Using artificial neural networks to model climate data to adapt transport infrastructure to climate change

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Abstract: *This paper examines an innovative approach for modeling the influence of climate parameters on transport infrastructure using artificial neural networks. Through them, detailed climatic data are generated by geographical positions and monthly and annual maps are created for Bulgaria's territory using the following parameters: surface temperature, diffuse fraction, horizontal solar irradiation, and average albedo of the terrain. Average ground temperature and monthly solar irradiation are essential for maintenance planning and developing strategies to adapt to extreme weather conditions, such as heat waves or frost, which can affect the condition and performance of the road surface. Average monthly temperatures can be used to design effective systems to prevent icing of road surfaces and improve drainage systems. By demonstrating the capabilities of accurate modeling and analysis, this paper highlights the importance of applying artificial neural networks in planning and improving the resilience of transport infrastructure against climate change.*
Keywords*: CLIMATE CHANGE, ARTIFICIAL NEURAL NETWORKS, TRANSPORT INFRASTRUCTURE, SOLAR RADIATION*

1. Introduction

Climate change represents one of the most serious challenges of modern times, affecting various aspects of life and the economy. Transport infrastructure is particularly vulnerable to extreme weather conditions such as high temperatures, heat waves, heavy rainfall, and snowfall. These climatic factors can damage road surfaces, reducing their durability and increasing maintenance and repair costs. In this context, adapting transport infrastructure to climate change is essential to ensure its sustainability and functionality [1].

The current development aims to demonstrate the possibility of using artificial neural networks (ANN) to model climate parameters that are important for transport infrastructure. An essential task is to investigate how ANNs can analyze, store, and feed on demand by finely interpolating various climatic factors essential for road infrastructure design and maintenance. Using data from multiple sources, such as PVGIS and NASA POWER, and integrating this data into ANNs, aims to create reliable and accurate models to support informed decision-making for adapting transport infrastructure to climate change.

2. Methodology

2.1. Description of data used and characteristics

Artificial Neural Networks (ANN) represent a powerful tool for modeling climate parameters [2]. Here are the climate factors selected for this stage of development and how each may affect the climate assessment of transport infrastructure:

Ground temperature (at a height of 2 m above the ground):
- Crucial for determining the thermal load on road surfaces, which can cause them to expand or contract.
- It affects the choice of building materials that must withstand temperature fluctuations.
- An important factor in planning winter road maintenance, such as de-icing and snow removal.

Diffuse fraction of solar irradiation:
- An indirect measure of cloudiness appears.
- Its value is related to visibility and road safety, especially in areas with high cloud cover.
- Determines the need for additional lighting on road sections.

Global horizontal solar irradiation:
- Crucial for determining the thermal load from solar radiation on road surfaces, which can lead to their expansion or contraction.
- It affects the choice of road surface materials resistant to UV radiation.

Global inclined solar irradiation (on inclined surfaces):
- It is used to assess the potential for using solar panels in road infrastructure, such as snow protection equipment.
- This is important for the design of road facilities, such as bridges and tunnels, where shadows can affect safety and visibility.

Albedo (reflectivity) of the terrain:
- It affects the reflection of sunlight from road surfaces, which can affect the temperature and resistance of materials.
- The parameter is essential in calculating reflected solar irradiation, and it is a component in calculating global inclined solar irradiation.
- Albedo reflects success in designing adequate road surfaces to minimize the heat island effect in urban areas.

Each of these factors can be analyzed and modeled using ANNs to provide accurate and reliable data to support the design and maintenance of road infrastructure in different climates.

More broadly, this includes calculating the probability of road icing, snow accumulation, road conditions under different weather scenarios, and the potential impact of climate change on road safety and durability.

2.2. Sources of climatic data for the territory of Bulgaria

Finding climatic data of Bulgarian origin is a significant and complex challenge. Therefore, data on foreign origin was used. Three primary data sources were used to train and test the ANN (PVGIS [3], NASA POWER [4], and NEO – NASA Earth Observations [5]). Choosing GIS data with climate data for training Artificial Neural Networks (ANNs) instead of traditional data from weather stations has several key advantages:

Broad geographic scope and coverage: PVGIS and NASA POWER data offer global coverage with high spatial resolution. This is particularly important for ANN training as it allows the analysis of climate patterns and parameters in different geographic regions, including hard-to-reach and little-explored areas.

Data content and diversity: PVGIS, NASA POWER, and NEO – NASA Earth Observations provide an extensive set of weather and climate data, including solar radiation, temperature changes, humidity, wind conditions, and more. This variety of information is essential for developing complex and accurate models through ANNs.

Constant update and availability: Data from the satellite systems are updated regularly, which ensures continuous access to up-to-date information. This is important for maintaining the relevance and accuracy of ANN models that can respond to ongoing climate change.

Standardization and compatibility: Data from these sources are standardized and easily compatible with different analytical tools and software platforms, facilitating their integration and processing in the context of ANN.

These advantages make PVGIS and NASA POWER highly suitable for ANNs, providing the rich and diverse data set needed to create reliable and accurate predictive models.

2.2.1. PVGIS (Photovoltaic Geographical Information System) [3]

This system provides detailed data on solar irradiance and meteorological parameters that are critical for modeling solar energy and related climate aspects. PVGIS information can be used to analyze the influence of solar radiation on road conditions.

As stated on the PVGIS website, the JRC-PVGIS database is built based on satellite measurements between 1998 and 2016. The data is provided by the Climate Monitoring Satellite Application Facility (CM-SAF) and has a time step of 1 hour and a spatial resolution of approximately 2.5 km (1'30"). The PVGIS-CMSAF database covers the same territory as the Meteosat satellite, which includes Europe, Africa, and parts of South America.

Later, the CM-SAF team created a new solar database called PVGIS-SARAH using a different algorithm successfully implemented in Asia in the previous version of PVGIS. This database also covers the PVGIS-CMSAF territory. In 2020, an updated version called PVGIS-SARAH2 was published.

PVGIS's spatial resolution is about 2.5 km. These solar data are of a new generation and significantly better in terms of spatial and temporal resolution and accuracy.

Data is available online on request for a specific geographic location defined by latitude and longitude. To cover the territory of Bulgaria with high resolution, tens of thousands of requests for providing data on the monthly values of diffuse and global solar irradiation must be made manually and processed. The data is available via a Non-Interactive Service API, which allows data to be downloaded at the desired resolution with a program (e.g., VBA in the MS Excel environment) that makes API requests for locations specified with their geographic coordinates. The denser the network and the more requests, the more detailed information can be retrieved.

2.2.2. NASA POWER (Prediction of Worldwide Energy Resources) [4]

Solar data for the territory of Bulgaria can be found in different formats and on different NASA websites, being offered with different angular resolutions and organization. These data cover solar horizontal irradiation for the period 1981 to 2021, as well as its diffuse component since 2001. The data can be viewed using the visualization software POWER Data Access Viewer, available online.

This database provides extensive information on climate parameters collected by various NASA satellite missions. Data from NASA Power includes temperature, humidity, wind conditions, and other important weather indicators critical to understanding the climate factors affecting road infrastructure.

Using this data will allow ANN to train and test models that can predict climate conditions with high accuracy and reliability. This, in turn, will improve the ability to plan and react to different weather conditions, thereby increasing the safety and efficiency of the road infrastructure.

Upon request, NASA Power generates text files (in ASCII, CSV, and other formats) with the necessary data, which can be further processed with other software. Data can be organized by day (in the menu Temporal Average: Daily) or month (in the menu Temporal Average: Interannual).

According to the information on the site, the solar data is from MERRA-2 (Modern-Era Retrospective Analysis for Research and Applications, Version 2), a relatively low-resolution NASA climate database: 0.5° × 0.625°. On the same site, other valid climate data with a resolution of 0.5° are available, such as information on winds (direction and strength at different heights), humidity, temperature (at ground level and 2 m above it), atmospheric pressure, etc. Through interpolation, the system can provide this information for a specific location.

In addition to the data for past years, monthly climate data summarized (averaged) over a longer period is also available through the POWER Data Access Viewer (in the Temporal Menu Average: Climatology). Among them are data on heating and cooling degrees, terrain albedo, solar irradiation, temperatures, and others.

2.2.3. NEO - NASA Earth Observations [5]

Data on the NEO—NASA Earth site Observations are organized into five main areas: Atmosphere, Energy, Land, Life, and Ocean. Each of these areas includes between 10 and 20 datasets. Monthly solar values, arranged in maps, are available in the Energy area under the name “Solar Insolation.” Unfortunately, this data includes only the global cumulative solar energy and lacks information on its diffuse component.

Various useful and interesting data with different resolutions can be downloaded from this site:

- 1.0° (matrix of size 360 × 180 elements);
- 0.5° (matrix size 720 × 360);
- 0.25° (matrix size 1440 × 720);
- 0.1° (matrix size 3600 × 1800).

This site offers climate data and information on the altitude of the earth's surface in meters, with a maximum resolution of 0.1°. For Bulgaria's latitude, this corresponds approximately to a resolution of 8.16 km in the east-west direction and 11.12 km in the north-south direction. These data were used for the relief in Bulgaria.

2.3. Downloaded data

The neural networks are trained with data downloaded mostly from PVGIS [3] and the NASA POWER website [4].

Data on diffuse fraction, global horizontal irradiation, and temperature by month from 2005 to 2020, with a resolution of 0.1°, were downloaded from the PVGIS site via API requests. For this task, data was downloaded in CSV format from the SARAH2 database for an area slightly larger than that of Bulgaria, covering a latitude of 41° to 44.5° and a longitude of 22° to 29° (see Fig. 1) for the period from 2005 to 2020.

In the east-west direction, the area is divided into 70 parts, and in the north-south direction—into 35, for a total of 2450 regions with dimensions of 0.1° × 0.1°.

The downloaded data are averaged and saved in a format suitable for ANN training. This format includes information on the month, latitude and longitude, a diffuse fraction (D / G), mean daily solar irradiation (G), and mean diurnal temperature for the respective month. Locations inside the Black Sea or the Mediterranean Sea, identified by the zero temperature values provided by PVGIS, were removed from the file. As a result, 26,412 records remain in the database.

POWER Data Access Viewer site allows climate data to be downloaded from a specified point or region (POWER Regional Data Access) from 1981 to 2020. Albedo data starts in 1984 and has a resolution of 0.5°, based on the MERRA2 database, which has a resolution of 0.5° × 0.625°. In general, this is a relatively low resolution that will not provide a high-quality end result.

Fig. 1. Dimensions of the analyzed territory of Bulgaria and adjacent areas. Dividing the territory into parts.

Data has been downloaded in ASCII or CSV format for an area with latitude 41° to 44.5° and longitude 22° to 29° from 2005 to 2020. The downloaded file has a header of 10 lines and 1568 lines of albedo data by month (16 years × 98 regions on the territory of Bulgaria). Some initial analyses were performed on these data.

Elevation data downloaded from NEO – NASA Earth Observations with the same resolution.

When working with ANNs, it is desirable to work with territories/values with a slightly more extensive range than necessary to increase accuracy for the desired range.

3. Modeling with artificial neural networks

3.1. Trained neural networks

The artificial ones used neural networks were trained as part of the developments in the monograph “Artificial Neural Networks for Energy Efficiency” [2]. Four of them (see Fig. 2) are suitable for the present development:

- ANN with 5 input neurons, 30 neurons in the hidden layer, and 1 neuron in the output layer to determine surface temperatures based on a given month, geographic coordinates, elevation, and terrain slope. Training terminates after 47,000 epochs, with a correlation coefficient between training and resulting values $R^2 = 0.997$ and the test set – with $R^2 = 0.997$.
- ANN with 4 input neurons, 40 neurons in the hidden layer, and 1 neuron in the output layer to determine the diffuse fraction (ratio between monthly values of diffuse and global solar irradiation, i.e., a measure of average cloud cover) based on a given month, geographically location coordinates and altitude. Training terminates after 108,300 epochs, with a correlation coefficient between training and output values of $R^2 = 0.964$, and with the test set, with $R^2 = 0.962$.
- ANN with 5 input neurons, 20 neurons in the hidden layer, and 1 neuron in the output layer to determine the horizontal solar irradiation based on a given month, geographical location coordinates, altitude, and diffuse fraction. Training terminates after 23,000 epochs, with a correlation coefficient between training and output values of $R^2 = 0.999$, and with the test set, with $R^2 = 0.999$.
- An ANN with 4 input neurons, 40 neurons in the hidden layer, and 1 neuron in the output layer to determine monthly albedo values of the surrounding terrain based on a given month, geographic coordinates, altitude, and temperature. Training terminates after 3,788,910 epochs, with a correlation coefficient between training and output values of $R^2 = 0.979$ and the test set, with $R^2 = 0.976$.

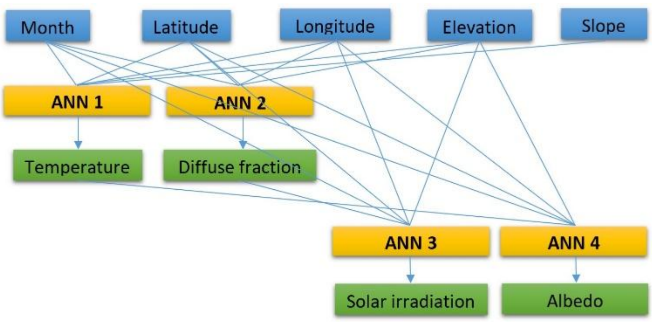

Fig. 2. Schema of the connections between inputs (in blue) and outputs (in green) in the project's integrated four artificial neural networks (in yellow).

Fig. 3. Page content for ANN retrieval of monthly and annual climate data (temperature, diffuse fraction, horizontal solar irradiation, and albedo) by geographic location.

3.2. Using trained ANNs in HTML pages with Javascript code

The approach of using trained ANNs in HTML pages with JavaScript programming code included is developed in the same monograph [2]. This approach has been further developed for this project, and the web pages are available in a small website at [6]:

1) **Page for climate data by geographical positions**. Data on average monthly temperatures, diffuse fraction, horizontal solar irradiation (kWh/m^2/mo), and albedo for all 12 months are displayed for a given geographical position on a map of Bulgaria. The displayed points on the map can be settlements, highways, and roads of different classes. In addition, summary values of these parameters for the year are also output, as shown in Fig. 3.

2) **Page for monthly and annual climate data maps**. Monthly maps (for a specified month) and annual maps with variable resolution (0.1°, 0.05°, 0.02°, 0.01°) are drawn for selected parameters: surface temperature, diffuse fraction, horizontal solar irradiation, and albedo.

The page displays a map of meters' elevation (see Fig. 4) and terrain slope. The monthly maps are divided into four groups for relevant climate parameters, 12 for each month. There are four annual maps, one for each parameter.

Fig. 5 demonstrates an example of page work for compiling monthly and annual climate maps using ANN (for temperature, diffuse fraction, horizontal solar irradiation, and albedo). The map shows the average diffuse fraction for the month of January (average for the period 2005 – 2020).

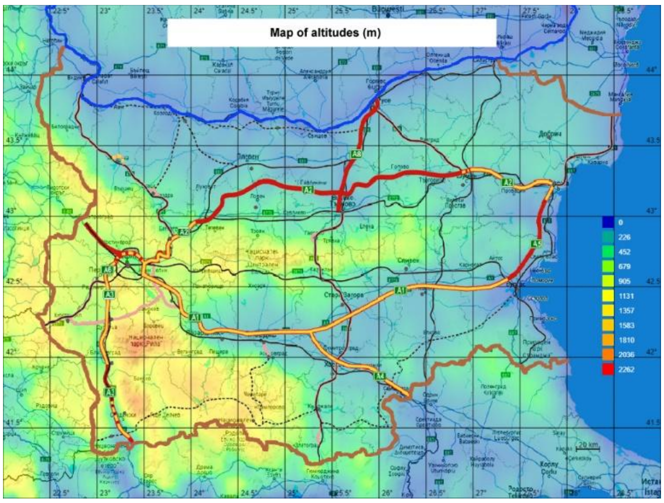

Fig. 4. Map of altitudes in meters of the considered territory of Bulgaria.

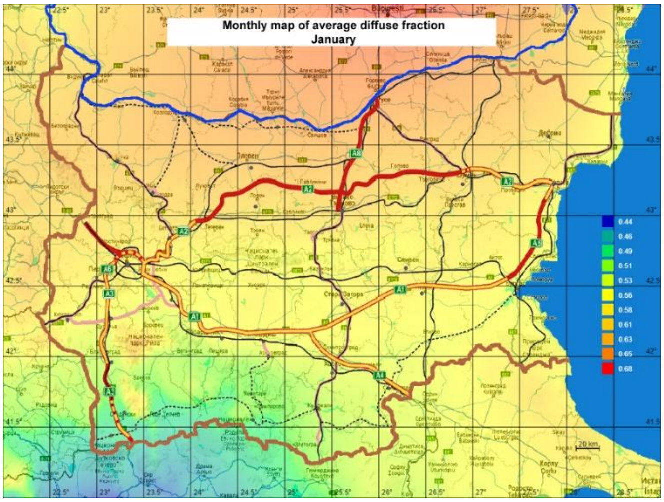

Fig. 5. An example of the work of the page for compiling monthly and annual climate maps using ANN (for temperature, diffuse fraction, horizontal solar irradiation, and albedo). The map shows the average diffuse fraction for January (average for the period 2005 – 2020).

4. Applications of the developed pages

4.1. Page for climate data by geographic position

Climate data for 2005 – 2020 by geographical positions provides valuable information that can be used to adapt transport infrastructure to climate change. Here are some possible applications of this data:

Road infrastructure design and improvement: Elevation and average monthly temperature data can help design roads that are resilient to extreme weather conditions, such as heavy rainfall, snowfall, or high temperatures.

Maintenance and rehabilitation planning: Analysis of horizontal solar irradiation and albedo can be used to plan the maintenance of road surfaces, taking into account potential wear and degradation from UV radiation and temperature changes.

Optimizing lighting: Global horizontal solar irradiation and diffuse fraction data can be used to optimize the planning and placement of street lighting, choosing the most efficient locations and angles to maximize the use of natural light and reduce energy costs.

Adaptation to climate change: Average annual temperatures and solar radiation data can be used to analyze climate change trends and adapt transport infrastructure to cope with expected changes, such as increasing the resistance of road surfaces to high temperatures or improving drainage systems to cope with increased rainfall.

Developing sustainable transport solutions: Climate information can support the development of sustainable transport solutions, such as building green corridors to reduce urban heat and improve air quality and planning cycling and pedestrian routes adapted to local climatic conditions.

Prevention of erosion and landslides: Elevation data can help analyze the risk of erosion and landslides, especially in areas with significant climate change. This is key to preventing damage to road infrastructure.

These applications illustrate how detailed information on climate conditions can be used to improve and adapt transport infrastructure to current and future climate challenges, thereby increasing its resilience and efficiency.

4.2. Page for monthly and annual climate data maps

The monthly and yearly maps of climate data for 2005 – 2020 offer a valuable tool for analysis and planning, especially in adapting transport infrastructure to climate change. Here are some possible applications of the data provided in this area:

Infrastructure planning and design: Elevation and terrain slope data can be used to plan new roads, railways, and bridges, considering the potential risks of flooding, erosion, and landslides. This is particularly important in areas where climate change may increase the frequency and intensity of these phenomena.

Adaptation to extreme temperature conditions: Monthly and annual temperature maps provide information on changes in climate conditions, which is critical for adapting transport infrastructure to extreme temperature conditions. This may include choosing materials that are more resistant to thermal expansion and contraction and planning maintenance and repair activities.

Optimizing the use of solar energy: Global horizontal solar irradiation and albedo data can be used to optimize the placement and design of solar panels on the roofs of transport facilities, such as stations, bus stops, and parking lots, to produce clean energy.

Water resources management: Analysis of climate data can help manage water resources, especially in planning drainage systems for roads and railways. This is important to prevent flooding and ensure the safety of passengers and vehicles.

Improving infrastructure resilience: Annual climate data maps can be used to assess long-term climate trends, which is essential for designing sustainable transport infrastructure that can withstand changes in climate conditions.

Education and research: The data provided can be used in educational programs and research aimed at understanding and adapting to climate change and developing innovative solutions to reduce the environmental impact of transport infrastructure.

These applications highlight the importance of access to accurate and detailed climate data for developing strategies to adapt transport infrastructure to future climate challenges.

5. Conclusions

The research presents an innovative approach for modeling the influence of climatic parameters on the transport infrastructure through artificial neural networks. The main conclusions of the present study are the following:

- **Applicability of ANNs for modeling climate data**: ANNs are proving to be a powerful tool for analyzing and modeling climate parameters critical to transportation infrastructure. Using historical climate data and interpolation, ANNs can generate accurate and reliable forecasts for various climate conditions.
- **Improving infrastructure resilience**: Using ANNs to model climate data provides an opportunity to enhance the resilience of transport infrastructure against climate change. This includes designing anti-icing systems, optimizing drainage systems, and selecting appropriate building materials.
- **Expanding planning and maintenance capabilities**: Models built using ANNs provide detailed monthly and annual maps of climate parameters. These maps can be used to plan road maintenance and rehabilitation and adapt infrastructure to extreme weather conditions.
- **Versatility of application**: The information generated through ANN can be used in transport infrastructure and other fields such as agriculture, water resources management, and urban planning. This highlights the importance of accurate climate data for various sectors of the economy.

Future research may focus on expanding the database and improving the accuracy of the models, as well as investigating other climate parameters that may affect transportation infrastructure. In addition, integrating ANNs with different analytical tools can lead to more effective and sustainable climate change adaptation solutions.

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