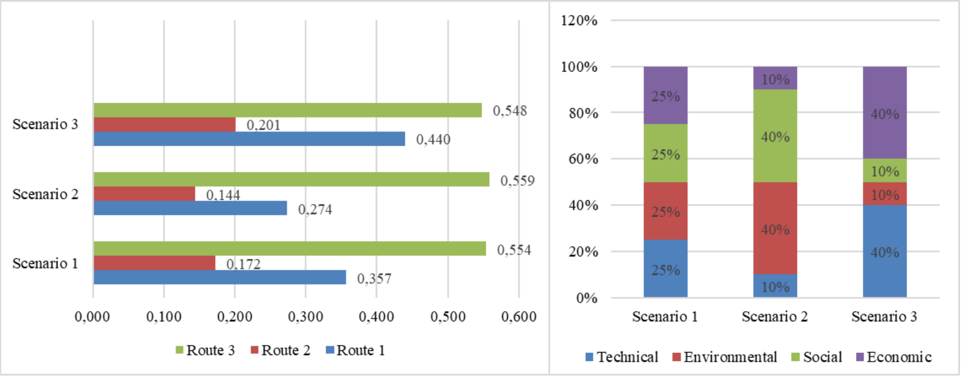

Fig. 6. Results of sensitivity analysis for three scenarios.

4 Conclusions

This paper introduces an integrated multi-criteria decision analysis methodology for Arctic transportation infrastructure planning, combining technical, environmental, social, and economic criteria. This methodology incorporates Arctic-specific quantitative, qualitative, and binary factors and implements Harrington's desirability scale framework for qualitative factors. The proposed approach focuses on assessing Arctic infrastructure through min-max normalised scoring systems and a hierarchical equal weighting approach within a single, fully operational framework.

The research contributes to methodological innovations by integrating the evaluation of traditional technological and economic factors for decision-making with environmental and social factors, considering the specifics of Arctic territories. This approach considers the varying degree to which the territory has been studied, the challenging conditions for conducting work, the need to construct new infrastructure and rehabilitate existing roads, and the long distances covered by the routes. It also considers environmental constraints and the location of indigenous peoples' territories and wildlife migration corridors. This approach provides a replicable methodology for similar projects in Arctic regions.

The paper provides an example of a comprehensive evaluation of three route alternatives for the Kolmozero lithium deposit. It illustrates the importance of traditional reindeer herding zones and indigenous peoples' settlements, as well as the requirement for wildlife connectivity, in Arctic infrastructure planning. These factors can potentially outweigh traditional technical and economic considerations. Crossings of national parks and reserves, as well as intersections with extensive bodies of water, create significant cost escalation and operational complexity. Sensitivity analysis demonstrates that the methodology remains stable under all reasonable variations in group weights.

The methodology provides a foundation for infrastructure planning in Arctic regions and can be directly implemented into early-stage feasibility studies and route screening to support decision-making for regional authorities and project developers.

It should be noted that the social criteria were assessed according to official data on reindeer herding zones and Sami settlements. Direct consultation with Sami communities did not take place at the route evaluation stage. However, consultations with representatives of indigenous communities should be carried out at the detailed design stage, when the final route alignment is determined. Future research should focus on weighting and normalisation procedures. It is recommended to analyse alternative weighting scenarios using the expert judgements of local communities, regional authorities and project developers. In addition, further environmental factors should be taken into account, such as the risk of permafrost degradation and potential greenhouse gas emissions.

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