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# Cognitive Sustainability

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## Guest Editor's Foreword

With great pleasure, I introduce this special issue of *Cognitive Sustainability*, supported by the **Waclav Felczak Foundation**'s Mazurka Grant. This edition aims to strengthen Polish-Hungarian scientific cooperation and enhance Polish researchers' visibility in the sustainability field.

In this issue, we present six insightful articles from Polish authors, each contributing valuable perspectives and innovative solutions to contemporary sustainability challenges. These contributions reflect sustainability research's dynamic and interdisciplinary nature, showcasing advancements in policy, technology, and cognitive tools. As we navigate the complexities of sustainable development, the collaboration between Polish and Hungarian scientists becomes increasingly vital.

In the words of Albert Einstein, "*We cannot solve our problems with the same thinking we used when we created them.*" This issue embodies the innovative thinking required to address the pressing environmental challenges of our time.

I hope you find this collection of articles both enlightening and inspiring, and I look forward to the continued growth of Polish-Hungarian scientific partnerships.

Sincerely,

Dr. Pál Péter Kolozsi Ph.D.
Guest Editor, *Cognitive Sustainability*

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# Forecasting the number of road accidents caused by pedestrians in Poland using neural networks

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**Abstract**

Every year, fewer traffic accidents occur in Poland and throughout the world. Pandemics have recently impacted this number, but it is still relatively high. All efforts should be made to lower this figure. The article's main goal is to project the number of pedestrian-related traffic accidents in Poland based on yearly statistics. from 2001. A projection for the years 2024–2030 was created using police data. Various neural network models were employed to predict the number of incidents. The findings indicate that a stabilisation in traffic accidents is yet to be expected. One way to look at this is as a result of both Poland's population reduction and the growing number of cars on the road. The number of random samples (training, test, and validation) selected has little effect on the outcomes (Road safety statistics in the EU, 2024, Poland Population, 2024, Poland Number of Registered, 2024).

**Keywords**

road accident, pandemic, forecasting, neural networks, pedestrian

## 1. Introduction

Road accidents occurred when at least one of the parties engaged was a moving vehicle that resulted in property damage or personal harm in a location meant for public transportation or widely utilised. The WHO estimates that 1.3 million individuals lose their lives in car crashes each year. Worldwide, the average country experiences a 3% decline in GDP due to traffic accidents. For children and young adults between the ages of five and twenty-nine, traffic accidents constitute the main cause of mortality (WHO, 2018). By 2030, the UN General Assembly wants a 50% decrease in traffic accident fatalities and injuries.

When judging how serious a traffic incident is, one factor to consider is its extent (Baranyai and Sipos, 2022). For the responsible authorities to develop road safety legislation aimed at averting accidents and reducing injuries, fatalities, and property damage, the severity of incidents must be estimated (Tambouratzis et al., 2014; Zhu et al., 2019; Mekonnen et al., 2022).

Before implementing countermeasures to prevent or reduce the number of serious road accidents, it is imperative to identify the critical elements that influence accident severity (Arteaga et al., 2020). A multi-node Deep Neutral Network (DNN) architecture is presented by Yang et al. (2022) to forecast varying degrees of injury, death, and property damage. It makes it possible to accurately and thoroughly assess the severity of traffic accidents.

The accident figures come from several sources. Usually, government agents use the appropriate government entities to collect and evaluate them. Numerous sources are used to collect data, such as police reports, insurance company databases, and hospital records. As a result, the transportation industry is doing an extensive data analysis on traffic accidents (Gorzelanczyk et al., 2020).

The most significant information source for analysing and forecasting traffic events is intelligent transportation systems. GPS equipment mounted on moving cars may be used to analyse this data (Chen, 2017). Roadside microwave vehicle detection systems can continually capture information about moving automobiles, such as vehicle type, speed, and traffic volume (Khaliq et al., 2019). A license plate recognition system may likewise gather large amounts of traffic data over a predetermined time (Rajput et al., 2015). Social media is another possible source of information on traffic and accidents, albeit the reporters' lack of expertise may make their reporting less accurate (Zheng et al., 2018)

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Working with various data sources presents challenges that must be addressed before accident data can be considered useful. Accurate analytical findings can be achieved by merging heterogeneous traffic accident data and combining multiple data sources (Abdullah & Emam, 2015).

In order to determine the severity of the issue and establish a connection between traffic participants and accidents, Vilaça et al. (2017) conducted a statistical analysis. The study suggests enacting additional traffic safety measures and raising the bar for traffic law requirements.

A statistical examination of traffic safety in a chosen Polish area was conducted by Bąk et al. (2019) using the number of traffic accidents as a proxy for the amount of research on accident causes. Multivariate statistical analysis was employed in the study to examine the safety variables of accident causes.

The sort of traffic issue being handled determines the source of accident data to use for analysis. Combining statistical models with additional data from real driving or other information gleaned from intelligent traffic systems enhances accident prediction and accident eradication accuracy (Chand et al., 2021).

The literature offers several techniques for predicting the probability of accidents. Time series approaches are the most popular techniques for forecasting accident frequency (Helgason, 2016; Lavrenz et al., 2018). However, they have the drawback of being unable to evaluate the forecast's accuracy based on previous predictions and frequently having a residual autocorrelation component (Forecasting based on time series, n. d.). While Sunny et al. (2018) employed the Holt-Winters exponential smoothing approach, Procházka et al. (2017) used a multi-seasonality model for their forecasts. One of the model's drawbacks is that exogenous variables cannot be included (Al-Madani, 2018).

The frequency of traffic accidents has been predicted using curve-fitting regression models of Al-Madani (2018) and Monedero et al. (2021) for analysing the number of fatalities, as well as the vector autoregressive model, which has the disadvantage of requiring many observations of variables to estimate their parameters (Wójcik, 2014) accurately. In turn, these need only a few basic linear connections (Piłatowska, 2012) and an order of autoregression (Mamczur, 2020), supposing the series is already stable.

Random Forest regression was used by Biswas et al. (2019) to forecast the frequency of traffic accidents. The data comprise groups with linked features that are similarly relevant to the original data, the approach and peak prediction are unstable, and smaller groups are preferred over bigger ones in this case. For the given forecasting problem, Chudy-Laskowska and Pisula (2015) employed an autoregressive quadratic trend model, a univariate periodic trend model, and an exponential smoothing model. A moving average model may also be utilised to foresee the problem. However, this approach has drawbacks, such as poor forecast accuracy, data loss within a sequence, and an inability to consider trends and seasonal variations (Kashpruk, 2020).

To ensure that the process remains stable, Prochazka and Camaj (2017) employed the GARMA approach, which confines the parameter space. Forecasting frequently uses the ARMA model for stationary systems (Dutta et al., 2020; Karlaftis et al., 2009); it uses the ARIMA or SARIMA model for non-stationary processes. These approaches have the benefit of giving the models under examination considerable flexibility. However, they also have the drawback of requiring more research competence from the researcher than, say, regression analysis (Łobejko, 2015). The linearity of the ARIMA model is another drawback (Szmuksta-Zawadzka & Zawadzki, 2009).

An ANOVA test was employed in Chudy-Laskowska and Pisula's work (2015) to forecast the frequency of traffic accidents. This approach's drawback is that it makes several extra assumptions. The most important among them is the sphericity premise, which might result in incorrect findings. Neural network techniques are also used to forecast the frequency of vehicle accidents. One of the drawbacks of artificial neural networks (ANNs) is that they require prior expertise in this area (Wrobel, 2017), as the final result depends on the network's initial conditions. Additionally, because ANNs are often called "black boxes", where input data is entered and the model outputs results without knowing the analysis, it is impossible to interpret results conventionally (Data mining techniques, n. d.).

Kumar et al. (2019) used the Hadoop model as a state-of-the-art prediction technique. This strategy's drawback is its inability to handle tiny data sets (Top Advantages and Disadvantages of Hadoop 3, n. d.). Karlaftis and Vlahogianni (2009) forecasted using the Garch model. This strategy's intricate model and form provide a problem (Perczak & Fiszeder, 2014). Nevertheless, McIlroy and his team's ADF test has the drawback of having insufficient power to detect the autocorrelation of the random component (McIlroy et al., 2019).

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Another significant factor is the number of accidents per 10,000 people (NRA). In Poland, where there are 37.6 million people, there were 20,936 traffic accidents in 2023. By entering the data into equation 1, we can determine that in Poland in 2023, there were 5.56 traffic accidents per 1,000 people that a pedestrian caused.

$$NRA = \frac{NR}{NI} * 1000 \qquad (1)$$

where:

*NR* – number of road accidents

*NI* – number of inhabitants

An accident involving a pedestrian is a traffic incident in which a pedestrian is hit by a vehicle. The most common cause of this type of accident is a vehicle driver's failure to prioritise a pedestrian.

Based on the data above, the author projected the number of pedestrian-related accidents on Polish roadways. The amount of accidents was anticipated using neural networks.

## 2. Materials and methods

Pedestrians are involved in a significant number of traffic accidents each year. The epidemic has decreased the number of traffic accidents in recent years, which has impacted the predicted value. Pedestrians remain the primary cause of many traffic accidents, even during the pandemic. Because of this, every effort should be made to lower this number and show how it will change over the next several years (Figure 1):

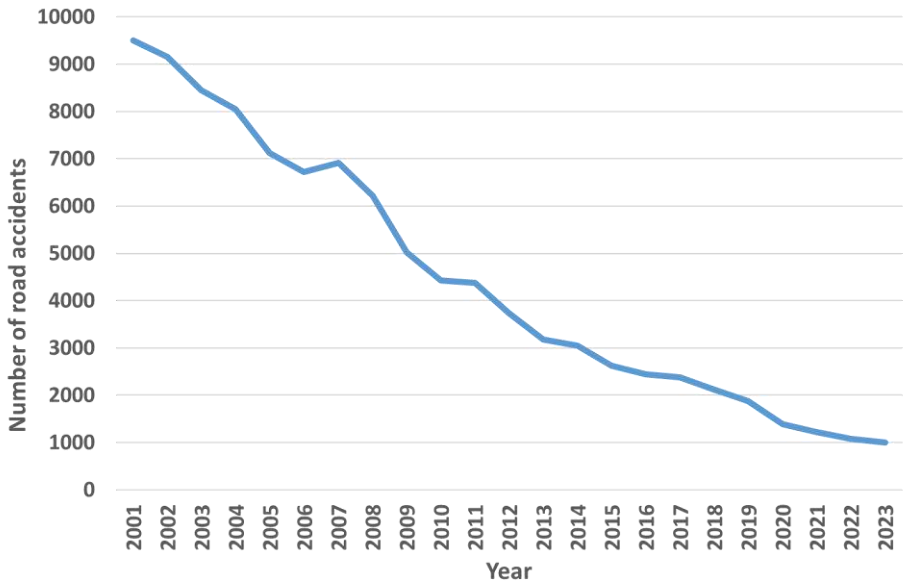


Figure 1. Number of road accidents in Poland caused by pedestrians in years 2001-2023 (Road Accident Statistics, 2024)

The number of traffic accidents in Poland was predicted using a subset of neural network models. One benefit of this approach is that it mimics how the human brain functions. A neural network comprises nodes with inputs, weights, variances, and outputs. The Statistica software was used to choose the ideal weights throughout the investigation. The model and parameters used will determine the outcome of the forecast made using this approach.

One way to think of a neural network is as a mathematical construct that functions by drawing on the nervous system. They usually consist of several layers that together form the network's architecture. Thanks to a procedure known as training, the first layer includes data regarding text, pictures, numbers, and sounds. The network may use hundreds of inputs in this procedure before drawing specific judgments. Artificial neurons, which are mathematical functions that mimic the activity of organic neurons, are the fundamental building blocks of neural networks. Artificial neurons have several inputs but only give one output value, like organic neurons. When it comes to biological neurons, this is comparable to dendrites. Artificial intelligence development is centred around neural networks. Rather, this field of study aims to develop models that use intelligent behaviour, such as

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knowledge generalisation (Lake et al., 2017). Forecasting using neural networks extends to the frequency of traffic incidents (Oronowicz-Jaśkowiak, 2019).

The Statistica software and its built-in artificial neural network modules corrected the ideal weights throughout testing. A multilayer perceptron (MLP) neural network, including layers of hidden neurons, was employed for prediction. In the cases under analysis, the number of neurons in the intermediate layer varied between two and eight. A single neuron in the output layer represented the time series output values of the number of traffic accidents. The model and model parameters used will determine the predictive outcomes of the approaches presented. The measure of predictive brilliance was derived from the following prediction errors, which were found using equations (2–7).

- *ME* – mean error

$$ME = \frac{1}{n}\sum_{i=1}^{n}(Y_i - Y_p) \quad (2)$$

- *MAE* – mean error

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|Y_i - Y_p| \quad (3)$$

- *MPE* – mean percentage error

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\frac{Y_i - Y_p}{Y_i} \quad (4)$$

- *MAPE* - mean absolute percentage error

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{|Y_i - Y_p|}{Y_i} \quad (5)$$

- *SSE* – mean square error

$$SSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - Y_p)^2} \quad (6)$$

- $M^2$ – Theil's measure

$$M^2 = \frac{\sum_{i=1}^{N}(Y_i - Y_p)^2}{\sum_{i=1}^{N}{Y_i}^2} \quad (7)$$

Where:

*n* – length of forecast horizon,
*Y* – the observed value of road accidents,
$Y_p$ – the forecasted value of road accidents.

Neural network models with the lowest mean and absolute percentage errors were utilised to forecast the frequency of traffic incidents caused by pedestrians.

**3. Results**

Data from the Polish Police from 2001 to 2023 were used to anticipate the number of pedestrian-related traffic accidents in Poland each year. The study was carried out using the *Statistica* software, assuming two random sample sizes:

1. training 70%, test 15% and validation 15%.
2. training 80%, test 10% and validation 10%,

with the following number of learning networks: 20, 40, 60, 80, 100, and 200, the MP error value was minimal (Tables 1–2). Consequently, the row for which the MAPE error value is the smallest is highlighted in every table.

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Table 1. Summary of neural network learning for the case of random sample sizes training 70%, testing 15% and validation 15%

| Network number | Network name | Quality (training) | Quality (testing) | Quality (validation) | Learning algorithm | Error function | Activation (hidden) | Activation (output) | Errors | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | ME | MAE | MPE | MAPE | SSE | Theil |
| 20 | MLP 1-7-1 | 0.986150 | 0.999572 | 0.999618 | BFGS 58 | SOS | Logistics | Linear | 10.75 | 118.67 | 0.64% | 5.13% | 158.68 | 0.0035 |
| 20 | MLP 1-3-1 | 0.985445 | 0.999616 | 0.999819 | BFGS 30 | SOS | Tanh | Tanh | 0.91 | 108.71 | 0.69% | 4.34% | 158.32 | 0.0039 |
| 20 | MLP 1-8-1 | 0.986154 | 0.999553 | 0.999526 | BFGS 38 | SOS | Exponential | Linear | 13.69 | 123.14 | 1.03% | 5.53% | 160.56 | 0.1426 |
| 20 | MLP 1-7-1 | 0.985622 | 0.999519 | 0.999496 | BFGS 30 | SOS | Logistics | Tanh | 3.40 | 112.19 | 0.37% | 4.70% | 156.76 | 0.1489 |
| 20 | MLP 1-2-1 | 0.986174 | 0.999562 | 0.999561 | BFGS 115 | SOS | Tanh | Linear | 12.08 | 122.62 | 0.89% | 5.41% | 159.89 | 0.0044 |
| 40 | MLP 1-8-1 | 0.986163 | 0.999162 | 0.999959 | BFGS 46 | SOS | Exponential | Logistics | 11.43 | 105.37 | 0.80% | 4.24% | 145.17 | 0.0035 |
| 40 | MLP 1-8-1 | 0.985171 | 0.999716 | 0.999998 | BFGS 31 | SOS | Exponential | Tanh | 1.33 | 125.22 | 2.12% | 6.00% | 175.96 | 0.0039 |
| 40 | MLP 1-4-1 | 0.986051 | 0.999316 | 0.999991 | BFGS 39 | SOS | Tanh | Logistics | 2.04 | 93.60 | 0.34% | 3.70% | 147.77 | 0.1426 |
| 40 | MLP 1-7-1 | 0.985798 | 0.999664 | 0.999999 | BFGS 10 | SOS | Exponential | Linear | 10.26 | 111.76 | 0.99% | 4.81% | 166.33 | 0.1489 |
| 40 | MLP 1-3-1 | 0.986067 | 0.999361 | 0.999920 | BFGS 98 | SOS | Tanh | Exponential | 22.27 | 148.97 | 1.59% | 6.42% | 181.60 | 0.0044 |
| 60 | MLP 1-6-1 | 0.986325 | 0.999100 | 0.999991 | BFGS 66 | SOS | Logistics | Logistics | 2.37 | 97.62 | 0.20% | 3.84% | 144.97 | 0.0035 |
| 60 | MLP 1-2-1 | 0.983635 | 0.999799 | 0.999990 | BFGS 65 | SOS | Logistics | Tanh | 39.87 | 135.60 | 0.26% | 6.24% | 191.27 | 0.0039 |
| 60 | MLP 1-6-1 | 0.986157 | 0.999497 | 1.000000 | BFGS 39 | SOS | Exponential | Exponential | 32.95 | 129.90 | 3.14% | 6.19% | 167.26 | 0.1426 |
| 60 | MLP 1-6-1 | 0.986250 | 0.998836 | 0.999990 | BFGS 139 | SOS | Exponential | Logistics | 1.77 | 97.97 | 0.24% | 3.94% | 151.12 | 0.1489 |
| 60 | MLP 1-8-1 | 0.985932 | 0.999524 | 0.999994 | BFGS 27 | SOS | Logistics | Exponential | 89.93 | 163.09 | 7.00% | 9.09% | 206.06 | 0.0044 |
| 80 | MLP 1-6-1 | 0.986358 | 0.999241 | 0.999987 | BFGS 125 | SOS | Exponential | Logistics | 0.60 | 105.92 | 0.03% | 4.16% | 143.98 | 0.0035 |
| 80 | MLP 1-4-1 | 0.986446 | 0.999461 | 0.999990 | BFGS 93 | SOS | Tanh | Logistics | 3.47 | 100.47 | 0.14% | 3.87% | 141.03 | 0.0039 |
| 80 | MLP 1-5-1 | 0.985687 | 0.999678 | 0.999982 | BFGS 10 | SOS | Exponential | Linear | 8.30 | 123.63 | 2.35% | 5.89% | 173.19 | 0.1426 |
| 80 | MLP 1-8-1 | 0.986897 | 0.999011 | 0.999997 | BFGS 128 | SOS | Tanh | Logistics | 16.80 | 98.26 | 0.92% | 3.95% | 149.29 | 0.1489 |
| 80 | MLP 1-3-1 | 0.984466 | 0.999551 | 0.999990 | BFGS 38 | SOS | Logistics | Logistics | 36.41 | 131.87 | 4.22% | 6.88% | 185.54 | 0.0044 |
| 100 | MLP 1-6-1 | 0.986010 | 0.998618 | 0.999978 | BFGS 27 | SOS | Tanh | Exponential | 10.05 | 97.84 | 0.11% | 3.98% | 151.64 | 0.0035 |
| 100 | MLP 1-7-1 | 0.985505 | 0.999306 | 1.000000 | BFGS 14 | SOS | Exponential | Logistics | 8.95 | 131.35 | 2.04% | 6.20% | 167.54 | 0.0039 |
| 100 | MLP 1-3-1 | 0.985645 | 0.999704 | 0.999994 | BFGS 70 | SOS | Exponential | Tanh | 4.06 | 124.70 | 2.10% | 5.88% | 172.86 | 0.1426 |
| 100 | MLP 1-7-1 | 0.984607 | 0.998820 | 0.999976 | BFGS 27 | SOS | Tanh | Logistics | 51.42 | 143.59 | 4.92% | 7.28% | 194.61 | 0.1489 |
| 100 | MLP 1-8-1 | 0.985894 | 0.999662 | 0.999997 | BFGS 5 | SOS | Exponential | Linear | 16.41 | 120.91 | 2.13% | 5.36% | 164.46 | 0.0044 |
| 200 | MLP 1-3-1 | 0.985868 | 0.999317 | 0.999990 | BFGS 23 | SOS | Tanh | Exponential | 19.32 | 105.97 | 2.26% | 4.70% | 156.12 | 0.0035 |

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| Network number | Network name | Quality (training) | Quality (testing) | Quality (validation) | Learning algorithm | Error function | Activation (hidden) | Activation (output) | Errors | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | ME | MAE | MPE | MAPE | SSE | Theil |
| 200 | MLP 1-3-1 | 0.985318 | 0.999582 | 0.999994 | BFGS 45 | SOS | Logistics | Logistics | 67.28 | 148.61 | 5.33% | 7.75% | 185.06 | 0.0039 |
| 200 | MLP 1-5-1 | 0.986394 | 0.999298 | 0.999993 | BFGS 75 | SOS | Logistics | Logistics | 0.35 | 98.57 | 0.04% | 3.82% | 141.47 | 0.1426 |
| 200 | MLP 1-6-1 | 0.986375 | 0.999501 | 0.999995 | BFGS 147 | SOS | Tanh | Logistics | 1.15 | 99.08 | 0.02% | 3.78% | 140.57 | 0.1489 |
| 200 | MLP 1-2-1 | 0.986022 | 0.999476 | 0.999996 | BFGS 38 | SOS | Exponential | Exponential | 1.50 | 109.98 | 1.12% | 4.66% | 155.36 | 0.0044 |
| | | | | | | | | **Minimal** | **0.35** | **93.60** | **0.02%** | **3.70%** | **140.57** | **0.0035** |

Table 2. Summary of neural network learning for the case of random sample sizes training 80%, testing 10% and validation 10%

| Network number | Network name | Quality (training) | Quality (testing) | Quality (validation) | Learning algorithm | Error function | Activation (hidden) | Activation (output) | Errors | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | ME | MAE | MPE | MAPE | SSE | Theil |
| 20 | MLP 1-2-1 | 0.985248 | 1.000000 | 1.000000 | BFGS 21 | SOS | Logistics | Tanh | 12.66 | 118.11 | 1.33% | 5.43% | 175.00 | 0.0035 |
| 20 | MLP 1-8-1 | 0.982742 | 1.000000 | 1.000000 | BFGS 13 | SOS | Tanh | Logistics | 47.05 | 199.46 | 8.00% | 12.47% | 289.52 | 0.0039 |
| 20 | MLP 1-5-1 | 0.983835 | 1.000000 | 1.000000 | BFGS 27 | SOS | Tanh | Tanh | 16.06 | 140.85 | 3.04% | 7.02% | 185.14 | 0.1426 |
| 20 | MLP 1-8-1 | 0.987041 | 1.000000 | 1.000000 | BFGS 144 | SOS | Exponential | Logistics | 3.67 | 96.72 | 0.07% | 3.75% | 140.34 | 0.1489 |
| 20 | MLP 1-6-1 | 0.986373 | 1.000000 | 1.000000 | BFGS 15 | SOS | Logistics | Linear | 0.61 | 119.18 | 1.64% | 5.39% | 169.11 | 0.0044 |
| 40 | MLP 1-6-1 | 0.984883 | 1.000000 | 1.000000 | BFGS 41 | SOS | Logistics | Tanh | 16.06 | 123.82 | 2.45% | 5.71% | 172.02 | 0.0035 |
| 40 | MLP 1-7-1 | 0.985665 | 1.000000 | 1.000000 | BFGS 28 | SOS | Tanh | Tanh | 9.93 | 121.73 | 2.25% | 5.66% | 170.86 | 0.0039 |
| 40 | MLP 1-3-1 | 0.954971 | 1.000000 | 1.000000 | BFGS 6 | SOS | Linear | Exponential | 188.25 | 428.49 | 20.90% | 26.88% | 575.59 | 0.1426 |
| 40 | MLP 1-2-1 | 0.986078 | 1.000000 | 1.000000 | BFGS 62 | SOS | Exponential | Tanh | 14.73 | 115.27 | 1.00% | 5.12% | 170.69 | 0.1489 |
| 40 | MLP 1-4-1 | 0.985140 | 1.000000 | 1.000000 | BFGS 25 | SOS | Logistics | Tanh | 18.13 | 111.72 | 0.15% | 4.97% | 174.49 | 0.0044 |
| 60 | MLP 1-4-1 | 0.956187 | 1.000000 | 1.000000 | BFGS 6 | SOS | Linear | Exponential | 219.06 | 435.85 | 22.40% | 27.74% | 586.77 | 0.0035 |
| 60 | MLP 1-7-1 | 0.984718 | 1.000000 | 1.000000 | BFGS 28 | SOS | Exponential | Exponential | 33.61 | 175.52 | 5.67% | 10.25% | 237.16 | 0.0039 |
| 60 | MLP 1-7-1 | 0.979533 | 1.000000 | 1.000000 | BFGS 7 | SOS | Logistics | Exponential | 137.72 | 301.82 | 15.77% | 20.11% | 440.74 | 0.1426 |
| 60 | MLP 1-4-1 | 0.985228 | 1.000000 | 1.000000 | BFGS 18 | SOS | Tanh | Tanh | 24.83 | 134.35 | 1.70% | 7.15% | 186.08 | 0.1489 |
| 60 | MLP 1-4-1 | 0.985445 | 1.000000 | 1.000000 | BFGS 22 | SOS | Exponential | Tanh | 15.91 | 132.92 | 2.92% | 6.56% | 178.70 | 0.0044 |
| 80 | MLP 1-5-1 | 0.984004 | 1.000000 | 1.000000 | BFGS 25 | SOS | Exponential | Logistics | 42.53 | 185.12 | 7.07% | 11.52% | 266.63 | 0.0035 |
| 80 | MLP 1-3-1 | 0.986307 | 1.000000 | 1.000000 | BFGS 8 | SOS | Linear | Linear | 10.70 | 130.48 | 1.10% | 5.76% | 163.79 | 0.0039 |
| 80 | MLP 1-7-1 | 0.986307 | 1.000000 | 1.000000 | BFGS 6 | SOS | Linear | Linear | 10.11 | 130.12 | 1.06% | 5.73% | 163.63 | 0.1426 |

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| Network number | Network name | Quality (training) | Quality (testing) | Quality (validation) | Learning algorithm | Error function | Activation (hidden) | Activation (output) | Errors | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | ME | MAE | MPE | MAPE | SSE | Theil |
| 80 | MLP 1-3-1 | 0.983467 | 1.000000 | 1.000000 | BFGS 18 | SOS | Logistics | Tanh | 15.85 | 132.93 | 1.79% | 6.60% | 191.52 | 0.1489 |
| 80 | MLP 1-2-1 | 0.985699 | 1.000000 | 1.000000 | BFGS 88 | SOS | Tanh | Tanh | 18.95 | 116.26 | 1.01% | 5.28% | 175.44 | 0.0044 |
| 100 | MLP 1-2-1 | 0.980835 | 1.000000 | 1.000000 | BFGS 4 | SOS | Exponential | Tanh | 152.57 | 261.74 | 14.98% | 17.76% | 389.68 | 0.0035 |
| 100 | MLP 1-5-1 | 0.981812 | 1.000000 | 1.000000 | BFGS 14 | SOS | Logistics | Logistics | 77.48 | 230.84 | 10.33% | 14.48% | 328.62 | 0.0039 |
| 100 | MLP 1-5-1 | 0.981972 | 1.000000 | 1.000000 | BFGS 5 | SOS | Exponential | Linear | 32.76 | 193.92 | 6.86% | 11.39% | 273.65 | 0.1426 |
| 100 | MLP 1-8-1 | 0.975335 | 1.000000 | 1.000000 | BFGS 5 | SOS | Linear | Tanh | 13.48 | 214.31 | 5.45% | 11.51% | 283.43 | 0.1489 |
| 100 | MLP 1-5-1 | 0.981904 | 1.000000 | 1.000000 | BFGS 14 | SOS | Logistics | Exponential | 67.07 | 224.30 | 9.85% | 14.64% | 328.61 | 0.0044 |
| 200 | MLP 1-7-1 | 0.982855 | 1.000000 | 1.000000 | BFGS 11 | SOS | Logistics | Exponential | 78.88 | 211.08 | 9.66% | 13.70% | 303.74 | 0.0035 |
| 200 | MLP 1-2-1 | 0.984554 | 1.000000 | 1.000000 | BFGS 38 | SOS | Exponential | Exponential | 53.59 | 184.81 | 7.27% | 11.34% | 256.84 | 0.0039 |
| 200 | MLP 1-3-1 | 0.984417 | 1.000000 | 1.000000 | BFGS 76 | SOS | Tanh | Logistics | 27.98 | 88.21 | 0.75% | 3.42% | 147.43 | 0.1426 |
| 200 | MLP 1-8-1 | 0.986698 | 1.000000 | 1.000000 | BFGS 32 | SOS | Tanh | Linear | 20.01 | 108.99 | 0.42% | 4.41% | 159.41 | 0.1489 |
| 200 | MLP 1-5-1 | 0.975155 | 1.000000 | 1.000000 | BFGS 4 | SOS | Linear | Tanh | 19.52 | 204.69 | 3.79% | 10.75% | 283.68 | 0.0044 |
| | | | | | | | | **Minimal** | **0.61** | **88.21** | **0.07%** | **3.42%** | **140.34** | **0.0035** |

https://doi.org/10.55343/CogSust.102

It is possible to conclude that based on the test findings shown, the number of pedestrian-related traffic incidents will stabilise in the upcoming years, almost regardless of the random sample size used. The average percentage error is reduced when the proportion of the training set is higher than that of the test and validation sets. The error was 3.70% for the training set (70%), 3.42% for the test set (15%), and 15% for the validation test in the proportions (70 : 15 : 15). The findings are impacted, on the one hand, by the rising number of automobiles on Polish roads and the recent epidemic (Fig. 3).

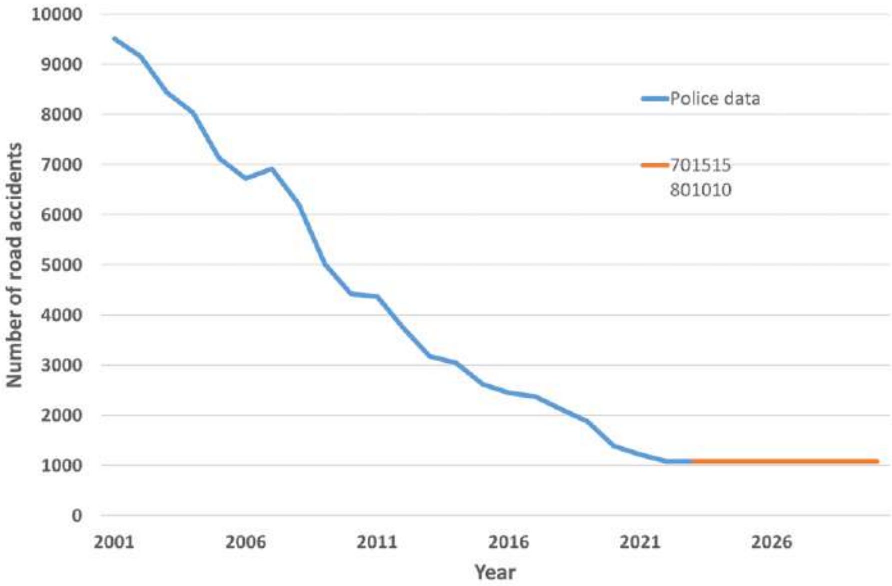


Figure 3. Projected number of road accidents for 2024-2030

**4. Conclusion**

The frequency of accidents caused by pedestrians was predicted using neural networks, and the study was conducted in the *Statistica* environment. The computer evaluated the study's weights in a way that minimised both the mean absolute error and the mean absolute percentage error.

Based on the data collected, we may still anticipate stabilising the number of traffic accidents. On the one hand, the recent epidemic and the growing number of cars on the road impact this. The computed forecast errors show how accurate the models were.

Measures to further reduce the number of traffic accidents should be implemented in light of the forecasts that have been obtained. One solution could be increased penalties for traffic offences on Polish roads, effective January 1, 2022. Undoubtedly, the pandemic affected the research findings that were acquired since it drastically altered the number of traffic accidents.

In their future study, the authors want to employ other statistical techniques and account for additional elements impacting the frequency of accidents to ascertain the total number of traffic accidents. These might include the amount of traffic, the kind of weather, the driver's age who caused the collision, or exponential techniques for calculating the frequency of traffic accidents.

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# A fuzzy-based method of assigning train managers to task types

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**Abstract**

Besides an employee's skill level, several personal qualities may affect the implementation of a task during job activities. Thus, it might be hypothesised that the effectiveness of railway personnel depends on the relationship between their abilities and the types of available duties. This article presents research results on the compatibility of personnel and performed duties focusing on train managers. This profession is important due to passenger safety, and there is a lower scientific interest in this job than in the case of train drivers. A complex survey has been conducted in cooperation with volunteers from the rail industry. As a result, groups of duties and personnel profiles have also been elaborated in cooperation with railway industry experts. A fuzzy logic-based method was built to classify the train managers. Then, a self-assessment was conducted as the final step; experts were asked to assess the managers' attitudes. The overall model was tested during validation. The automatised fuzzy-based method recognised 80 % of managers and indicated good clusters.

**Keywords**

railway, train managers, personal profiles, task types, fuzzy logic

## 1. Introduction

A high employee turnover characterises Poland's labour market: the change rate in 2022 was about 21%. In the railroad sector, the job change rate is lower than the average due to the specific nature of the tasks. However, the rate is significant and challenges the current management of railroad personnel. Increased turnover leads to an increased risk of human error in operational processes. A newly hired employee must be adequately prepared to perform his specific duties. Typically, such an employee may lack the necessary skills and have limited knowledge of the tasks.

Additionally, they often have not yet performed the required tasks enough times to achieve the desired quality in their work. This is apparent in his mistakes, and the longer he takes to perform his tasks. Considering various research results, the most undesirable events recorded by the rail transportation system are caused by errors and negligence of employees.

In order to avoid accidents and improve the performance of new personnel, a commonly used approach is to change and improve the training of new employees. Solutions are being sought to allow employees to acquire and develop the competencies required for their jobs more quickly and effectively. One of the answers to these needs is virtual reality (VR) technology. It allows us to replicate the work environment of operational employees faithfully.

However, there is the problem of not having enough employees. Thus, the employer cannot take personnel for tasks, taking them from a larger set of people. In addition to an employee's skill level, several personal qualities can affect the implementation of the task during job activities. Thus, the hypothesis can be made that the effectiveness of the personnel depends on the relationship between their abilities and the types of available duties.

A literature review has been conducted to find sources addressing the formulated problem. One research direction focuses on the work schedule and its influence on system safety (Roets & Folkard, 2022). The main goal is to find situations with optimised employee work schedules that minimise, for example, the operational risk. On the one hand, the workload is analysed to determine the probability of undesirable events and identify factors to reduce this likelihood. On the other hand, a risk-based approach is used to analyse the consequences of events and assess the influence of the schedule on them. However, personal abilities and qualities and their influence on the risk function are not considered, not even in analysing undesirable event occurrences (Frantasov et al., 2021).

Notable are organisational methods in the research field to improve employee performance (Haryanto et al., 2022; Liu et al., 2021). The research demonstrates a dedicated approach to personnel management, focusing primarily on training and preparation (Balakina et al., 2023). However, it does not consider the given duty's operational aspects and specific

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parameters. A general view on a whole one-employee group gives the typical human reliability approach (Harrison et al., 2022) or explores stress issues (Xu et al., 2022) without discussing personal abilities despite learnt skills. Planning and work optimising methods limit the decision factors to working time (Gołębiowski, 2020), permissions related to tracks or vehicles (Jütte et al., 2011), general costs (Preis et al., 2023) or flexibility in work planning (Ludewig, 2005; Matusova & Gogolova, 2017).

Considering the gap found, the following research questions can be formulated.

1. Is it possible to identify specific groups of duty types and compatible profiles related to railway personnel?
2. Is it possible to design a method to assign personnel to the most accurate profile?
3. Do people performing duties according to their profile work more efficiently?

This article presents the research results on the compatibility between personnel and their assigned duties. There are diverse jobs in the railway industry with different responsibilities. Thus, the paper is focused on train managers, who are crucial for passenger safety and have received less scientific interest than train drivers.

Section 2 presents groups of duties and personnel profiles developed in cooperation with experts from the railway industry. Section 3 presents the fuzzy logic-based method to classify the train managers, while Section 4 describes the validation experiment of the method. The paper ends with conclusions.

## 2. Data and methods

### 2.1. Train Manager Profiles

A survey was conducted among railway workers in Poland. The questionnaire was completed by 338 people in various positions, including traffic controller, rolling stock auditor, and train manager. No personal data from people has been used or collected. During the cooperation, the railway employees were anonymous to the researchers, and the results presented to the railway company were anonymous. Therefore, an ethical commission agreement was not necessary.

The respondents completed a three-part survey. The first part included questions on various metrics, such as the respondent's job position, gender, age, and length of service; they were also asked about the duration of the shift. In the second part, respondents were asked to subjectively identify their job's primary, periodic, and episodic duties. This part was open-ended to avoid suggesting answers to the respondents. This approach aimed to obtain information on which duties employees pay special attention to and perceive as part of their daily work. The third part of the survey asked respondents about the number and causes of incidents and accidents during their service. Railway employees also listed stress factors and what gives them satisfaction at work.

Based on the survey, three profiles of train managers were developed. The first is the passenger-orientated employee. A person who is open to the needs of co-workers and passengers, who easily establishes contact with the environment, who can empathise with others, who is patient, who adapts to situations as they arise, who is open to change, who builds on personal relationships, who shortens the existing distance between superior and subordinate, and who reacts quickly to problems as they arise. An adequate type of service has been developed for these characteristics, as shown in Table 1:

Table 1 Description of the preferred tasks: passenger-orientated train managers

| Route | Vehicles | Co-workers | Passengers | Schedule |
|---|---|---|---|---|
| quiet, single route with a known level of disturbance; | modern/automated/ requiring proficiency in computer and automated systems. | lack of autonomy in action, seeking solutions from colleagues; | repeaters / people who commute daily to work / school | no need to work in a hurry; |

The second group is duty-orientated. This is a person with a high knowledge of the applicable regulations, who is inflexible, orderly, follows the applicable standards and regulations, carries out assigned tasks in a meticulous and detailed manner, thoughtfully makes decisions, and builds hierarchical relationships in which the separation of superior and subordinate is clearly outlined. An adequate type of service has been developed for these characteristics, as shown in Table 2:

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Table 2 Description of preferred tasks - duty-orientated train managers

| Route | Vehicles | Co-workers | Passengers | Schedule |
|---|---|---|---|---|
| quiet, single-route | modern/automated/ requiring proficiency in computer and automated systems. | giving instructions, no group decision required; | mostly passengers of express trains, international trains | repetitive courses and routines; |

The third group is the balanced type. A disciplined and orderly person looking for the optimum solution in problematic situations based on the rules in force and the opportunities present, following procedures but able to abandon them if a critical analysis of the situation shows a low level of efficiency or effectiveness in their application, open to change and challenges but maintaining a rational assessment of the situation at hand, making decisions in a considered manner but taking into account the time resources available. An appropriate service type has been developed for these characteristics, as shown in Table 3.

Table 3 Description of preferred tasks – balanced train managers

| Route | Vehicles | Co-workers | Passengers | Schedule |
|---|---|---|---|---|
| with heavy traffic increasing the likelihood of conflicts with other trains / delays | any may be vulnerable | Dialogue, decisions made by looking for the best solution available, and the need to control colleagues resulting from | Copes with demanding passengers | high number of trips per time unit; |

Another survey was then carried out in cooperation with the railway company. This time, the trainers grouped the employees according to the above criteria, who were then invited to participate in an anonymous survey dedicated to the employee group. Within a given question, respondents ranked the predefined answers from least important (in which case they assigned the number 1) to most important. Among all the questions, for six questions, a variation in responses was observed according to employee type:

1. C1. Indication of the most effective team management style (1 – least important, 5 – most important):
   - I listen to the team of conductors, and we plan activities together and hold them accountable (control) as a team,
   - I define the tasks to be performed, identify the person responsible and then hold him/her accountable for the results.
   - I define the tasks to be performed, and I identify the persons who could perform them, but first, I determine whether they agree to it, I support them in the implementation, and I supervise the correct performance of the tasks,
   - I present the team with a list of tasks to be performed and expect them to share them and determine how to perform them, and I only monitor their performance afterwards.
   - other.
2. C2. Indicate the most stressful situations (1 – least stressful, 8 – most stressful):
   - aggressive passenger,
   - need to reroute the train / relocate passengers, e.g. due to damage on the train or an accident of another train,
   - a new member of the train crew who has no professional experience,
   - a significant delay/stop on the train service,
   - sudden loss of health of one of the passengers,
   - passengers having to travel in uncomfortable conditions (e.g. out of service toilet, no air conditioning),
   - suicide on the tracks
   - other.
3. C3. Ways of dealing with stressful situations (1 – least used, 5 – most used):
   - I lock myself in a compartment to think about possible alternative actions or solutions to the problem,
   - I call a meeting of the whole train crew to identify possible courses of action,
   - make the necessary decisions quickly, as response time is of the utmost importance;
   - I wait for the situation to develop and follow the procedures,
   - other.

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4. C4. What is most important in the daily work of a train manager (1 – least important, 6 – most important):
   - to know the procedures and stick to them regardless of the conditions that occur during work,
   - have a good relationship with the team and work in a pleasant atmosphere,
   - carry out repetitive journeys on the same routes with the same team,
   - operate on routes where there are no accidents and few 'difficult passengers',
   - have a well-organised team that knows its responsibilities and can react quickly in emergencies,
   - other.
5. C5. What is most important in emergencies (1 – least important, 7 – most important):
   - know the procedures and stick to them no matter what the conditions are during the work,
   - know who to call in order to be able to take quick action,
   - keep a cool head and wait for accidents to develop,
   - have a well-organised team that knows its responsibilities and can react quickly in an emergency,
   - ensure that passengers have access to basic information to keep them calm while waiting for a solution to be developed,
   - ensure that passengers have access to all information related to the emergency,
   - other.
6. C6. What makes a successful train manager (1 – least important, 6 – most important):
   - if I have a well-organised team that is cooperative and able to react quickly even in difficult emergencies,
   - if my employees feel satisfied with the performance of their daily duties and are not afraid of new professional challenges,
   - if I reach such a level of knowledge that I can/can advise other train managers with less experience/knowledge,
   - if I am paid in such a way that I am satisfied with my salary,
   - if I enjoy the respect of colleagues and company management,
   - other.

### 2.2. The fuzzy model for the assignment of railway workers to tasks, together with models for the evaluation and classification of railway workers

The method consists of two stages. First, a questionnaire about the employee's perception of the job is carried out. This is followed by inference based on the answers given and assignment to a particular group using fuzzy models.

A Mamdani-type fuzzy modelling method was used. A minimum approach was adopted for the 'and' relationship, and a maximum approach was adopted for 'or'. Implication is based on minima, while aggregation is based on maxima. Defuzzification is centroidal.

Interviews and questionnaires led to the emergence of ratings assigned to specific responses, which also characterised the types of employees involved. For each response, the mean value within the employee category was calculated. Then, it was examined using a parametric test for two averages at a significance level of alpha = 0.1 (comparing each with each) to see if a statistical conclusion could be drawn on the difference in these values. If such a difference was shown for two or three pairs, then a given response was found to be specific for one or two groups relative to the others. The given response became the assessment model's feature (and input variable).

As a result, the following responses were listed as characteristic, differentiating groups of employees:

1. C1 – Team management: I define the tasks to be performed myself; I identify the person responsible and then hold him/her accountable for the results.
2. C2 – Stress (three characteristic responses were identified, so a separate model was developed for this trait, which is the input to the total train manager model):
   - Stress: aggressive passenger
   - Stress: a new member of the train crew with no work experience
   - Stress: having to travel by passengers in uncomfortable conditions (e.g. out of service toilet, no air conditioning)

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3. C3 – Coping with Stress: I convene a meeting of the entire conductor team to identify possible courses of action.
4. C4 – The most important thing in daily work is to know the procedures and stick to them, regardless of the conditions during the work.
5. C5 – The most important in an emergency is to know who to call so that you can take quick action
6. C6 – Achieving success: If I reach a level of knowledge that I can/should advise other training managers with less experience/knowledge

Membership functions were developed for the input variables with the number of points assigned for a given response on the horizontal axis. A sub-model was developed for stressful situations in the main model. Details of the stress sub-model are presented in Figures 1–4 (input and output membership functions) and Table 4 (inference rules).

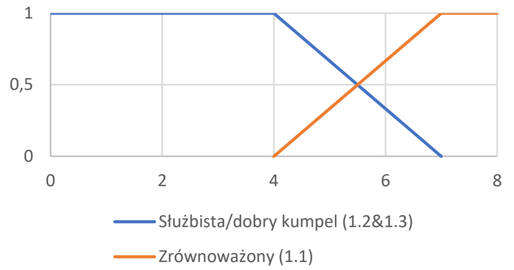


Figure 1 Membership functions for the input variable aggressive passenger of the stress submodel

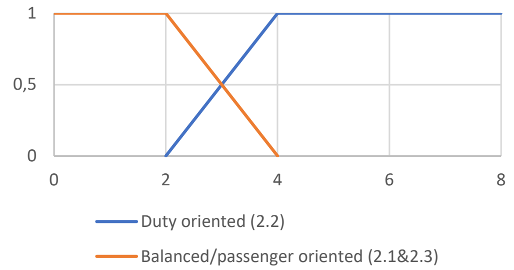


Figure 2 Membership functions for the input variable of the stress sub-model

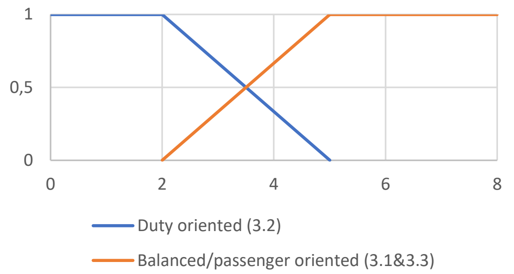


Figure 3 Membership functions for the stress sub-model input variable

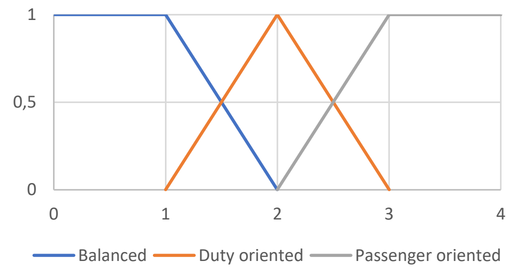


Figure 4 Membership functions for the stress sub-model output variable

Table 4 Inference rules for the stress situation model

| Rule | C1 | C2 | C3 | Type | Rule | C1 | C2 | C3 | Type |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.1 | 2.1&3 | 3.1&3 | 1 | 5 | 1.2&3 | 2.1&3 | 3.1&3 | 3 |
| 2 | 1.1 | 2.1&3 | 3.2 | 1 | 6 | 1.2&3 | 2.1&3 | 3.2 | 2 |
| 3 | 1.1 | 2.2 | 3.1&3 | 3 | 7 | 1.2&3 | 2.2 | 3.1&3 | 3 |
| 4 | 1.1 | 2.2 | 3.2 | 2 | 8 | 1.2&3 | 2.2 | 3.2 | 2 |

The types of membership functions have been chosen in cooperation with experts from the rail industry. The characteristic values of these functions are the result of the survey performed. According to the elaborated classification rules, the instructors divided the employees into types and then anonymised the responses in the given category. The rounded to the integer average values were used for the characteristic point elaboration.

Sometimes, membership functions are combined for two types of employees. This results in close average values and a positive result from the parametric test on the equality of two means. A team of scientists and experts from the rail industry has developed the inference rules presented in Table 4.

The same approach has been used for the overall model. The types of functions have been chosen by cooperation between scientists and experts from the rail industry. The characteristic values of these functions also result from the same survey conducted by volunteer train managers.

There are six input variables and one output variable. Their membership functions are presented in Figures 5–11. The 144 inference rules are shown in Tables 5 and Table 6.

https://doi.org/10.55343/CogSust.108

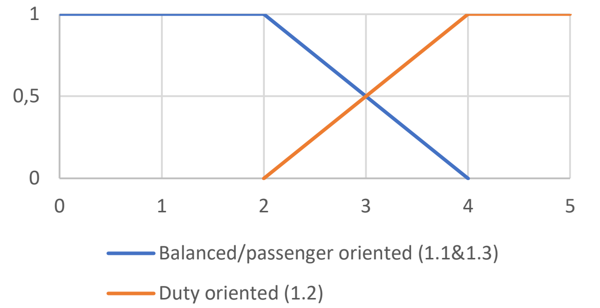


Figure 5 Membership functions for input variable C1 – Team management: I define the tasks to be performed myself; I identify the person responsible and then hold him/her accountable for the results.

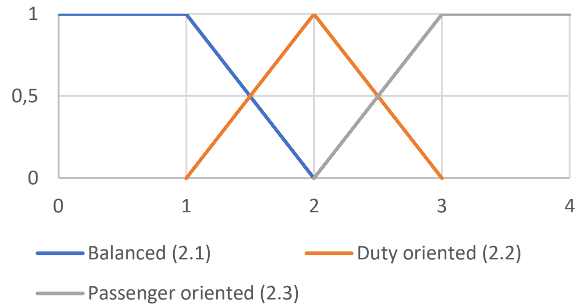


Figure 6 Membership functions for input variable C2 – Stress

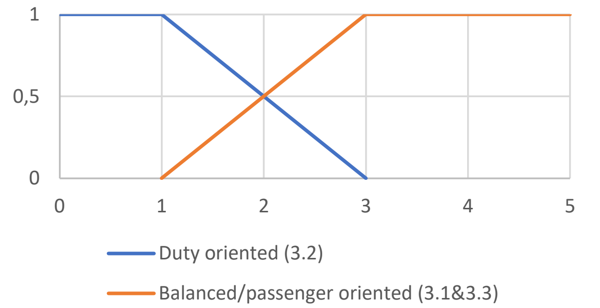


Figure 7 Membership functions for input variable C3 – dealing with stress: I convene a meeting of the entire conductor team to identify possible courses of action.

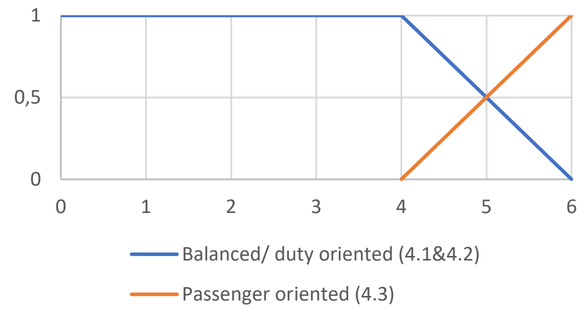


Figure 8 Membership functions for input variable C4 – The most important in daily work: know the procedures and stick to them, whatever the conditions during the work

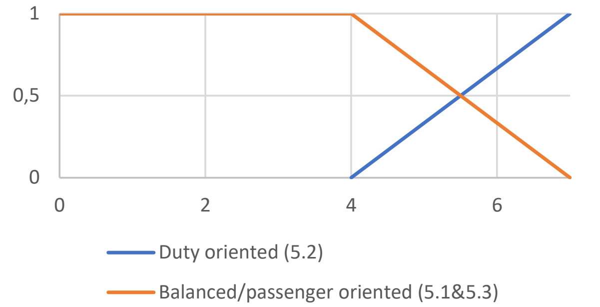


Figure 9 Membership functions for input variable C5 – The most important in an emergency: Know who to call so you can take quick action

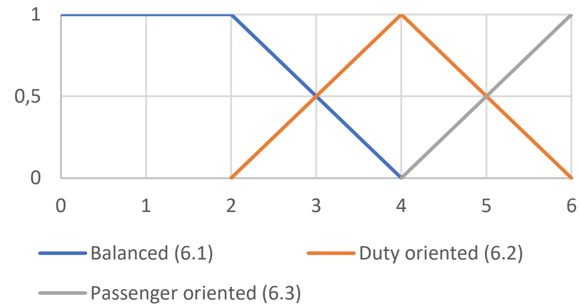


Figure 10 Membership functions for input variable C6 – Achieving success: if I reach a level of knowledge that I can/should advise other train managers with less experience/knowledge

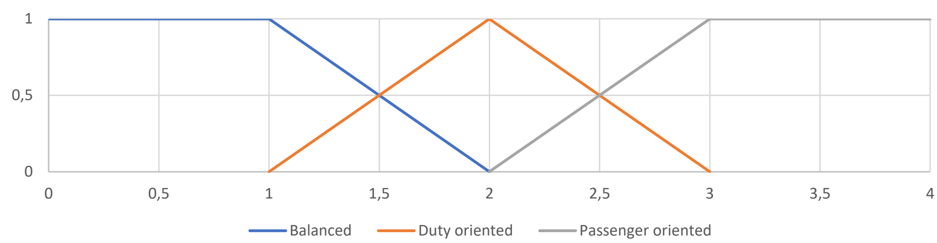


Figure 11 Membership functions for the output variable of the evaluation of the train driver category

https://doi.org/10.55343/CogSust.108

Table 5 Inference rules 1–100 for the model for assigning categories to a train driver

| Rule | C1 | C2 | C3 | C4 | C5 | C6 | Type | Rule | C1 | C2 | C3 | C4 | C5 | C6 | Type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1.1&3 | 2.1 | 3.1&3 | 4.1&2 | 5.1&3 | 6.1 | 1 | **51** | 1.1&3 | 2.3 | 3.1&3 | 4.1&2 | 5.1&3 | 6.3 | 3 |
| **2** | 1.1&3 | 2.1 | 3.1&3 | 4.1&2 | 5.1&3 | 6.2 | 1 | **52** | 1.1&3 | 2.3 | 3.1&3 | 4.1&2 | 5.2 | 6.1 | 1 |
| **3** | 1.1&3 | 2.1 | 3.1&3 | 4.1&2 | 5.1&3 | 6.3 | 1 | **53** | 1.1&3 | 2.3 | 3.1&3 | 4.1&2 | 5.2 | 6.2 | 2 |
| **4** | 1.1&3 | 2.1 | 3.1&3 | 4.1&2 | 5.2 | 6.1 | 1 | **54** | 1.1&3 | 2.3 | 3.1&3 | 4.1&2 | 5.2 | 6.3 | 3 |
| **5** | 1.1&3 | 2.1 | 3.1&3 | 4.1&2 | 5.2 | 6.2 | 2 | **55** | 1.1&3 | 2.3 | 3.1&3 | 4.3 | 5.1&3 | 6.1 | 3 |
| **6** | 1.1&3 | 2.1 | 3.1&3 | 4.1&2 | 5.2 | 6.3 | 1 | **56** | 1.1&3 | 2.3 | 3.1&3 | 4.3 | 5.1&3 | 6.2 | 3 |
| **7** | 1.1&3 | 2.1 | 3.1&3 | 4.3 | 5.1&3 | 6.1 | 1 | **57** | 1.1&3 | 2.3 | 3.1&3 | 4.3 | 5.1&3 | 6.3 | 3 |
| **8** | 1.1&3 | 2.1 | 3.1&3 | 4.3 | 5.1&3 | 6.2 | 3 | **58** | 1.1&3 | 2.3 | 3.1&3 | 4.3 | 5.2 | 6.1 | 3 |
| **9** | 1.1&3 | 2.1 | 3.1&3 | 4.3 | 5.1&3 | 6.3 | 3 | **59** | 1.1&3 | 2.3 | 3.1&3 | 4.3 | 5.2 | 6.2 | 3 |
| **10** | 1.1&3 | 2.1 | 3.1&3 | 4.3 | 5.2 | 6.1 | 1 | **60** | 1.1&3 | 2.3 | 3.1&3 | 4.3 | 5.2 | 6.3 | 3 |
| **11** | 1.1&3 | 2.1 | 3.1&3 | 4.3 | 5.2 | 6.2 | 2 | **61** | 1.1&3 | 2.3 | 3.2 | 4.1&2 | 5.1&3 | 6.1 | 1 |
| **12** | 1.1&3 | 2.1 | 3.1&3 | 4.3 | 5.2 | 6.3 | 3 | **62** | 1.1&3 | 2.3 | 3.2 | 4.1&2 | 5.1&3 | 6.2 | 2 |
| **13** | 1.1&3 | 2.1 | 3.2 | 4.1&2 | 5.1&3 | 6.1 | 1 | **63** | 1.1&3 | 2.3 | 3.2 | 4.1&2 | 5.1&3 | 6.3 | 3 |
| **14** | 1.1&3 | 2.1 | 3.2 | 4.1&2 | 5.1&3 | 6.2 | 2 | **64** | 1.1&3 | 2.3 | 3.2 | 4.1&2 | 5.2 | 6.1 | 2 |
| **15** | 1.1&3 | 2.1 | 3.2 | 4.1&2 | 5.1&3 | 6.3 | 3 | **65** | 1.1&3 | 2.3 | 3.2 | 4.1&2 | 5.2 | 6.2 | 2 |
| **16** | 1.1&3 | 2.1 | 3.2 | 4.1&2 | 5.2 | 6.1 | 1 | **66** | 1.1&3 | 2.3 | 3.2 | 4.1&2 | 5.2 | 6.3 | 2 |
| **17** | 1.1&3 | 2.1 | 3.2 | 4.1&2 | 5.2 | 6.2 | 2 | **67** | 1.1&3 | 2.3 | 3.2 | 4.3 | 5.1&3 | 6.1 | 3 |
| **18** | 1.1&3 | 2.1 | 3.2 | 4.1&2 | 5.2 | 6.3 | 2 | **68** | 1.1&3 | 2.3 | 3.2 | 4.3 | 5.1&3 | 6.2 | 3 |
| **19** | 1.1&3 | 2.1 | 3.2 | 4.3 | 5.1&3 | 6.1 | 1 | **69** | 1.1&3 | 2.3 | 3.2 | 4.3 | 5.1&3 | 6.3 | 3 |
| **20** | 1.1&3 | 2.1 | 3.2 | 4.3 | 5.1&3 | 6.2 | 2 | **70** | 1.1&3 | 2.3 | 3.2 | 4.3 | 5.2 | 6.1 | 3 |
| **21** | 1.1&3 | 2.1 | 3.2 | 4.3 | 5.1&3 | 6.3 | 3 | **71** | 1.1&3 | 2.3 | 3.2 | 4.3 | 5.2 | 6.2 | 2 |
| **22** | 1.1&3 | 2.1 | 3.2 | 4.3 | 5.2 | 6.1 | 1 | **72** | 1.1&3 | 2.3 | 3.2 | 4.3 | 5.2 | 6.3 | 3 |
| **23** | 1.1&3 | 2.1 | 3.2 | 4.3 | 5.2 | 6.2 | 2 | **73** | 1.2 | 2.1 | 3.1&3 | 4.1&2 | 5.1&3 | 6.1 | 1 |
| **24** | 1.1&3 | 2.1 | 3.2 | 4.3 | 5.2 | 6.3 | 3 | **74** | 1.2 | 2.1 | 3.1&3 | 4.1&2 | 5.1&3 | 6.2 | 2 |
| **25** | 1.1&3 | 2.2 | 3.1&3 | 4.1&2 | 5.1&3 | 6.1 | 1 | **75** | 1.2 | 2.1 | 3.1&3 | 4.1&2 | 5.1&3 | 6.3 | 1 |
| **26** | 1.1&3 | 2.2 | 3.1&3 | 4.1&2 | 5.1&3 | 6.2 | 2 | **76** | 1.2 | 2.1 | 3.1&3 | 4.1&2 | 5.2 | 6.1 | 1 |
| **27** | 1.1&3 | 2.2 | 3.1&3 | 4.1&2 | 5.1&3 | 6.3 | 3 | **77** | 1.2 | 2.1 | 3.1&3 | 4.1&2 | 5.2 | 6.2 | 2 |
| **28** | 1.1&3 | 2.2 | 3.1&3 | 4.1&2 | 5.2 | 6.1 | 2 | **78** | 1.2 | 2.1 | 3.1&3 | 4.1&2 | 5.2 | 6.3 | 2 |
| **29** | 1.1&3 | 2.2 | 3.1&3 | 4.1&2 | 5.2 | 6.2 | 2 | **79** | 1.2 | 2.1 | 3.1&3 | 4.3 | 5.1&3 | 6.1 | 1 |
| **30** | 1.1&3 | 2.2 | 3.1&3 | 4.1&2 | 5.2 | 6.3 | 2 | **80** | 1.2 | 2.1 | 3.1&3 | 4.3 | 5.1&3 | 6.2 | 2 |
| **31** | 1.1&3 | 2.2 | 3.1&3 | 4.3 | 5.1&3 | 6.1 | 3 | **81** | 1.2 | 2.1 | 3.1&3 | 4.3 | 5.1&3 | 6.3 | 3 |
| **32** | 1.1&3 | 2.2 | 3.1&3 | 4.3 | 5.1&3 | 6.2 | 2 | **82** | 1.2 | 2.1 | 3.1&3 | 4.3 | 5.2 | 6.1 | 1 |
| **33** | 1.1&3 | 2.2 | 3.1&3 | 4.3 | 5.1&3 | 6.3 | 3 | **83** | 1.2 | 2.1 | 3.1&3 | 4.3 | 5.2 | 6.2 | 2 |
| **34** | 1.1&3 | 2.2 | 3.1&3 | 4.3 | 5.2 | 6.1 | 2 | **84** | 1.2 | 2.1 | 3.1&3 | 4.3 | 5.2 | 6.3 | 3 |
| **35** | 1.1&3 | 2.2 | 3.1&3 | 4.3 | 5.2 | 6.2 | 2 | **85** | 1.2 | 2.1 | 3.2 | 4.1&2 | 5.1&3 | 6.1 | 1 |
| **36** | 1.1&3 | 2.2 | 3.1&3 | 4.3 | 5.2 | 6.3 | 3 | **86** | 1.2 | 2.1 | 3.2 | 4.1&2 | 5.1&3 | 6.2 | 2 |
| **37** | 1.1&3 | 2.2 | 3.2 | 4.1&2 | 5.1&3 | 6.1 | 2 | **87** | 1.2 | 2.1 | 3.2 | 4.1&2 | 5.1&3 | 6.3 | 2 |
| **38** | 1.1&3 | 2.2 | 3.2 | 4.1&2 | 5.1&3 | 6.2 | 2 | **88** | 1.2 | 2.1 | 3.2 | 4.1&2 | 5.2 | 6.1 | 2 |
| **39** | 1.1&3 | 2.2 | 3.2 | 4.1&2 | 5.1&3 | 6.3 | 2 | **89** | 1.2 | 2.1 | 3.2 | 4.1&2 | 5.2 | 6.2 | 2 |
| **40** | 1.1&3 | 2.2 | 3.2 | 4.1&2 | 5.2 | 6.1 | 2 | **90** | 1.2 | 2.1 | 3.2 | 4.1&2 | 5.2 | 6.3 | 2 |
| **41** | 1.1&3 | 2.2 | 3.2 | 4.1&2 | 5.2 | 6.2 | 2 | **91** | 1.2 | 2.1 | 3.2 | 4.3 | 5.1&3 | 6.1 | 1 |
| **42** | 1.1&3 | 2.2 | 3.2 | 4.1&2 | 5.2 | 6.3 | 2 | **92** | 1.2 | 2.1 | 3.2 | 4.3 | 5.1&3 | 6.2 | 2 |
| **43** | 1.1&3 | 2.2 | 3.2 | 4.3 | 5.1&3 | 6.1 | 2 | **93** | 1.2 | 2.1 | 3.2 | 4.3 | 5.1&3 | 6.3 | 3 |
| **44** | 1.1&3 | 2.2 | 3.2 | 4.3 | 5.1&3 | 6.2 | 2 | **94** | 1.2 | 2.1 | 3.2 | 4.3 | 5.2 | 6.1 | 2 |
| **45** | 1.1&3 | 2.2 | 3.2 | 4.3 | 5.1&3 | 6.3 | 3 | **95** | 1.2 | 2.1 | 3.2 | 4.3 | 5.2 | 6.2 | 2 |
| **46** | 1.1&3 | 2.2 | 3.2 | 4.3 | 5.2 | 6.1 | 2 | **96** | 1.2 | 2.1 | 3.2 | 4.3 | 5.2 | 6.3 | 2 |
| **47** | 1.1&3 | 2.2 | 3.2 | 4.3 | 5.2 | 6.2 | 2 | **97** | 1.2 | 2.2 | 3.1&3 | 4.1&2 | 5.1&3 | 6.1 | 2 |
| **48** | 1.1&3 | 2.2 | 3.2 | 4.3 | 5.2 | 6.3 | 2 | **98** | 1.2 | 2.2 | 3.1&3 | 4.1&2 | 5.1&3 | 6.2 | 2 |
| **49** | 1.1&3 | 2.3 | 3.1&3 | 4.1&2 | 5.1&3 | 6.1 | 1 | **99** | 1.2 | 2.2 | 3.1&3 | 4.1&2 | 5.1&3 | 6.3 | 2 |
| **50** | 1.1&3 | 2.3 | 3.1&3 | 4.1&2 | 5.1&3 | 6.2 | 3 | **100** | 1.2 | 2.2 | 3.1&3 | 4.1&2 | 5.2 | 6.1 | 2 |

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Table 6 Inference rules 81–144 for the model for assigning categories to a train driver

| Rule | C1 | C2 | C3 | C4 | C5 | C6 | Type | Rule | C1 | C2 | C3 | C4 | C5 | C6 | Type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **101** | 1.2 | 2.2 | 3.1&3 | 4.1&2 | 5.2 | 6.2 | 2 | **123** | 1.2 | 2.3 | 3.1&3 | 4.1&2 | 5.1&3 | 6.3 | 3 |
| **102** | 1.2 | 2.2 | 3.1&3 | 4.1&2 | 5.2 | 6.3 | 2 | **124** | 1.2 | 2.3 | 3.1&3 | 4.1&2 | 5.2 | 6.1 | 2 |
| **103** | 1.2 | 2.2 | 3.1&3 | 4.3 | 5.1&3 | 6.1 | 2 | **125** | 1.2 | 2.3 | 3.1&3 | 4.1&2 | 5.2 | 6.2 | 2 |
| **104** | 1.2 | 2.2 | 3.1&3 | 4.3 | 5.1&3 | 6.2 | 2 | **126** | 1.2 | 2.3 | 3.1&3 | 4.1&2 | 5.2 | 6.3 | 3 |
| **105** | 1.2 | 2.2 | 3.1&3 | 4.3 | 5.1&3 | 6.3 | 3 | **127** | 1.2 | 2.3 | 3.1&3 | 4.3 | 5.1&3 | 6.1 | 3 |
| **106** | 1.2 | 2.2 | 3.1&3 | 4.3 | 5.2 | 6.1 | 2 | **128** | 1.2 | 2.3 | 3.1&3 | 4.3 | 5.1&3 | 6.2 | 3 |
| **107** | 1.2 | 2.2 | 3.1&3 | 4.3 | 5.2 | 6.2 | 2 | **129** | 1.2 | 2.3 | 3.1&3 | 4.3 | 5.1&3 | 6.3 | 3 |
| **108** | 1.2 | 2.2 | 3.1&3 | 4.3 | 5.2 | 6.3 | 2 | **130** | 1.2 | 2.3 | 3.1&3 | 4.3 | 5.2 | 6.1 | 3 |
| **109** | 1.2 | 2.2 | 3.2 | 4.1&2 | 5.1&3 | 6.1 | 2 | **131** | 1.2 | 2.3 | 3.1&3 | 4.3 | 5.2 | 6.2 | 2 |
| **110** | 1.2 | 2.2 | 3.2 | 4.1&2 | 5.1&3 | 6.2 | 2 | **132** | 1.2 | 2.3 | 3.1&3 | 4.3 | 5.2 | 6.3 | 3 |
| **111** | 1.2 | 2.2 | 3.2 | 4.1&2 | 5.1&3 | 6.3 | 2 | **133** | 1.2 | 2.3 | 3.2 | 4.1&2 | 5.1&3 | 6.1 | 2 |
| **112** | 1.2 | 2.2 | 3.2 | 4.1&2 | 5.2 | 6.1 | 2 | **134** | 1.2 | 2.3 | 3.2 | 4.1&2 | 5.1&3 | 6.2 | 2 |
| **113** | 1.2 | 2.2 | 3.2 | 4.1&2 | 5.2 | 6.2 | 2 | **135** | 1.2 | 2.3 | 3.2 | 4.1&2 | 5.1&3 | 6.3 | 3 |
| **114** | 1.2 | 2.2 | 3.2 | 4.1&2 | 5.2 | 6.3 | 2 | **136** | 1.2 | 2.3 | 3.2 | 4.1&2 | 5.2 | 6.1 | 2 |
| **115** | 1.2 | 2.2 | 3.2 | 4.3 | 5.1&3 | 6.1 | 2 | **137** | 1.2 | 2.3 | 3.2 | 4.1&2 | 5.2 | 6.2 | 2 |
| **116** | 1.2 | 2.2 | 3.2 | 4.3 | 5.1&3 | 6.2 | 2 | **138** | 1.2 | 2.3 | 3.2 | 4.1&2 | 5.2 | 6.3 | 2 |
| **117** | 1.2 | 2.2 | 3.2 | 4.3 | 5.1&3 | 6.3 | 2 | **139** | 1.2 | 2.3 | 3.2 | 4.3 | 5.1&3 | 6.1 | 3 |
| **118** | 1.2 | 2.2 | 3.2 | 4.3 | 5.2 | 6.1 | 2 | **140** | 1.2 | 2.3 | 3.2 | 4.3 | 5.1&3 | 6.2 | 2 |
| **119** | 1.2 | 2.2 | 3.2 | 4.3 | 5.2 | 6.2 | 2 | **141** | 1.2 | 2.3 | 3.2 | 4.3 | 5.1&3 | 6.3 | 3 |
| **120** | 1.2 | 2.2 | 3.2 | 4.3 | 5.2 | 6.3 | 2 | **142** | 1.2 | 2.3 | 3.2 | 4.3 | 5.2 | 6.1 | 2 |
| **121** | 1.2 | 2.3 | 3.1&3 | 4.1&2 | 5.1&3 | 6.1 | 1 | **143** | 1.2 | 2.3 | 3.2 | 4.3 | 5.2 | 6.2 | 2 |
| **122** | 1.2 | 2.3 | 3.1&3 | 4.1&2 | 5.1&3 | 6.2 | 2 | **144** | 1.2 | 2.3 | 3.2 | 4.3 | 5.2 | 6.3 | 3 |

As a result, values from 0 to 4 are obtained (Figure 11). Some margin is left to interpret the results by experts for the range from 1.0–1.5 (a mixture of balanced and duty-orientated) and for the range 2.5–3.0 (a mixture of passenger-orientated and duty-orientated). In the other cases:

- 0 to 1 – balanced,
- 1.5 to 2.5 – duty-orientated,
- 3.0 to 4.0 – passenger-orientated.

## 3. Results and Validation

To validate the method, a sample of people was given a questionnaire as a data source for the models assigning staff categories (as described earlier). A second part of the questionnaire was prepared, in which they were asked to give answers characterising the services (self-assessment). It was done according to the description placed in Tables 1–3.

A section on the level of errors and shortcomings within the service followed this. For each question, the respondent could give one of four answers: agree, possibly, disagree, or not applicable.

- I sometimes lack time to fulfil all my duties,
- It bothers me when I have to finish tasks after work,
- I can cope with situations where I have delayed the train,
- I would prefer a different way of managing the team to which I belong,
- I usually find working with people (passengers or co-workers) difficult.

The results were analysed in three steps. First, an employee category was assigned according to the method. Then, a team of scientists and experts determined from the answers in the second part of the questionnaire which types of tasks the employee performed on the job (the team did not know at the time which category was assigned according to the method). In the final step, the team evaluated the third part of the questionnaire and determined whether the employee had indicated significant difficulties in the tasks that he or she performed. After this, the database was merged. The occurrence of

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significant errors on the job was assigned if the train manager indicated a response of at least 'possibly' for at least four questions or agreed on at least two questions.

The results of the experiment performed are shown in Table 7. In this part, 41 volunteers working as train managers participated. The respondents were not the same as in the previous survey,

Table 7 Validation of the method

| Category – Method score | Description of tasks according to the self-assessment | Are there any significant errors/defects in the performance of tasks on the job? | Should there be any failures according to the method, | Result |
|---|---|---|---|---|
| Passenger-orientated | Passenger-orientated | No. | No. | Correct. |
| Passenger-orientated | Passenger-orientated | No. | No. | Correct. |
| Passenger-orientated | Duty-orientated | yes, | yes, | Correct. |
| **Passenger-orientated** | **Passenger-orientated** | **yes,** | **No.** | **Not correct.** |
| **Passenger-orientated** | **Balanced** | **No.** | **yes,** | **Not correct.** |
| Duty-orientated | Passenger-orientated | yes, | yes, | Correct. |
| Duty-orientated | Duty-orientated | No. | No. | Correct. |
| Duty-orientated | Duty-orientated | No. | No. | Correct. |
| Duty-orientated | Balanced | yes, | yes, | Correct. |
| Balanced | Duty-orientated | yes, | yes, | Correct. |
| Duty-orientated | Balanced | yes, | yes, | Correct. |
| **Balanced** | **Passenger-orientated** | **No.** | **yes,** | **Not correct.** |
| Balanced | Balanced | No. | No. | Correct. |
| Balanced | Balanced | No. | No. | Correct. |
| Passenger-orientated | Balanced | yes, | yes, | Correct. |
| Duty-orientated | Balanced | yes, | yes, | Correct. |
| **Balanced** | **Balanced** | **yes,** | **No.** | **Not correct.** |
| Passenger-orientated | Passenger-orientated | No. | No. | Correct. |
| Passenger-orientated | Passenger-orientated | No. | No. | Correct. |
| Passenger-orientated | Balanced | yes, | yes, | Correct. |
| Passenger-orientated | Duty-orientated | yes, | yes, | Correct. |
| Passenger-orientated | Passenger-orientated | No. | No. | Correct. |
| Passenger-orientated | Balanced | yes, | yes, | Correct. |
| Passenger-orientated | Balanced | yes, | yes, | Correct. |
| Balanced | Balanced | No. | No. | Correct. |
| **Duty-orientated** | **Passenger-orientated** | **No.** | **yes,** | **Not correct.** |
| Duty-orientated | Passenger-orientated | yes, | yes, | Correct. |
| Duty-orientated | Duty-orientated | yes, | yes, | Correct. |
| Duty-orientated | Duty-orientated | No. | No. | Correct. |
| Duty-orientated | Balanced | yes, | yes, | Correct. |
| Passenger-orientated | Passenger-orientated | No. | No. | Correct. |
| Duty-orientated | Duty-orientated | No. | No. | Correct. |
| **Duty-orientated** | **Duty-orientated** | **yes,** | **No.** | **Not correct.** |
| Duty-orientated | Duty-orientated | No. | No. | Correct. |
| Duty-orientated | Duty-orientated | No. | No. | Correct. |
| Balanced | Balanced | No. | No. | Correct. |
| Balanced | Balanced | No. | No. | Correct. |
| **Duty-orientated** | **Duty-orientated** | **yes,** | **No.** | **Not correct.** |
| **Balanced** | **Balanced** | **yes,** | **No.** | **Not correct.** |
| Balanced | Balanced | No. | No. | Correct. |
| Balanced | Balanced | No. | No. | Correct. |

Of 41 volunteers, 17 were women and 24 men. The youngest volunteer was 34 years old, and the oldest was 56 years old. The first column of Table 7 shows the train manager category of the volunteers according to the presented method. The second column presents the real job description they do. The third column informs if the personnel have regular difficulties in the job. The next column indicates whether there should be difficulties based on discrepancies between the category resulting from the model and the description of the survey participants. Finally, the last column shows if there is a correlation between the model and the real data.

Five out of 41 participants were incorrectly evaluated. Their category seems correct, but significant difficulties occur during the job performance. On the other hand, 3 of the 41 volunteers had no match, but no significant difficulties were noted at the same time. It means that 80.5% of analysed train managers have been assigned to groups correctly (Results: Correct – 33 persons), 7.3 % have been assigned incorrectly (they should have no difficulties, but they have) (Results: not correct – Difficulty: yes – 3 persons) and the remaining 12.2 % (Results: not correct – Difficulty: no – 5 persons) should have difficulties according to the model, but they do not have.

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## 4. Conclusions

The paper aimed to show that personal qualities may influence personnel performance regarding employee tasks. A large-scale survey has been performed to identify the train manager categories. The final validation experiment with 41 people shows that the model worked correctly for 80.5%. It also means that a proper assignment of tasks influences the scale of difficulties during job duties. Answering the research questions, it is possible to prepare a combination of profiles and duty types, and the people who are properly assigned have fewer difficulties in their daily jobs.

In the experiment, 7.3% of participants were identified as not properly assigned according to the model, and they had, in fact, significant difficulties in their daily jobs. At the same time, 12.2% of the participants were also identified as not properly assigned, but they had no significant job problems. However, the experiment should be confirmed in additional research.

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# Cognitive tools for enhancing sustainability in liquid fuel and internal combustion engine development

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**Abstract**

This paper reviews the literature on cognitive tools applied in developing internal combustion engines (ICE) and liquid fuels, focusing on modeling, simulation, data collection, and AI applications. Methods include 0D and 1D models, 3D-CFD (Computational Fluid Dynamics) simulations, real-world calculations, advanced data acquisition, and AI frameworks. Results indicate that these tools enhance development efficiency, reduce environmental impact, and promote sustainable technologies. The conclusion highlights the transformative potential of cognitive tools for sustainable mobility solutions.

**Keywords**

cognitive tools, sustainability, mobility, liquid fuels, internal combustion engine

## 1. Introduction

With the interplay between mobility and advancements in information technology, the cognitive dimension of mobility is getting stronger. Modern mobility, transport and its management, the development and production of vehicles, related social sciences, artificial intelligence and its applications, and cognitive info-communication are intertwined. This space is described by the concept of cognitive mobility (Zöldy et al., 2024). The main purpose of this concept is to give a holistic picture of mobility and interpret it in a broad space. This approach reveals what new cognitive abilities can be built into mobility and how transport can be optimised at the system level. A cognitive approach to fuel and motor propellant development helps bridge the gap between chemical engineers who develop liquid propellants and vehicle engineers who develop vehicles (Zöldy and Baranyi, 2023).

The increasing importance of safety aspects was the first driving force that positively influenced the cognitive level of vehicles. The safety devices were mainly mechanical aids for the driver at the beginning. In recent decades, the role of driver assistance devices in vehicles has increased. Research has increasingly focused on the potential benefits and pitfalls of using artificial and natural approaches to designing intelligent systems that can perceive, interact, learn, and make decisions.

Cognitive tools play an increasingly important role in development as well. They speed up the development processes, reduce asset costs, and increase the possibility of variation. Making the development process more efficient reduces its environmental footprint and helps new results spread more quickly, thus reducing the environmental impact. This study reviews the literature on cognitive tools used during virtual engine development, focusing specifically on the applicability of modeling and validation tools, advanced data collection, and artificial intelligence.

## 2. Modeling and Simulation Tools

The cognitive approach in virtual engine development is based on a well-considered integration of three main simulation areas: (i) 0D and one-dimensional models, (ii) 3D-CFD (Computational Fluid Dynamics) Simulations, and (iii) the real working process calculations. Due to their very different temporal and spatial resolution, these simulation areas have different modeling and input requirements; thus, their fields of application also vary. They differ widely in complexity, predictive ability, and computation time. The computation time comparison of the three areas is presented in Figure 1.

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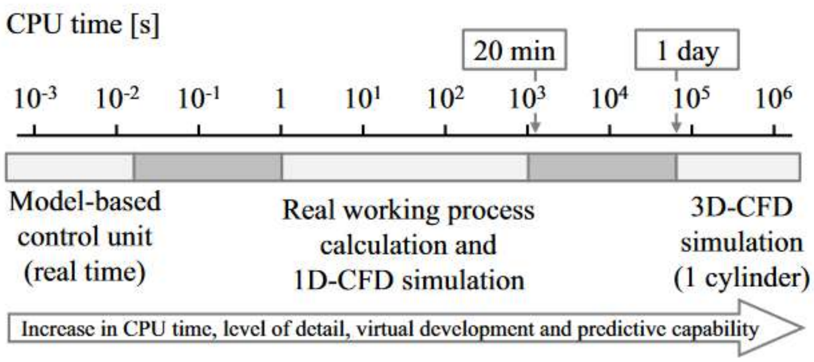


Figure 1. Computational time comparison (Wentsch, 2019)

Modelling and simulation are crucial in developing internal combustion engines and liquid fuels; thus, it is imperative to strengthen their role in future sustainable mobility. Simulation tools help in the development process to understand complex physical and chemical processes, optimise engine performance and reduce emissions. With the help of accurate, verified simulations and the increasing number of cases that can be examined, choosing a good solution for a wide array of problems will become easier.

### 2.1. 0D and 1D Models

0D and 1D models can be used for fast calculations and system-level simulations. Zero-dimensional (0D) models focus on the thermodynamic processes inside the engine. These models only consider time, not the spatial dependence of temperature and concentration distribution parameters. In these models, the variable conditions of the combustion chamber within an engine operating cycle are described by the generally valid differential equations of the mass and energy balance and the thermal equation of the state of the working fluid (Wentsch, 2019).

1D-CFD (Computational Fluid Dynamics) simulations of internal combustion engines are particularly convenient for investigating different engine strategies (gas exchange processes, i.e. valve timing, turbocharging). They are also well suited to investigating transient engine operating conditions and their prediction to optimise the entire characteristic field. They can also be used, mainly due to their versatility, to study the entire behaviour of the vehicle (Nyerges and Zöldy, 2020).

The 1D-CFD models allow the rapid determination of many engine parameters and general design features, but they are limited when assessing the geometric effects on the flow field. The injection processes are highly three-dimensional and cannot be adequately described by 1D-CFD simulations (Kondor, 2024).

### 2.2. 3D-CFD Simulations

3D-CFD simulations are currently the most complex and comprehensive modelling approach for the numerical investigation of fluid dynamics problems. For this purpose, the internal combustion engine or its investigated part is discretised into a computational grid of many finite volumes. Its number of grid cells can reach the order of millions. This is the basis for calculating the reactive flow field, calculated using partial differential equations as a function of time and three spatial coordinates. Coupling mass, momentum and energy conservation equations with state equations enables a thorough description of the fluid flow inside the engine.

Three-dimensional computational fluid dynamics (3D-CFD) simulations provide detailed insights into combustion, fuel spray dynamics, and heat transfer. Tools like Ansys Forte and Converge CFD are commonly used for these simulations (Wentsch, 2019).

### 2.3. Real Working Process Calculations

This approach models the processes inside the cylinder using empirical and phenomenological models. It is also suitable for modelling combustion and emissions.

Thermodynamic modelling can be performed for one, two or more zone calculations. During the calculation, we assume perfect temperature and gas composition homogeneity within each zone. During combustion, the two-zone calculation divides the cylinder charge without spatial division of the zones into a burned zone containing high-temperature exhaust gas and an unburned zone containing fresh charge and residual exhaust gas. In the model, we assume that the flame front's

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thickness is negligible and can also be omitted thermodynamically. In contrast to the single-zone approach, this model provides information on the formation of emissions (primarily NO and CO) and the heat transfer of the wall, operating under the simplifying assumption that pressure p remains constant throughout the combustion chamber.

### 3. Data Acquisition Techniques

Data acquisition is essential for validating models and simulations and for real-time engine control and diagnostics.

#### 3.1. Engine Test Benches

One of the keys to engine and fuel development is engine brake pad measurements. The task is to keep all parameters constant except for the variable parameter (for example, octane number or density or compression end pressure on the engine side, injection time) to establish the sensitivity to the examined parameter (Valeika et al., 2024). With the development of modelling and simulations, an ever-increasing proportion of the researcher's work can be transferred to the virtual space. Key test values measure engine performance parameters such as torque, power, fuel consumption and emissions (Shepel et al., 2022). These systems almost always include pressure, temperature and flow sensors (Nagy, 2019). IC engine testing involves acquiring data from various engine-mounted sensors, the bench system, and IC engine control (Kaisan et al., 2020). The systems can be self-developed or purchased from the market. The most used sensors measure:

- braking torque,
- engine speed,
- engine performance,
- exhaust temperature,
- intake air pressure and temperature,
- coolant temperature,
- oil pressure and temperature,
- fuel and air mass flow,
- air-fuel ratio.

#### 3.2. In-Cylinder Pressure Sensors

Developing new technologies to reduce emissions and fuel consumption in internal combustion engines poses exciting challenges. In the case of spark-ignition engines, it is possible to increase combustion efficiency by approaching the knock limit. Alcohols mixed with or substituted for gasoline, with their high octane numbers, are a good example of accurate knocking and pressure loss monitoring.

Knock detection can be done using in-cylinder pressure sensors for effective combustion control in spark-ignition engines. However, their high cost and sensitivity to environmental influences limit their practical use on roads. Among the possible applications, the most cost-effective approach is to use accelerometer sensors placed on the surface of the motor. These can show sensitivity to knock. Although some gasoline vehicles are already equipped with knock sensors, the existing detection techniques require further improvements, such as improving the robustness of noise and speed, the ability to adapt to combustion conditions, and above all, the binary classification of "knock" or "non-knock" (Mrdja et al., 2019).

#### 3.3. Vibration and Acoustic Sensors

Acoustic sensors form the basis of time-frequency analyses, a technique better suited than standard Fourier transforms for capturing vibration signals with fixed non-stationary characteristics from accelerometers. Time-frequency plots offer deeper insights into vibration phenomena associated with knocking. The information provided by time-frequency techniques is essential for providing real-time closed-loop control methodology (Agocs et al., 2023). Time-frequency analysis of both the pressure traces and the vibration data is performed, and the results provide useful insights into the vibration signals associated with knocking (Ker et al., 2006). Leveraging this improved understanding, a real-time knock detection approach may be developed.

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## 4. Use of AI in Internal Combustion Engine and Liquid Fuel Development

Artificial intelligence (AI) and machine learning (ML) are increasingly used to enhance the development and optimisation of internal combustion engines and fuels. Introducing these cognitive tools in these areas also requires many resources due to the large data requirement of learning. However, using the devices directly (faster and more efficient developments) and indirectly (developing renewable, carbon dioxide-neutral propellants through them) promotes more sustainable mobility.

### 4.1. Fuel Design

Data-driven artificial intelligence (AI) frameworks facilitate the development of liquid propellants with tailored properties (Virt and Arnold, 2022). When used in an internal combustion engine, these increase efficiency and reduce carbon dioxide emissions (Zöldy, 2009; Yakovlieva et al., 2019 ). In one approach, fuel design can be viewed as a constrained optimisation problem (Kuzhagaliyeva et al., 2022)) with two main parts: (i) deep learning (DL) to predict the properties of pure components and mixtures and (ii) search algorithms to efficiently navigate the chemical space. This approach constructs the mixture hidden vector as a linear combination of the vectors of each component in each mixture. AI fuel design methods can be used to examine rapidly changing fuel compositions to optimise engine efficiency and reduce emissions. Artificial intelligence (AI) and machine learning (ML) are increasingly being used to enhance the development and optimisation of internal combustion engines and fuels (Cipriano et al., 2022).

### 4.2. Engine Performance Optimisation

The use of artificial neural networks in solving complex internal combustion engine problems is becoming increasingly widespread (Bhatt and Shrivastava, 2022). The processes taking place in the most widespread and researched engines, such as spark-ignition (SI), compression-ignition (CI) and homogeneous charge compression ignition (HCCI) engines, are investigated with various propellants, biodiesel, alcohol and gaseous fuels. The literature has shown different artificial neural network (ANN) models, such as multi-input–single-output and multi-input–multi-output approaches. Application of ANN can provide power and emission predictions, valve timing modelling, exhaust gas recirculation (EGR) rate estimation, knock intensity detection, noise prediction, , misfire detection, wall flux estimation, heat transfer coefficient modelling, engine wear determination and optimisation problems. Based on the literature analysis (Kumar et al., 2023), the number of neurons in the hidden layer between 10 and 20, as well as the logarithmic and tangent sigmoid transfer functions, give optimal results. Based on this, ANN can effectively predict the engine's complex performance, combustion, and emission characteristics and help cost-effectively search for sustainable alternative fuels that ensure advanced engine characteristics.

### 4.3. Co-optimisation of fuels and engines

The need to reduce the computation time and extend the simulated domain to the entire engine (including the 0D or the 3D turbocharged model) gave rise to combined development environments. Thanks to the combination of numerical models of injectors, fuels and combustion processes, these solutions meet the requirements of a fast and pragmatic virtual approach to promoting the industrial development of sustainable and environmentally friendly internal combustion engines of the future (Chiodi et al., 2024). Combined simulations have a robust methodology. They can simultaneously help engine development, optimise and characterise individual components, and discover new fuel solutions to optimise combustion efficiency and emissions. The effect of various fuels (hydrogen, methanol, synthetic and biofuels) on different engine geometries can be modelled and analysed through these systems.

## Conclusions

This study offered an overview of the cognitive tools whose application can facilitate the transformation of traditional technologies to more environmentally friendly solutions, such as the application of $CO_2$-neutral internal combustion engines and liquid fuels. The presented cognitive tool system is spreading daily and helps make processes and results more sustainable.

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# Environmental process maturity: A sustainable theoretical framework for Polish ports

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**Abstract**

Ports are critical nodes in global trade and logistics, playing a vital role in the sustainability agenda due to their significant environmental and social impacts. Despite increasing attention to sustainability, there is limited research on frameworks that holistically assess the environmental process maturity of ports, especially in the context of Polish ports. This study aims to address the gap by proposing a conceptual model to assess the environmental process maturity of ports, integrating environmental performance, stakeholder engagement, and regulatory alignment. The model focuses on providing actionable insights for port authorities to enhance sustainability. The study employs a conceptual approach, synthesising information from sustainability frameworks, Corporate and Social Responsibility (CSR) models, and maturity assessments. Key constructs are operationalised through specific indicators to evaluate maturity levels across five progressive stages – Initial, Developing, Established, Integrated, and Optimised. The model is tailored to the unique challenges of Polish ports and contextualised within broader European Union sustainability goals. The proposed model bridges the gap between theoretical sustainability principles and practical applications. It provides a structured framework to evaluate and improve environmental processes, offering a roadmap for ports to transition from basic compliance to strategic environmental leadership. The model's adaptability enables benchmarking and alignment with global best practices. This study contributes to the discourse on sustainable port management by introducing an integrative framework for assessing environmental process maturity. It provides theoretical advancements and practical tools for enhancing port sustainability performance, particularly in Polish and European contexts.

**Keywords**

Environmental process maturity, sustainable port management, stakeholder engagement, regulatory compliance, Polish ports.

## 1. Introduction

Ports are critical nodes in global trade and logistics networks, serving as gateways for the movement of goods across continents. Their strategic role extends beyond economic contributions to include environmental and social impacts, making them pivotal actors in the sustainability agenda. With increasing global attention on environmental challenges such as climate change, air pollution, and resource depletion, the operations of ports are now scrutinised for their environmental sustainability (Dávid et al., 2024; Peris-Mora et al., 2005). This scrutiny is amplified by their significant contributions to greenhouse gas emissions, noise pollution, and habitat degradation, necessitating proactive and integrated environmental strategies (Klimek et al., 2019; Sogut and Erdogan, 2022).

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While sustainability in ports has gained scholarly attention (Housni et al., 2022; Mańkowski and Charłampowicz, 2021), research has largely focused on individual measures such as energy efficiency, emissions reduction, or green certifications. There is limited understanding of how ports can holistically develop and assess the maturity of their environmental processes. Existing frameworks, such as those for digital transformation and corporate social responsibility, often lack the specificity to address the environmental complexities of port operations. This gap is particularly evident in Polish ports, which face unique challenges related to infrastructural constraints, regulatory frameworks, and aligning local practices with broader European Union sustainability goals (Argyriou et al., 2019; Notteboom et al., 2020).

This paper aims to address this gap by proposing a conceptual model for assessing the environmental process maturity of Polish ports. This study seeks to provide a structured approach to evaluate and guide environmental maturity by drawing from existing sustainability frameworks, maturity models, and empirical insights from port operations. The model will offer theoretical insights into environmental process integration and practical guidance for port authorities, policymakers, and stakeholders seeking to enhance sustainability performance.

As ports increasingly operate at the intersection of economic efficiency and environmental responsibility, this research is timely and necessary. Focusing on Polish ports, this study provides a contextualised understanding of environmental process maturity while contributing to broader discourses on sustainable port management. The findings aim to advance theoretical knowledge and offer actionable recommendations for achieving higher levels of environmental sustainability in the port sector (Charłampowicz and Mańkowski, 2024; Klimek et al., 2019; Notteboom et al., 2020; Sogut and Erdogan, 2022).

This paper is organised as follows: the next section comprehensively reviews the relevant literature. Section 3 introduces the conceptual framework for assessing environmental process maturity in ports. Section 4 discusses the proposed model, followed by an exploration of its theoretical contributions in Section 5. Managerial implications are addressed in Section 6. Finally, the concluding section summarises the key findings, outlines research limitations, and suggests directions for future studies.

## 2. Literature review

The theoretical foundation of this study is grounded in integrating sustainability frameworks and maturity models within the context of port operations. Sustainability in ports involves balancing economic growth, environmental protection, and social responsibility (Klimek et al., 2019). This study adopts a systemic perspective, viewing ports as complex systems where environmental process maturity reflects the extent to which environmental practices are integrated into operations, strategy, and stakeholder engagement.

Environmental sustainability in ports has traditionally been examined through the lenses of Corporate and Social Responsibility (CSR) and operational efficiency. Klimek et al. (2019) emphasise the role of CSR in fostering stakeholder engagement and environmental stewardship, particularly in Polish ports. However, current practices often remain fragmented, focusing on isolated initiatives such as emissions reduction or energy efficiency without a cohesive framework for process integration (Sogut and Erdogan, 2022).

Sustainability reporting frameworks provide valuable insights into performance measurement but fall short in evaluating process maturity (Boullauazan et al., 2023; Notteboom et al., 2020). These frameworks highlight critical metrics like emissions monitoring and waste management but lack the granularity needed to assess the development and integration of environmental processes across maturity stages. Furthermore, while tools such as the EcoPorts initiative promote environmental monitoring, they do not adequately address process standardisation or continuous improvement (Argyriou et al., 2019).

Despite advancements in sustainability initiatives, the concept of environmental process maturity in ports remains underexplored (Charłampowicz and Mańkowski, 2024; Haezendonck and Van Den Berghe, 2020). While models like the Digital Readiness Index for Smart Ports provide maturity assessments for technological innovation (Philipp, 2020), comparable frameworks for environmental processes are lacking. Additionally, there is a limited understanding of how stakeholder engagement and regulatory compliance contribute to advancing environmental maturity (Sogut and Erdogan, 2022). The need for an integrative model that aligns environmental, social, and economic dimensions is particularly pressing for Polish ports, which face unique challenges related to their infrastructural and regulatory environments.

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The major constructs of this study include environmental process maturity, stakeholder engagement, and regulatory compliance. Environmental process maturity is defined as the extent to which a port integrates environmental considerations into its operational and strategic frameworks, encompassing dimensions such as emissions reduction, energy efficiency, and waste management (Argyriou et al., 2019; Charłampowicz and Mańkowski, 2024; Klimek et al., 2019). Stakeholder engagement refers to the active involvement of port users, local communities, and policymakers in environmental initiatives (Olofsson et al., 2023). Regulatory compliance encompasses adherence to international and local environmental standards, such as those highlighted in the European Sea Ports Organization's EcoPorts initiative (Notteboom et al., 2020).

Operationalising these constructs requires a structured approach. For instance, environmental process maturity can be assessed through indicators such as adopting renewable energy, implementing emissions monitoring systems, and achieving green certifications (Notteboom et al., 2020; Sogut and Erdogan, 2022). Stakeholder engagement can be measured through surveys, public consultations, and partnerships (Klimek et al., 2019). Regulatory compliance can be evaluated by analysing adherence to emissions standards and waste management protocols (Argyriou et al., 2019; Chlomoudis et al., 2024).

The relationships between these constructs are critical to developing an environmental process maturity model. Stakeholder engagement acts as a catalyst for advancing environmental maturity by fostering collaboration and accountability (Klimek et al., 2019). Regulatory compliance provides a baseline for environmental practices, ensuring that ports meet minimum standards while striving for continuous improvement (Argyriou et al., 2019). Together, these constructs form an interconnected framework that drives the evolution of environmental processes from basic compliance to strategic integration and innovation.

By synthesising insights from existing literature, this study addresses the gap in assessing environmental process maturity in ports. The proposed model advances theoretical understanding and provides practical tools for enhancing sustainability in Polish ports, contributing to the broader discourse on sustainable port management.

## 3. Conceptual framework for assessing environmental process maturity in ports

The proposed model for assessing environmental process maturity in ports builds upon the identified gaps in the literature, providing a comprehensive framework that integrates environmental performance, stakeholder engagement, and regulatory alignment into a structured maturity assessment tool. This model is particularly tailored to address Polish ports' specific challenges and opportunities, considering their strategic role in the Baltic region and the European Union's sustainability mandates (European Commission, 2019).

At its core, the model conceptualises environmental process maturity as a multi-dimensional construct comprising three interrelated dimensions: environmental performance, stakeholder engagement, and regulatory alignment. Each dimension is operationalised through specific criteria and indicators, allowing for the systematic evaluation of a port's maturity level. The five maturity levels – Initial, Developing, Established, Integrated, and Optimised – represent a progression from basic compliance to strategic environmental leadership.

The environmental performance dimension evaluates implementing practices to reduce the port's environmental impact, including emissions reduction, energy efficiency, and waste management—indicators for this dimension based on established frameworks such as EcoPorts (Notteboom et al., 2020). Ports at the initial maturity level typically exhibit ad hoc or reactive environmental practices, while those at the optimum level demonstrate advanced integration of green technologies such as renewable energy systems and hydrogen-powered equipment.

The second dimension, stakeholder engagement, measures the extent to which ports collaborate with and respond to the needs of their stakeholders, including local communities, port users, and regulatory bodies. Stakeholder engagement is a critical component of CSR (Klimek et al., 2019), fostering trust and collaboration essential for advancing environmental maturity (Olofsson et al., 2023). This dimension includes indicators such as structured stakeholder consultations, public environmental performance reporting, and partnerships for sustainability initiatives.

The third dimension, regulatory alignment, assesses the port's adherence to local, national, and international environmental standards. This dimension emphasises compliance and proactive alignment with emerging standards such as the European Green Deal and International Maritime Organization (IMO) emissions reduction targets (Argyriou et al., 2019). For instance, ports at the initial maturity level may meet only basic regulatory requirements, whereas those at the optimum level actively contribute to developing new environmental policies and standards.

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The model's evaluation process involves three key stages: assessment, benchmarking, and improvement planning. During the assessment stage, ports are evaluated against defined indicators for each dimension using data collection methods, including performance audits, stakeholder surveys, and compliance reviews. Benchmarking involves comparing the port's performance with best practices from leading ports. Finally, improvement planning enables ports to develop targeted action plans for advancing to higher maturity levels, incorporating feedback mechanisms to ensure continuous progress.

To illustrate the model's practical application, Table 1 provides an example of the evaluation criteria and maturity levels of the environmental performance dimension. These adaptable criteria can be customised to address specific local and regional contexts.

Table 1. Environmental process maturity assessment for ports

| Maturity Level | Criteria for Environmental Performance |
|---|---|
| Initial | Minimal compliance with environmental regulations; limited implementation of basic waste management practices. |
| Developing | Adoption of structured emissions monitoring systems; basic energy efficiency measures. |
| Established | Integration of renewable energy sources; systematic waste segregation and recycling programs. |
| Integrated | Implementation of advanced emissions reduction technologies; active participation in international environmental initiatives. |
| Optimised | Use of cutting-edge green technologies (e.g., hydrogen-powered equipment); development of port-specific sustainability standards. |

The proposed model offers several advantages for Polish ports. By systematically evaluating their environmental process maturity, ports can identify specific areas for improvement, prioritise resource allocation, and develop strategies aligning with local challenges and global sustainability goals.

Additionally, the model provides a basis for comparative analysis, enabling ports to benchmark their progress against peers and industry leaders. This is particularly relevant for Polish ports seeking to align with the European Union's sustainability agenda while maintaining regional competitiveness.

## 4. Discussion

The proposed model for assessing port environmental process maturity aligns with and extends existing frameworks and studies on sustainability and CSR. Its emphasis on integrating environmental performance, stakeholder engagement, and regulatory alignment into a cohesive framework addresses the limitations of current models, such as the EcoPorts (Notteboom et al., 2020). While EcoPorts provides valuable tools for environmental monitoring, it lacks the depth required to evaluate the progression of environmental practices through maturity stages, a gap this model seeks to fill.

The model also builds on the theoretical underpinnings of CSR by operationalising stakeholder engagement as a critical dimension (Klimek et al., 2019). This approach enhances the traditional CSR perspective by embedding it within a maturity framework, providing a structured pathway for ports to evolve from basic compliance to advanced collaboration and innovation. Such integration is especially relevant given the emphasis that stakeholder-driven initiatives are pivotal for achieving long-term environmental goals (Olofsson et al., 2023).

Compared to technological maturity models (Philipp, 2020), the proposed model incorporates environmental and regulatory dimensions often absent from technology-focused assessments. By including regulatory alignment, the model addresses the dynamic nature of environmental standards and the need for ports to comply with and influence emerging policies. This dimension is particularly important in light of the European Green Deal and the International Maritime Organization's GHG reduction targets (Eide et al., 2011; Shi and Gullett, 2018).

The structured progression across five maturity levels – Initial, Developing, Established, Integrated, and Optimised – adds a developmental perspective to evaluating environmental practices. Unlike existing frameworks, which often present static assessments, this model allows for longitudinal progress tracking, enabling ports to benchmark their development against best practices and industry leaders such as Rotterdam and Hamburg. The model's adaptability to local contexts, including Polish ports, further enhances its applicability, addressing the unique infrastructural and regulatory challenges these ports face.

## 5. Theoretical Contribution

This study contributes to the existing body of knowledge by advancing the conceptual understanding of environmental process maturity in ports. Unlike prior research studies that often focus on individual sustainability measures, this model provides an integrated framework that links environmental performance, stakeholder engagement, and regulatory alignment. The study introduces a novel way of assessing and guiding sustainability practices by operationalising these dimensions within a structured maturity framework. The added value can also be seen from a methodological perspective, particularly in the method used to identify the maturity levels the ports have reached or aim to achieve concerning environmental aspects.

The model also reinterprets CSR in the context of ports by embedding it within the maturity progression, demonstrating how stakeholder engagement can evolve from basic consultations to strategic partnerships. Furthermore, it extends the scope of regulatory compliance by emphasising proactive contributions to policy development, offering a new lens through which the relationship between ports and regulatory frameworks can be viewed. These contributions highlight ports' potential to transition from passive adopters of environmental standards to active leaders in sustainability innovation.

## 6. Managerial implications

The proposed model offers actionable insights for port authorities and policymakers seeking to enhance sustainability practices. By identifying specific indicators for environmental performance, stakeholder engagement, and regulatory alignment, the model provides a roadmap for systematic improvement. Port managers can use the model to assess their maturity level, identify gaps, and prioritise interventions, such as investing in renewable energy technologies or strengthening stakeholder collaboration mechanisms.

Moreover, the model's adaptability allows ports to tailor the framework to their unique contexts, balancing global sustainability standards with local challenges. For instance, Polish ports can leverage the model to align with the European Green Deal while addressing regional infrastructural constraints. The structured progression of maturity levels also enables ports to set clear, achievable goals, fostering a culture of continuous improvement.

The model is a benchmarking tool, enabling ports to compare their performance with industry leaders and adopt best practices. This comparative analysis can inform strategic decisions, such as resource allocation and policy advocacy, ensuring that sustainability initiatives are effective and scalable. By integrating environmental process maturity into strategic planning, ports can enhance their competitiveness while contributing to broader sustainability goals.

## 7. Conclusions

This study introduces a comprehensive model for assessing environmental process maturity in ports, addressing a critical gap in the literature. The model's integration of environmental performance, stakeholder engagement, and regulatory alignment provides a holistic framework for evaluating and advancing sustainability practices. Key findings highlight the importance of structured maturity progression, stakeholder-driven initiatives, and proactive regulatory compliance.

The study offers significant practical implications, particularly for Polish ports, which can use the model to navigate the dual challenges of regional constraints and global sustainability mandates. However, the model's applicability is not without limitations. Its reliance on specific indicators may require customisation for diverse operational contexts, and its effectiveness depends on the availability of accurate data and stakeholder buy-in. Moreover, the presented model is a conceptual framework which has not been verified empirically.

Future research could explore the model's implementation in a broader range of port settings, examining its adaptability and impact across different regions. Additionally, longitudinal studies could assess the long-term effectiveness of the model in driving environmental improvements, contributing to the evolving discourse on sustainable port management.

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# Driving Green: Economic Policies Fuelling Sustainable Mobility and Future Prospects in Poland

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**Abstract**

Poland is actively implementing economic policies to promote sustainable mobility, driven by the need to align with European Union (EU) directives and improve environmental sustainability. This paper aims to provide a comprehensive overview of these policies, focusing on emission standards, technology standards, performance standards and the use of taxes and subsidies. Data and methods include reviewing legislative documents, policy analysis and case studies from major Polish cities. The results indicate considerable progress in reducing emissions, promoting electric vehicles (EVs) and improving public transport infrastructure. However, challenges such as excessive costs and infrastructure constraints remain. The conclusion highlights the importance of continuous policy development and investments in sustainable technologies to achieve long-term environmental goals.

**Keywords**

Sustainable Mobility, Economic Policy Instruments, Emission Standards, Electric Vehicles (EVs)

## 1. Introduction

Sustainable mobility has become an essential focus for policymakers worldwide, especially in increasing urbanisation and environmental concerns (Buzási and Csete, 2015). In Poland, the pursuit of sustainable mobility is influenced by the need to comply with European Union (EU) regulations and the broader goal of reducing greenhouse gas emissions. This paper examines the economic policy instruments Poland has introduced to promote sustainable mobility, including emission standards, technology standards, performance standards, and taxes and subsidies (Reckien et al., 2023).

The concept of sustainable mobility encompasses various strategies to reduce the environmental impact of transport. These include the adoption of clean technologies such as electric vehicles (EVs), the introduction of low emission zones (LEZs), and the promotion of public transport and non-motorised modes of transport with the use of cognitive tools (Zöldy and Baranyi, 2023). Previous studies have highlighted the effectiveness of these measures in improving air quality and reducing the carbon footprint in urban areas (Zöldy et al., 2024; Török, 2017).

Poland's journey towards sustainable mobility began in the 1990s with the Euro Emissions Standards, which set limits on how much pollutants vehicles emit. Over the years, Poland has gradually tightened these standards and introduced additional measures such as the Electromobility and Alternative Fuels Act, which encourages the use of electric vehicles and the development of charging infrastructure. Despite these efforts, challenges remain, such as the high cost of electric vehicles and limited charging infrastructure in rural areas.

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The central question of this article is to assess the effectiveness of Poland's economic policy instruments in promoting sustainable mobility and to identify areas where further improvements can be made. This topic is essential because achieving sustainable mobility is crucial for improving air quality, reducing greenhouse gas emissions and improving urban areas' overall quality of life. By examining Polish policies and their outcomes, this article aims to provide insights to inform future policy development and implementation.

**2. Mobility Emission Standards in Poland**

Poland's journey towards implementing emission standards for mobility began in the 1990s, driven by the rapid increase in motorisation and the associated deterioration of air quality. Initial efforts focused on aligning with European Union (EU) directives requiring stricter vehicle emission controls. Introducing Euro emission standards played a crucial role in shaping Poland's regulatory framework. These standards, ranging from Euro 1 to Euro 6, set limits on the amount of pollutants that vehicles are allowed to emit, including nitrogen oxides ($NO_x$), carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) (Carasso et al., 2023).

Introduction of Euro standards: Poland introduced the Euro 1 standard in the mid-1990s and gradually moved to stricter standards. In 2015, the Euro 6 standard became mandatory for all new vehicles, significantly reducing the permitted emission levels (Carasso et al., 2023). In recent years, Poland has introduced Low Emission Zones (LEZs) in major cities such as Warsaw, which will come into force in July 2024. These zones restrict access for vehicles not meeting specific emission criteria based on the Euro standard (Fransen et al., 2023). The Electromobility and Alternative Fuels Act, enacted in 2018, promotes using electric and alternative fuel vehicles. It includes incentives for purchasing electric vehicles (EV) and developing charging infrastructure (Giuliano, 2012).

From 2024, Poland will continue to improve its emission standards and policies to align them with EU regulations and improve air quality. Key aspects of the status include the implementation of LEZs. Cities such as Warsaw are pioneering with the introduction of LEZs, which aim to reduce urban air pollution by restricting the entry of high-emission vehicles. These zones are expected to be expanded to other cities in the coming years (Fransen et al., 2023). Moreover, the government offers subsidies and tax incentives to encourage the adoption of electric vehicles. In addition, there is a strong push to expand the electric vehicle charging network nationwide (Giuliano, 2012).

Poland continues to enforce strict emission standards for new vehicles and ensures compliance with the latest Euro 6d-TEMP and Euro 7 standards (Carasso et al., 2023). Despite considerable progress, Poland faces challenges in fully implementing and enforcing emission standards. These include the excessive cost of electric vehicles, limited charging infrastructure in rural areas, and the need for educational campaigns to promote sustainable mobility practices.

Future directions include further integration of renewable energy sources for electric vehicle charging, expansion of LEZs and continuous adaptation to evolving EU regulations. Poland's commitment to reducing vehicle emissions is crucial to improving air quality and public health and achieving international climate goals.

**3. Mobility-Related Technology Standards in Poland**

Poland's approach to mobility-related technology standards has evolved significantly over the past decades, mainly due to the need to align with EU directives and improve environmental sustainability. Key focus areas have included fuel quality standards and the implementation of the Renewable Energy Directive (RED).

EU regulations have shaped Poland's fuel quality standards to reduce harmful emissions and improve air quality. Introducing the Euro standards for vehicle exhaust emissions was crucial in this process. These standards limit the pollutants vehicles emit, including fuel sulphur content (Carasso et al., 2023).

Early adoption: Poland started to align its fuel quality standards with EU directives in the early 2000s. The introduction of Euro 4 and 5 standards marked essential milestones, as the sulphur content in diesel and petrol was reduced to 50 ppm and 10 ppm, respectively (Carasso et al., 2023). Current standards: From 2024, Poland will comply with the Euro 6 standard, which further tightens the limits on sulphur content and other pollutants. This adjustment will ensure that Poland's fuel quality meets the highest standards in the EU (Carasso et al., 2023).

The Renewable Energy Directives (RED) are cornerstones of Poland's strategy to increase the share of renewable energy in the transport sector. The directive requires that a certain percentage of energy used in transport come from renewable sources.

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1. RED I: The first Renewable Energy Directive (RED I), adopted in 2009, set a target for EU Member States to reach a 10% share of renewable energy in the transport sector by 2020. Poland implemented various measures to achieve this goal, including subsidies for biofuels and incentives for EVs (Mazur, 2022).

2. RED II: The revised directive (RED II), adopted in 2018, increased ambition by setting a target of at least 14% renewable energy in the transport sector by 2030. Poland has worked towards this goal by promoting advanced biofuels (Virt & Arnold, 2022) and expanding its EV infrastructure (Mazur, 2022).

Poland continues to make progress in implementing and enforcing mobility-related technology standards. Regarding fuel quality, Poland's compliance with Euro 6 standards ensures that fuel quality remains high, contributing to lower emissions and improved air quality (Carasso et al., 2023). The country is actively working towards RED II targets. These include increasing the share of renewable energy in the transport sector by promoting biofuels with a particular focus on innovative solutions, for example, pyro oils (Kondor, 2024) and expanding EV infrastructure (Mazur, 2022).

Although considerable progress has been witnessed, Poland faces challenges in fully implementing these standards. These include the high cost of renewable energy technologies, the need for further infrastructure development, and ensuring compliance across all sectors.

Future directions include continued alignment with EU regulations, increased investment in renewable energy technologies and public education campaigns to promote sustainable mobility practices. Poland's commitment to these standards is crucial for achieving its environmental and sustainability goals.

**4. Mobility-Related Performance Standards in Poland**

Poland's mobility-related performance standards have evolved significantly over the past few decades, primarily driven by the need to align with EU regulations and improve environmental sustainability. Key focus areas include new vehicle carbon dioxide ($CO_2$) emissions and the limitation of infrastructure use to reduce environmental impact.

**New Vehicle $CO_2$ Emission Standards**

Poland's efforts to introduce stricter $CO_2$ emission standards for new vehicles began in the early 2000s, following EU directives to reduce greenhouse gas emissions in the transport sector. The EU $CO_2$ emission standards for passenger and light commercial vehicles have significantly impacted Poland's regulatory framework. In the early adoption phase, Poland adopted the EU $CO_2$ emission standards, which initially set a target of 130 grams of $CO_2$ per kilometre (g $CO_2$/km) for new passenger cars by 2015 (Dybowski, 2021). This target was further reduced to 95 g $CO_2$/km by 2021 (Dybowski, 2021). From 2024, Poland will comply with the latest EU rules, which aim to reduce average $CO_2$ emissions from new cars by 55% below 2021 levels by 2030 (Dybowski, 2021). This ambitious target is part of the EU's broader strategy to achieve climate neutrality by 2050.

To complement efforts to reduce emissions, Poland has taken various measures to limit the use of infrastructure by high-emission vehicles and promote sustainable mobility. Large cities such as Warsaw have introduced low-emission zones that restrict access to vehicles that do not meet specific emission criteria (World Bank, 2015). These zones aim to reduce urban air pollution and promote using clean vehicles. On the other hand, urban mobility plans: Poland has developed sustainable urban mobility plans (SUMPs) for several cities that focus on reducing traffic congestion, promoting public transport and improving cycling and pedestrian infrastructure (World Bank Group, 2020). These plans are part of a broader strategy to create more sustainable and liveable urban environments.

Poland continues to make progress in implementing and enforcing mobility-related performance standards. Critical aspects of the current status include tighter emission controls: Poland enforces strict $CO_2$ emission standards for new vehicles and ensures compliance with the latest EU regulations (EU Urban Mobility Observatory, 2023) and the implementation of LEZs will be expanded to more cities, with plans to restrict high-emission vehicles further and promote cleaner alternatives (World Bank, 2015). Promoting sustainable mobility is the third strategic direction; through Sustainable Urban Mobility Plans (SUMPs) and other initiatives, Poland actively promotes sustainable mobility practices, including using public transport, cycling and walking (World Bank Group, 2020).

The challenges Poland faces in fully implementing these standards include the high cost of cleaner vehicles, the need for further infrastructure development, and ensuring public compliance with new regulations.

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Future directions include continued alignment with EU regulations, increased investment in sustainable mobility infrastructure and public awareness campaigns to promote environmentally friendly practices. Poland's commitment to these standards is critical to achieving its environmental and sustainability goals.

**5. Taxes and Subsidies as Regulatory Tools in Mobility**

Poland's use of taxes and subsidies as regulatory tools in mobility has evolved significantly in recent decades, mainly due to the need to align with EU directives and improve environmental sustainability. These tools have been crucial in shaping the country's transport policy, promoting clean technologies and reducing emissions.

Poland has introduced various fuel taxes to discourage using emission-intensive vehicles. These taxes comply with EU regulations and aim to reduce fossil fuel consumption. Excise tax on fuel has been a key component, with higher rates applying to diesel and petrol (Government of Poland, 2023). Poland has also introduced differentiated vehicle registration taxes based on $CO_2$ emissions to encourage using environmentally friendly vehicles. Higher taxes are imposed on vehicles with higher emissions to encourage consumers to choose cleaner alternatives (Mazur, 2022).

Two main subsidies are used in Poland to promote alternative mobility forms. The country actively promotes the adoption of electric vehicles through various subsidies and incentives. The government offers financial incentives to purchase electric vehicles, including grants and tax breaks (Szalanski, 2024). These subsidies aim to make electric vehicles more affordable and attractive to consumers. Poland also provides subsidies for public transport systems to reduce dependence on private vehicles. These subsidies help maintain affordable fares and improve the quality and coverage of public transport services.

From 2024, Poland will further improve its regulatory framework by using taxes and subsidies to promote sustainable mobility. Key aspects of the current status include increased fuel taxes to comply with EU climate targets. These taxes are designed to reduce fossil fuel consumption and encourage the use of alternative energy sources (Government of Poland, 2023). The government has expanded its subsidy program for electric vehicles, offering higher grants and additional incentives for installing home charging stations (Mazur, 2022). This expansion is designed to accelerate the transition to electromobility. Meanwhile, Poland continues investing in public transport infrastructure, with significant subsidies for fleet modernisation and service expansion. These investments are crucial for reducing urban congestion and improving air quality.

Future directions include further alignment with EU regulations, increased investment in renewable energy infrastructure, and comprehensive strategies to support the transition to sustainable mobility. Poland's use of taxes and subsidies as regulatory tools is essential for achieving its environmental and sustainability goals.

**6. Conclusions**

Poland's path towards sustainable mobility, driven by the need to comply with EU directives and improve environmental sustainability, has shown significant progress by implementing various economic policy instruments. Introducing and enforcing emission standards, technology standards, performance standards, and the strategic use of taxes and subsidies have helped reduce emissions, promote the spread of EVs and improve public transport infrastructure.

Despite this progress, challenges remain, such as the high cost of electric vehicles, limited charging infrastructure in rural areas and the need for continuous public education on sustainable mobility practices. Addressing these challenges requires continuous policy development, increased investment in sustainable technologies and further alignment with evolving EU regulations.

Future efforts should focus on expanding low-emission zones, integrating renewable energy sources for charging electric vehicles and promoting innovative solutions such as advanced biofuels. By continuing to commit to these strategies, Poland can achieve its long-term environmental goals, improve air quality and increase the overall quality of life in urban areas.

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# Investigation of the future of electric mobility in the EU: the dependency on the USA

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**Abstract**

The article aims to investigate the future of electric mobility in the EU as a dependency on the USA. Therefore, the political changes in the USA were investigated, as well as how they might influence European electric mobility. The future of European electric mobility is investigated based on competition in the European and U.S. energy markets. In the 1990s, the United States' energy production and consumption were dominated by fossil fuels, with petroleum, natural gas, and coal being the primary sources. The U.S. also relied heavily on imports. By 2023, the U.S. energy mix had diversified significantly, with petroleum and natural gas still leading at 38% and 36% of energy production, respectively, but with notable contributions from renewable energy sources (9%) and nuclear energy (9%). The shift towards renewable energy has been influenced by political dynamics, with Democratic administrations promoting clean energy policies and international climate agreements while Republican administrations focusing on fossil fuel extraction and energy independence. U.S. foreign policy also plays a crucial role in shaping energy imports and exports, with geopolitical factors and trade agreements impacting the energy landscape. The political climate, particularly the return of Donald Trump to the presidency, could significantly affect domestic and international energy policies, including the development of renewable energy and the market penetration of electric vehicles. In this article, the author investigates the theoretical connection between the U.S. presidency, U.S. energy policy, and its effect on the EU energy policy and electric vehicle market penetration.

**Keywords**
Fossil fuels; Energy mix; Renewable energy; Energy policy; Electric vehicles

## 1. Introduction – The energy mixture of USA in the 1990s

To examine and understand the cognitive connection between the energy policies of the USA and the EU, from the future of electric mobility in the EU could be derived, the author has investigated the past of the USA from this point of view. Therefore, the energy mix of the USA is presented first (the 1990s and 2020s).

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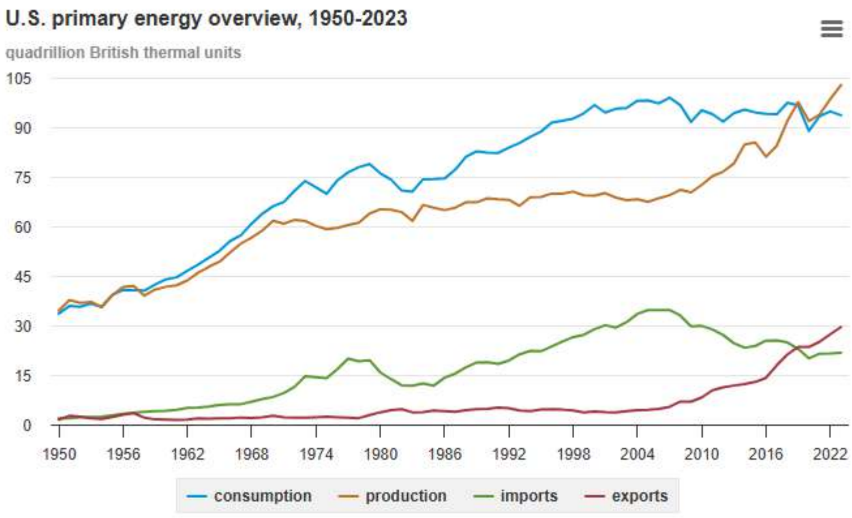


Figure 1. U.S. Primary Energy Overview 1950–2023
Source: EIA (2024a)

The energy mix in the United States in the 1990s can be described as follows (EIA, 2024a).

**Crude oil**: in the 1990s, it produced about 7-8 million barrels per day (b/d). Imports in the 1990s were around 8-9 million barrels per day(b/d).

**Natural Gas**: Natural gas production was about 18-20 trillion cubic feet yearly. Imports from Canada were around 2-3 trillion cubic metres per year.

**Coal**: U.S. coal production was about one billion tonnes per year.

**Nuclear power**: In the 1990s, U.S. nuclear power generation was about 600-700 billion kWh annually.

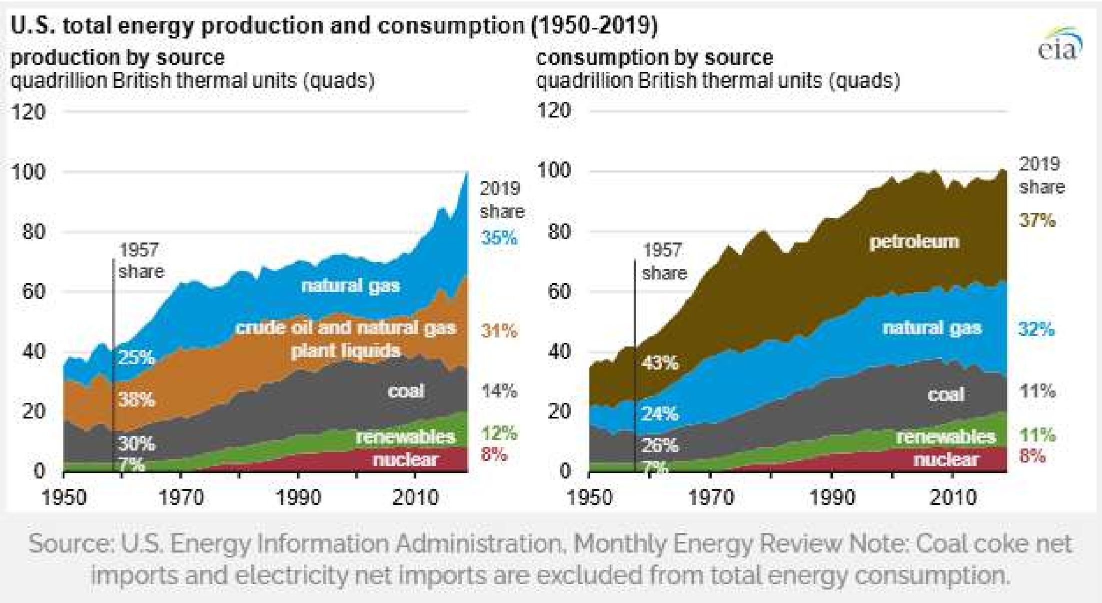


Figure 2. U.S. total energy production and consumption (1950–2019)
Source: EIA (2024a)

URL: https://www.hellenicshippingnews.com/in-2019-u-s-energy-production-exceeded-consumption-for-the-first-time-in-62-years/

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The current energy mix in the United States (Fig. 2) is diverse and consists of the following main sources (2019). Petroleum: 38% of energy production. Natural gas: 36% of energy production. Coal: 9% of energy production. Renewable energy sources account for about 9% of energy production. Within that, wind energy is 18%, solar energy is 11%, hydropower is 10%, and biomass and other renewables are the remaining parts—nuclear energy is 9% (Harris et al., 2018).

Energy consumption by sector (2023) in the U.S.: Electricity generation: 32% of energy consumption, Transport: 28% of energy consumption, Industry: 23% of energy consumption, Residential: 11% of energy consumption, Commercial: 6% of energy consumption. The U.S. energy mix has undergone significant changes in recent years, particularly due to the growing role of renewable energy sources. Fossil fuels continue to dominate, but renewables and nuclear energy also play a significant role in the country's energy supply (EIA, 2024b).

## 2. Political influence on renewable energies

The list of the presidents of the United States since the 1990s:

- Bill Clinton (Democrat) – 1993–2001
- George W. Bush (Republican) – 2001–2009
- Barack Obama (Democrat) – 2009–2017
- Donald Trump (Republican) – 2017–2021
- Joe Biden (Democrat) – 2021–present
- The next president, who will take office in 2025, will again be Donald Trump, who won the 2024 election as a Republican.

There is a clear connection between U.S. renewable energy policy and the party that holds the presidency (Fang, Parida, 2024). The main differences between the Democratic and Republican Party can be concluded as the Democratic Party supports renewable energy. The Inflation Reduction Act (IRA), passed during the Biden administration in 2022, provides significant incentives for developing renewable energy sources such as solar and wind power. The Democratic presidents Barack Obama and Joe Biden have supported U.S. participation in international climate agreements, such as the Paris Climate Agreement. Democratic administrations often introduce stricter environmental regulations to reduce greenhouse gas emissions and promote clean energy (Bordoff et al., 2024).

The Republican Party is in favour of extracting and using fossil fuels like oil, natural gas, and coal. Under Donald Trump, the U.S. has left the Paris Climate Agreement, and several environmental rules have been scrapped. Republican administrations always emphasise energy independence and dominance, increasing domestic fossil fuel extraction (Tyson and Kennedy, 2024). Additionally, Republican administrations tend to introduce fewer regulations to encourage growth in the energy industry and reduce burdens on businesses (Dews and Gross, 2024).

### 2.1 How the energy policy of the U.S. influences the decisions of import energy mix

U.S. foreign policy significantly impacts the country's energy import mix. The U.S. has close relations with major energy exporters, such as Canada and Mexico. Canada, for example, is the largest supplier of natural gas and oil to the U.S. Geopolitical conflicts, such as wars in the Middle East, can affect oil prices and the security of supply. U.S. foreign policy aims to secure and maintain energy supplies in these regions. The U.S. can impose sanctions on major oil exporters like Iran and Venezuela, reducing the amount of oil imported and increasing prices. U.S. trade agreements, such as the USMCA (United States–Mexico–Canada Agreement), facilitate energy imports and exports with neighbouring countries (Kern, 2006).

The U.S. rejoined the Paris Agreement in 2021, on the first day of the Biden administration. The country's participation in the Paris Climate Agreement influenced the country's energy policy, particularly developing renewable energy sources and reducing greenhouse gas emissions.

### 2.2 How could U.S. policy affect EU energy imports?

The victory of the Republican Party, particularly Donald Trump's return to the presidency, will affect European energy imports in several ways. Trump's policies are clear: increase fossil fuel production, especially oil and natural gas. This will increase U.S. exports of LNG (liquefied natural gas) to Europe, reducing our dependence on other sources, such as Russia.

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Trump is expected to backtrack on tougher climate policy measures, including withdrawal from the Paris Climate Agreement, which will weaken the momentum for global climate action. The EU will need to take a greater role in international climate policy. Trump's "America First" policy will likely cause trade tensions with the EU, and new tariffs and trade restrictions may make energy imports and exports more difficult, affecting European energy prices and the security of supply. Trump's administration is also set to reduce support for renewables, which could slow the U.S. green transition, creating an opportunity for the EU to strengthen its position in the clean technology market and increase its competitiveness (Tagliapietra and Trasi, 2024).

### 3. Comparison of energy prices

A comparison of energy prices between the United States and Europe from the 1990s to the present, based on purchasing power parity, clearly shows how energy prices have developed.

In the 1990s, it was clear that Europe had higher average electricity prices than the U.S. due to higher taxes and regulatory costs. In Germany, for example, prices ranged from USD 0.20 to 0.25/kWh. Conversely, the USA had average electricity prices of around USD 0.08–0.10/kWh. In the 2020s in Europe, prices increased significantly, especially due to the energy crisis. In Germany, prices are around USD 0.30–0.35/kWh. The USA has consistently maintained lower prices, ranging from USD 0.13 to 0.15/kWh.

In the 1990s, European natural gas prices were higher due to import dependency. Prices were around USD 5–7/MMBtu. Meanwhile, prices in the USA were lower, around USD 2–3/MMBtu. In the 2020s in Europe, prices increased significantly, especially due to the Russian–Ukrainian conflict and the energy crisis. Prices are now in the range of USD 20–30/MMBtu, but in the U.S., prices remained lower, at around USD 4–6/MMBtu.

Gasoline prices in Europe in the 1990s were higher due to higher taxes. Prices were around USD 1.50 to 2.00 per litre. In the USA, prices were lower, around USD 0.50-0.70 per litre. In the 2020s, in Europe, prices remained higher, at around USD 1.80–2.20 per litre, but in the USA, the prices remained lower at around USD 0.80–1.00 per litre (https://www.statista.com/topics/839/gas-prices).

### 4. Market penetration of electric vehicles

#### 4.1 Market penetration of electric vehicles in the US

A victory for the Republican Party, particularly Donald Trump's return to the presidency, could have significant implications for the uptake of electric vehicles (EVs) in the U.S. (Kocsis Szürke et al., 2023; 2024). Trump's administration is expected to avoid stricter emissions standards and other environmental regulations promoting EV penetration. This is to slow EV market penetration and reduce incentives for manufacturers to develop EVs. The Republican administration may also reduce or eliminate tax incentives for EV purchases, such as the up to $7,500 tax credit provided by the Inflation Reduction Act (IRA). This can reduce the demand for EVs due to fewer or lower financial incentives. The rollout of EV charging networks is critical to the uptake of EVs, and slower development could hinder growth. Changes to regulations and subsidies could create market uncertainty, deterring manufacturers and investors from developing and producing EVs, particularly those who have made significant investments in the EV market (Guerra, 2024).

#### 4.2 Market penetration of electric vehicles in the EU

A Republican Party victory in the U.S. will undoubtedly indirectly impact the uptake of electric vehicles (EVs) in Europe. Here are some of the impacts. The Republican Party's possible decision to reduce subsidies for EVs and relax emission standards will inevitably slow the uptake of EVs in the U.S., which may indirectly affect the European market. This is because U.S. car manufacturers are expected to have fewer resources for EV development, slowing down innovation and technological progress globally. The Republican Party's leadership may increase trade tensions between the U.S. and the EU, affecting the flow of EV components and technologies. Tariffs and trade restrictions may make it harder for European car manufacturers to enter the U.S. market and source components from the U.S. Regulatory changes in the U.S. may create market uncertainty, deterring global investors from developing and producing EVs, especially those that have made significant investments in the EV market. The slowdown in EV development in the U.S. might allow European carmakers to strengthen their position in the global market, while stricter EU emission standards and support programmes will further stimulate EV development and uptake in Europe (Lynch et al., 2023).

### 5. Conclusion

The U.S. energy mix has changed significantly recently, with renewables growing. Fossil fuels remain dominant, but renewables and nuclear energy are also key components of the country's energy supply.

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The Democratic Party is unequivocally committed to renewable energy, has introduced the most stringent environmental regulations, and is a key participant in international climate agreements. In contrast, the Republican Party is steadfast in its support of fossil fuel extraction, emphasising energy independence and dominance and introducing a limited number of regulations. This stark difference between the parties has far-reaching implications for U.S. energy policy and renewable energy development.

U.S. foreign policy has a significant impact on the energy import mix. Geopolitical alliances and conflicts, trade policies and sanctions, and energy independence and security all play a crucial role. These factors contribute to the stability and diversification of the country's energy supply.

A Republican Party victory is expected to have mixed effects on European energy imports. Exports of fossil fuels from the U.S. may increase, but trade tensions and climate policy backtracking might pose challenges for the EU. The EU must strengthen its climate policy and technological competitiveness to adapt to these changes.

Energy prices in Europe are higher than in the U.S., especially for electricity and natural gas. The U.S. has lower energy prices because it produces more energy and has lower taxes. In Europe, higher taxes and regulatory costs push up prices.

The Republican Party's victory in the U.S. will undoubtedly lead to indirect impacts on the uptake of electric cars in Europe, notably through regulatory changes, trade tensions and market uncertainties. European car manufacturers must adapt to these changes and strengthen their development and innovation efforts.

The EU plans to take several steps to reduce fossil fuel use and meet climate change targets. The European Commission's 'Fit for 55' package targets reducing the EU's greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. Only zero-emission vehicles will be allowed in new cars starting in 2035. The EU will extend the Emissions Trading Scheme (ETS) to maritime transport and strengthen requirements for aviation. The EU's target is for 40% of energy consumption to come from renewable sources by 2030. This includes increasing the share of wind, solar and other clean energy sources. The EU will introduce a carbon cap and trade mechanism, imposing a tax on imported products such as steel, cement, and aluminium to protect European industry from cheaper and more polluting imports. The EU has set tougher energy efficiency targets, including improving the energy efficiency of buildings and industrial plants. The European Commission has proposed the creation of a Climate Social Fund to help households and small businesses invest in energy efficiency and buy electric vehicles. Meanwhile, the EU aims to phase out subsidies for fossil fuels and instead support renewable energy sources.

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