Winter Accessibility of RES in the Russian Arctic

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Accessibility can be defined as how easily a location is reachable by another location. Transportation is challenging in the Arctic given its unique climate and geography (Instanes et al., 2015). Communities in the Arctic rely on winter roads and permanent roads to travel (Levin, 2017). Road accessibility depends on factors such as climate, topography, and permafrost (Stephenson, Smith, & Agnew, 2011). Winter roads, also known as ice roads, are temporary roads constructed of ice that travel over frozen land, lakes, and rivers (Stephenson et al., 2011; Instanes et al., 2015; Levin, 2017). These winter roads rely on the extremes in seasons to be accessible. Given these surfaces, which are wet in the summer but become hard enough to traverse in the winter, the winter season is often an optimal and cost-effective time to travel (Stephenson et al., 2011; Levin, 2017). The winter roads are only functional for a short range of months during the winter—usually only three months—while rivers can only be used for boat travel once all the ice melts in the summer. The transition months between the seasons hinder the transportation in these passageways (Argounova-Low, 2012).

Multi-Criteria Evaluation and Least-Cost Path Analysis

A multi-criteria evaluation (MCE) is used often in GIS to identify how suitable various physical locations are for a specific objective or phenomenon. This analysis layers various relevant attributes, which are then weighted and aggregated to select potential sites. The selected areas should ideally possess these characteristics. One benefit of MCE is the ability to change the weights of various datasets, which provides for flexibility. MCE can aid stakeholders by allowing for evidence-based decision-making under different scenarios (Eastman, 2005).

A least-cost path analysis refers to a path that has the least resistance, which is not necessarily the shortest in length. This process involves connecting cells between the origin and the destination so that the identified route is the most cost-effective, based on a least-cost distance raster (Albrecht, n.d.).
Least-cost paths and MCE are powerful, robust methodologies that can assist in identifying optimal paths between two points. Both have been used for a variety of purposes, such as identifying potential power line routes to minimize environmental impacts (Bagli, Geneletti, & Orsi, 2011), planning roadways (Yu, Lee, & Munro-Stasiuk, 2003), and identifying dispersal corridors for animals (Larue & Nielsen, 2008).

Similar work has been done in the Arctic. Atkinson, Deadman, Dudycha, and Traynor (2005) rely on these tools determine a suitable path to construct an all-weather road between a deep-water port in the Bathurst Inlet and resource extraction sites in the Slave Geological Province. They considered factors such as slope, sensitive soil locations, water bodies, and sensitive wildlife and cultural sites. Friction costs were assigned to each criteria and subsequently combined and weighted in raster format to calculate the total cost to traverse each cell. Routes were identified under three scenarios: one that heavily weights environmental sensitivities, one that strictly relies on engineering, and one that incorporates both. In short, Atkinson et al.'s (2005) methodology can be used as a foundation to calculate accessibility in the Arctic.

Arctic Transport Accessibility Model

Stephenson et al. (2011) developed the Arctic Transport Accessibility Model (ATAM) to determine transport suitability on both land and water. Winter roads can cross land and water bodies. For winter roads on land, suitability is determined by elevation below 500 m and/or slope below 5%, surface temperature at 0℃ or lower, and areas with at least 20 cm of snow. For roads that cross rivers and lakes, the surface temperature should be at most 0℃, and ice thickness should be at least 22.4 centimeters. Permanent roads are assumed to be traversable year-round. These factors were then aggregated to produce a travel cost raster for each month, which estimates the cost of traversing a specific cell.

In this context, the methods used in Atkinson et al. (2005) were combined with the criteria in Stephenson et al. (2011) to calculate the least-cost path in the Russian Arctic between RES and their nearest logistical nodes. “Nearest” is used here to mean the logistical node to which is the least costly to travel from a community. This was subsequently used to calculate the accessibility, defined in this analysis as the number of round trips within three months, of each renewable energy site (RES).

Data Acquisition and Processing

The data for this project came from multiple sources including a Global Climate Model (GCM), online repositories, and project partners. All data were masked to the Russian country boundaries, downloaded from NaturalEarth (2018), and resampled to a cell size of 500 m.

RES locations were provided by research conducted by Daria Gritsenko (2019, University of Helsinki) in spreadsheet format containing the following information (type of source such as biomass, amount of energy produced, on or off grid, operator name, and year established) and XY coordinates (and the region, state, and city).

The logistical nodes—ports and refineries—were downloaded from the National Geospatial-Intelligence Agency (2017) and manually plotted from EnergyBase (n.d.), respectively. The two ports selected for this analysis were Murmansk and Arkhangelsk, as they have good logistical connections to oil refineries in the Leningrad region and other ports; thus, these ports are the only two most likely to receive deliveries. Only the oil refineries within 1000 km of the Arctic Circle, along with two in the Russian Far East near China, were considered, creating a total of 12 oil refineries.

The Community Climate System Model (CCSM) 4.0 GCM, by the NCAR University Corporation for Atmospheric Research (2010), provided information on surface temperature, snowfall amount, and ice temperature. This project used the average surface temperature (Ts), and snow depth (SNOWDP) from September 2013 to May 2014, which is the length of the winter season in the Arctic conducive to winter road travel.

With these GCM variables, ice thickness was determined using the formula from Stephenson et al. (2011):

$$h_i=\sqrt{(h_0+K_iK_sh_s)2+2K_i\gamma_iLS}-K_iK_sh_s \qquad \text{[Eq. 1]}$$

where:
h_i=ice thickness on day K
h_0=ice thickness on day J
S=accumulated freezing degree days from day J to day K
h_s=snow depth
K_i=thermal conductivity of ice (2.21−0.011θ W m−1 °C−1)
K_s=thermal conductivity of snow (0.15 W m−1 °C−1)
γ_i=density of ice (917 kg m−3)
L=latent heat of ice (333.4 J g−1)
θ=ice temperature (°C).

Equation 1 was used for the entire 2013-2014 winter season. Thus, h_0 was the ice thickness at the start of the winter season (August 15, 2013, the earliest date in the winter season provided by CCSM 4.0)—which was 0 cm—and h_i was the ice thickness at the end of the winter season (May 15, 2014, the latest date in the winter season provided by CCSM 4.0). The average surface temperature data was used to estimate the accumulated freezing days (S): S was either set to 0 or 244 (days between August 15, 2013, and May 15, 2014) depending on whether the average surface temperature was above or below 0°C, respectively. In other words, it was assumed that if the average surface temperature for a cell was below 0°C, that cell had accumulated 244 days of freezing. Average surface temperature also served as a proxy for ice temperature.

The permanent road network was provided by Suter (2018) and DIVA-GIS (n.d.-b), and both were merged and converted to a raster using the Polyline to Raster tool in Esri ArcGIS 10.5. The road network, however, only shows permanent roads throughout Russia. All other cells in the raster were assumed to be possible paths for temporary winter roads (D. Gritsenko, personal communication, April 15, 2019). The elevation raster was downloaded from NOAA NCEI's ETOPO1 dataset (Amante & Eakins, 2009), and the digital elevation model was converted to a slope raster using the Slope tool.

Other downloaded data included lakes (NaturalEarth, 2009a; DIVA-GIS, n.d.-a) and rivers (NaturalEarth, 2009b; DIVA-GIS, n.d.-a); they were merged and converted into raster files. Once the data was processed and cleaned, it was ready for analysis (see Appendix for a summarized methodology graphic).

Multi-Criteria Evaluation

To evaluate the cost of traveling across the Russian Arctic, a cost for traversing each pixel was calculated based on the criteria in ATAM. The acquired data sources were reclassified, weighted, and aggregated using MCE. Two separate MCE calculations were performed, one to create the land suitability layer and another to create the water suitability layer, as the criteria for each differ.

Land suitability layer

First, the permanent road network was reclassified so that all roads had a value of 1; this is because permanent roads are the most ideal mode of travel and should be used when possible. For other areas in Russia that are not permanent roads, the ATAM criteria were used to calculate travel suitability over those areas. The data were rescaled to fall between 0 and 1 to prevent data layers with larger numbers from overpowering data layers with smaller numbers in the analysis. The method of assigning the new values was dependent on the ATAM criteria.

Some rasters were reclassified using a binary scheme (a raster with either 0 or 1 as values), which mask out areas that cannot be considered for a potential route. These were created for surface temperature (cannot be greater than 0°C), terrain (elevation cannot be greater than 500 m and slope cannot be greater than 5%), and snowfall (cannot be less than 20 cm).

Other rasters were reclassified on a continuous scale between 0 (low preference) and 1 (high preference) to help determine how good (or bad) a cell is for a potential path based on the criteria. Another surface temperature raster was created, rescaling only the temperature values below 0°C using linear rescale option in the Rescale by Function tool, with a lower temperature associated with a higher preference score. To prevent values greater than 0°C from affecting the rescale, the upper threshold was set to 0°C.
By default, in the Rescale by Function tool, the smallest and largest values of the input data are also the lower and upper threshold values, respectively, which are used in the tool for rescaling the input data. Changing the lower or upper threshold values allows the user to specify a range for rescaling that is narrower than the range of the input data. The user can also specify the new value of an input cell whose value is beyond this narrower range (Esri, n.d.-d). In this case, the upper threshold was set to 0°C, and values greater than 0°C were also assigned a preference score value of 0.

The weights and criteria were inputted into the following equation to determine land suitability on non-road areas:

land suitability= $tb \times eb \times sb \times ((w1 \times t)+(w2 \times m)+(w3 \times s))$ [Eq. 2]

where:
tb=surface temperature binary raster
eb=terrain binary raster
sb=snowfall binary raster
t=surface temperature

m=slope
s=snowfall amount
$w1,2,w3,$=weight factors so that $\Sigma^{3}_{i=1}\ wi=1$

Water suitability layer
Similar to the land cost layer, binary masks for ice thickness (for thickness less than 22.4 cm) and for surface temperature (for temperatures greater than 0℃) were created. A second ice thickness raster was rescaled using the linear function, with a lower threshold of 22.4 cm and greater thickness associated with higher preference scores. The rescaled surface temperature raster from the land cost analysis was re-used for this calculation.

The weights for the surface temperature and ice thickness criteria were each 0.50, since both are equally important in ensuring that a water body is traversable. The weights and criteria were inputted into the following equation:

water suitability= $tb \times ib \times ((w1 \times t)+(w2 \times i))$ [Eq. 3]

where:
tb=surface temperature binary raster
ib=water ice thickness binary raster
t=surface temperature
i=water ice thickness
$w1,w2$=weight factors (0.50) so that $\Sigma^{2}\ i=1\ \ \ wi=1$

Combined cost layer
Once both land and water layers were calculated, they were merged together, along with the reclassified permanent road network, to form one single suitability layer (with values closer to 1 indicating higher preference). To form a cost layer raster (with higher preference values given a value closer to 0 to indicate lower travel costs), the suitability layer was inverted through a linear rescale to fall between 0.01 (high preference, low cost) and 1 (low preference, high cost). The lower value was set to 0.01 and not 0 because the Cost Distance tool in ArcGIS only allows positive numbers (Esri, n.d.-b).

Least-Cost Path Analysis
Three main elements are needed to calculate a least-cost path: a cost distance layer, one or more destination points, and a cost direction raster (also known as a back-link raster). The back-link raster is used in conjunction with the other layers to trace the least-cost path from the origin to the destination by starting at the destination point and working towards the origin point (Esri, n.d.-a). Given that there are multiple destination points, a path is created between each origin and the destination to which is the least costly to travel (Esri, n.d.-c). The cost distance layer, which is the least accumulated cost distance from the origin, consists of one origin point and the cost layer raster (Esri, n.d.-c). This was created using the Cost Distance tool and done for each of the 81 RES origins. The Cost Distance tool also outputs a cost direction raster, which specifies the cardinal direction of the least-cost cell from each cell. Once the paths were created, they were exported and saved for later analysis.

Accessibility Estimation
As previously mentioned, this project defines accessibility as the number of round trips that can be made between a RES and its nearest logistical node over three months. To gain a rough estimate of the travel time for each path, travel times as determined by Stephenson et al. (2011) were used. Permanent roads were given a value of 0.5 min (500-m spatial resolution with a travel speed of 1 min per 1000 m). Suitable areas over water and non-road land areas (as determined by their respective suitability layers) were given values of 1.5 min (speed of 3 min per 1000 m) and 3 min (speed of 6 min per 1000 m), respectively. All non-suitable areas—excluding non-frozen water bodies—were given values of 12 min (speed of 24 min per 1000

m). The project did not use travel time in the least-cost path analysis since the travel times provided by Stephenson et al. (2011) are based on land cover type, which would have required land cover classification. The use of travel times here was simply to determine approximately how long it would take to travel along the paths. It was assumed that the vehicles would be moving continuously (24 hours a day and 7 days a week) and leave immediately after they arrive at their destinations. These travel times were overlaid on the previously-created least-cost paths to calculate the total travel time for each path.

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