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A REAL-TIME MONITORING SYSTEM FOR GEARvWEAR EVALUATION OF WIND TURBINE

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Abstract

The high failure risk of gearbox main gear wear limits the development of wind energy industry. However, it is not popular to systematically monitor the performance of wind turbine main gear wear because of higher cost and not easy implemented. This study proposes a real-time gear wear monitoring system, which consists of data processing, data visualisation and modelling evaluation. Because gear oil data is discrete and sparse, data optimisation strategy must be used to detect missing values, outliers and duplicate values. Timing-based curve comparison and correlation scatter plot are the main visualisation methods, and they provide effective and timely intrinsic content for the following modelling evaluation. Validation tests have shown that the software can effectively improve the evaluation system of wind turbine main gear wear, which provides a new methodology for evaluating gear wear in the wind energy sector.

Key Words

Main gearbox wear, real-time monitoring system, data optimisation strategy, wind turbines

1. Introduction

Wind energy is a very desirable green choice among many new energy sources because it is renewable and clean energy source with recyclability and high efficiency [1]–[3]. Doubly-fed induction generator (DFIG) is the most widely used wind turbine. In a doubly-fed unit, the required electrical energy is generated by a high-speed rotating generator and the impeller rotates at a slower speed, in order to increase the synchronous speed of the generator and to reduce the number of generator pole pairs, then a gearbox must be connected between the impeller and the generator to increase the speed up to the generator speed. However, a primary obstacle in harnessing this energy efficiently is the frequent malfunctioning of wind turbine gearboxes. These gearboxes operate under complex conditions, leading to gear wear that degrades performance or even results in failure [4]–[7]. Gearbox is one of the main components of doubly-fed wind turbine, and its operational reliability directly determines the safety and stability of the unit, while the operational life of the gearbox depends on the lubrication and cooling system [8], [9], as shown in Fig. 1 [21].

From 2015-01 to 2025-01, the top 27 countries/regions in the field of wind gear abrasion/wind turbine gear wear in the world are shown in Fig. 2(a), and the countries/regions with the most publications in this field are China (33 publications, 38.37%), United Kingdom (11 publications, 12.79%), and Germany (8 publications, 9.3%) are the second and third. As shown in Fig. 2(b), 2021 reaches the peak of 12 annual publications, and the fastest growth rate in 2021 is 71.43%, suggesting that the research in this field has been developed rapidly and is in a fast rising stage [10]. From 2015-01 to 2025-01, the top 14 national research institutes in the field of wind gear abrasion/wind turbine gear wear in the world are shown in Fig. 3(a), among which, Chongqing University [11] and Xinjiang University [15] occupy the top two places in terms of the number of publications with four and four articles published, and Tianjin Polytechnic University is in the third place with three articles published [3], [12], respectively. In addition, among the 86 papers retrieved, the top 14 journals in terms of the number of publications are shown in Fig. 3(b), among which the journals with the most publications are Tribology International (four articles) [4], [13]–[15], Proceedings of the Institution of Mechanical Engineers, Part J: Journal

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Figure 1. Schematic structure of wind turbine main gear system.

of Engineering (four articles) [16], [17], Mechanism and Machine Science (three articles) [6], [10], [18].

Wind power gearbox lubricants are mainly synthetic oils such as polyalphaolefin (PAO) and polyether (PAG), and the most common gear oil viscosity designation for wind turbine generators is ISO 320. Gearboxes are susceptible to wear and fatigue and insufficient lubrication during operation, resulting in frequent failures and high maintenance costs. Fernandes [15], [19] studied the influence of different gear oil technologies in the overall gearbox transmission efficiency, and the results showed that different energetic efficiency and different oil particle counting were obtained even when the same base oil was used. Carlos [20] demonstrated that a wind turbine gear oil added with ionic liquid can reduce the torque loss and improve the gearbox efficiency while producing less wear particles as observed in the oil analysis. Burkhart [21] compared six different new and used gear oils in order to identify performance differences and predict oil change intervals. Marques [22] tested two stage multiplying gearbox with helical gears and four fully formulated wind turbine gear oils, and the experimental results have shown that each wind turbine gear oil formulation generated different power loss resulting in distinct stabilised operating temperatures. The above literature dedicated to gear oils provides an important technical basis, but does not correlate oil analysis data with real-time diagnosis of main gear wear. He [23] developed a modern remote monitoring terminal for transmission line, Mao [24] proposed a green energy system modelling and optimisation, which improved energy utilisation efficiency and environmental friendliness. Evaluating the wear state of wind turbine gears by analysing gear oil performance indexes can not only detect problems in time, but also avoid huge losses caused by serious wear, but there are still relatively few wind turbines that can systematically monitor the performance of wind turbine main gear oil [25]–[27]. To tackle the challenges in wind turbine fault diagnosis, this paper provides reliable methods in integrating sparse gear oil data into automatic database, and develops a software system for real-time monitoring of wind turbine main gear wear and applied to wind turbine sites on an experimental basis, which is expected to be a powerful auxiliary tool for the reliable operation of wind turbines.

Table 1
Fundamental Information of Gear Oil Datasets

Type	Indicators of Wind Gear Oil
Chemical data	Viscosity (40°C), acid value
Physical data	Moisture, PQ, flash point
Metallic leaching elements	Ag, Al, Ba, Cd, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Sb, Si, Sn, Ti, V
Additive precipitating elements	P, Zn, B, Ca

2. Data Optimisation Strategy

The R software (version 4.4.1) was used to carry out all related programming work for its open source and high efficiency in data statistic and modelling [28].

2.1 Data Screening

The data for the wind turbine main gear oil comes mainly from offline data at long cycle intervals, which first needs to be entered into a computer and a special database file created. The software accesses the dataset through networking, which can greatly reduce costs and solve the problem of the lack of online monitoring instruments for certain indicators. Table 1 presents typical datasets of gear oil for a wind farm in south China. There are four main categories of oil indicator values data, *i.e.*, chemical data, physical data, metallic leaching elements, and additive precipitating elements. Data screening consists of handling three types of anomalous data, which are missing values, outliers and duplicates. NA is a logical constant of length 1 which contains a missing value indicator. NA can be coerced to any other vector type except raw. The generic function is.na indicates which elements are missing. 'any(is.na(df))' can be used for check for missing values in the data frame, 'colSums(is.na(df))' for the number of missing values for each variable in the data frame, and 'sum(is.na(df))' is used to calculate the total number of missing values for all variables in the data frame. The function of na.omit is useful for dealing with NAs in *e.g.*, data frames and returns the object with incomplete cases removed. In software scripts, 'na.omit()' can be used to remove rows of data records that contain missing values. 'boxplot()' function can quickly find outliers graphically in the data set, outliers can be handled by deleting the method, but because the gear oil data would have been sparse, it can be handled by replacing the

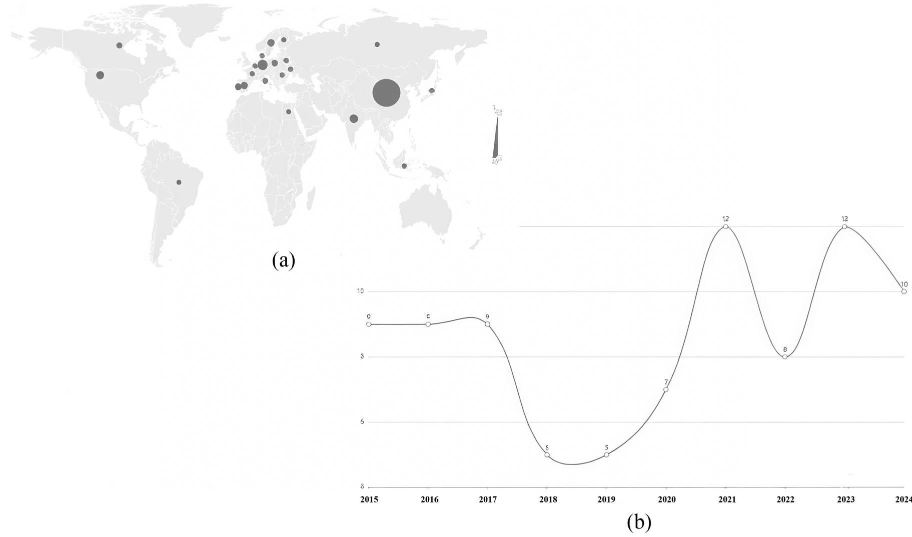


Figure 2. Literature publications in the field of wind gear wear.

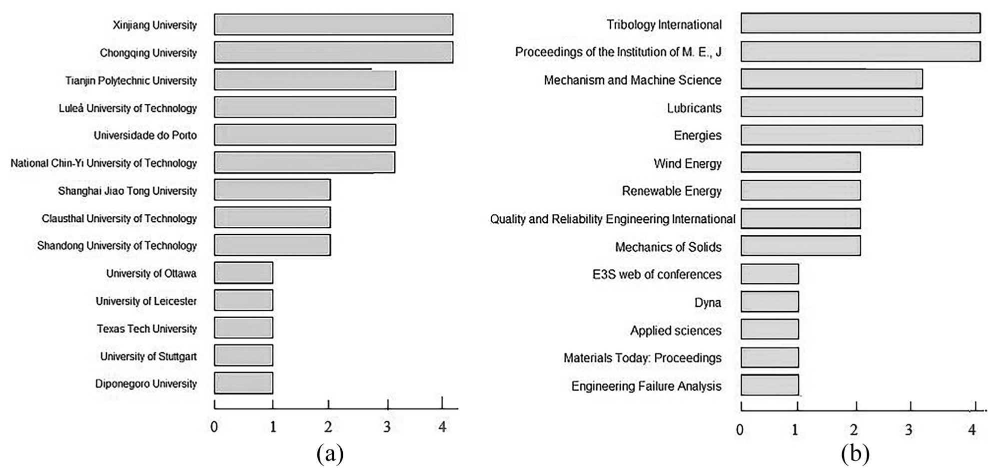


Figure 3. Main research institute and journals of Literature in the field of wind gear wear.

outliers with the median. The function of duplicated() determines which elements of gear oil data frame are duplicates of elements with smaller subscripts, and returns a logical vector indicating which elements (rows) are duplicates. 'df[!duplicated(df),]' code in R can be used for quickly identifying and removing duplicate values. These functions are all built-in functions of R language, which can effectively perform a series of numerical algorithm operations. For example, the duplicated() function uses a 'for' loop to traverse each element of the input vector and stores variables using a hash table or similar data structure, thus having better performance.

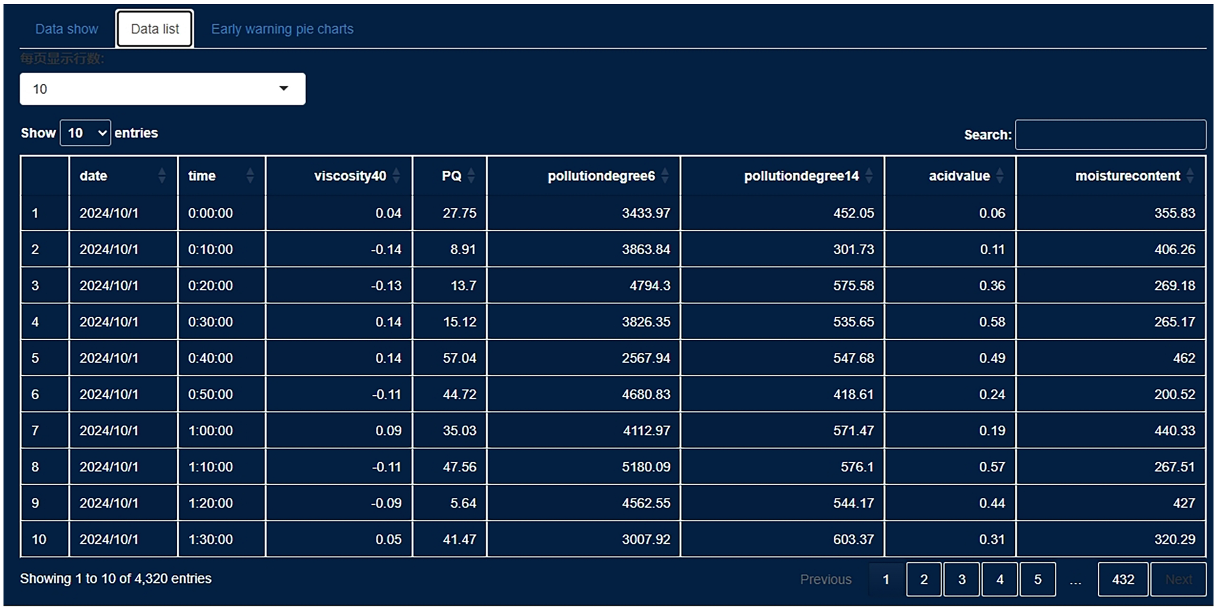
2.2 Data File Conversion

After data screening and data normalisation, newly generated dataset would be saved in another data file. To ensure efficient operation of the software, the data file format is generally set to '*.csv' format. Once the dataset is loaded into the software, the corresponding data can be displayed in real time, as shown in Fig. 4.

3. Development of Real-time Monitoring Software System

3.1 Overview of the Software Architecture

Shiny is an R language framework for building interactive web applications that allows users to develop dynamic web applications with minimal HTML, CSS, and JavaScript code. The main advantage of Shiny is that it can embed R's analytical and visualisation capabilities directly into a web application, making data analysis more intuitive and easy to interact with. By combining UI design and server logic, a variety of feature-rich applications can be created, including data visualisation, dynamic input, and responsive programming. Figure 5 presents the main interface of the real-time monitoring software system for gear wear evaluation of wind turbine. The main interface contains a column of basic turbine information on the lower left side, a column of the latest real-time data for the main gear oil in the centre, and a display of time-series values for some of the important indicators on the right side. Figure 6 provides a portion of the starting segment code of the



Data show | Data list | Early warning pie charts

Show 10 entries — Search:

	date	time	viscosity40	PQ	pollutiondegree6	pollutiondegree14	acidvalue	moisturecontent
1	2024/10/1	0:00:00	0.04	27.75	3433.97	452.05	0.06	355.83
2	2024/10/1	0:10:00	-0.14	8.91	3863.84	301.73	0.11	406.26
3	2024/10/1	0:20:00	-0.13	13.7	4794.3	575.58	0.36	269.18
4	2024/10/1	0:30:00	0.14	15.12	3826.35	535.65	0.58	265.17
5	2024/10/1	0:40:00	0.14	57.04	2567.94	547.68	0.49	462
6	2024/10/1	0:50:00	-0.11	44.72	4680.83	418.61	0.24	200.52
7	2024/10/1	1:00:00	0.09	35.03	4112.97	571.47	0.19	440.33
8	2024/10/1	1:10:00	-0.11	47.56	5180.09	576.1	0.57	267.51
9	2024/10/1	1:20:00	-0.09	5.64	4562.55	544.17	0.44	427
10	2024/10/1	1:30:00	0.05	41.47	3007.92	603.37	0.31	320.29

Showing 1 to 10 of 4,320 entries — Previous 1 2 3 4 5 … 432 Next

Figure 4. Display interface after data optimisation processing.

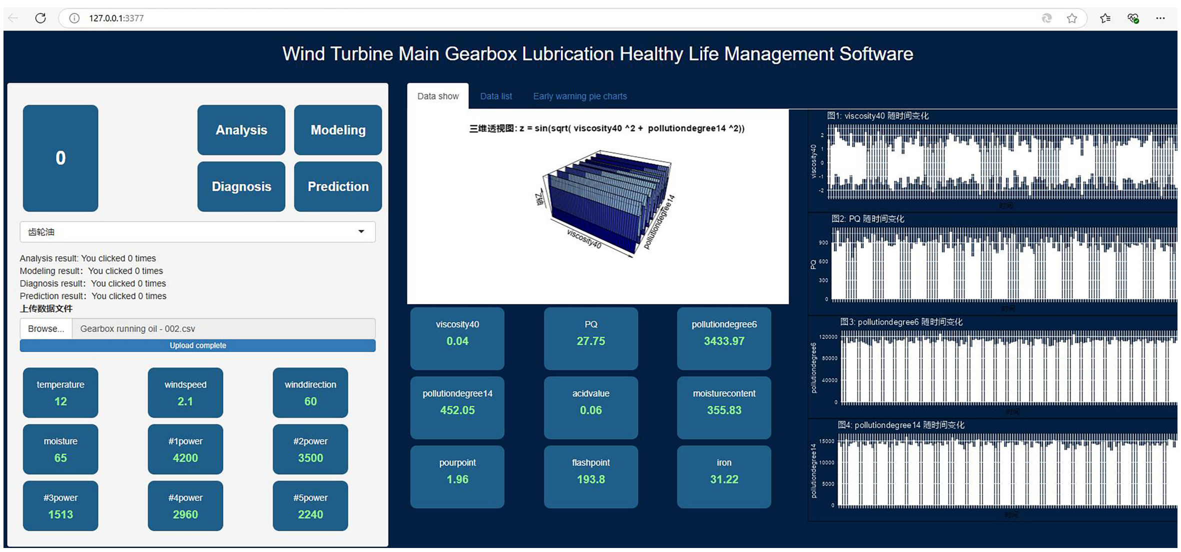


Figure 5. Software main interface of real-time gear wear monitoring system.

software. The code start segment represents the package file introduced by the software, which include packages of shiny (UI), stringr (data processing), readr (load of data file), ggplot2 and plotly (visualisation), etc.

3.2 Visualisation of Gear Oil Datasets

Timing-based curve can provide a comparison of the changes in various indicators of a wind farm at different time points, achieving rapid evaluation and analysis. The full testing cycle of wind turbine main gear oil is once every six months, and Fig. 7 gives the trend of typical oil index data of different wind turbines in a wind farm, where the horizontal coordinate represents the wind turbine number and the test time is December 2022. Figure 8 provides data for these gear oil indicators after one year. The gear oil indicators in the chart, in descending order, are viscosity (40 °C), elemental phosphorus, moisture, iron content, PQ value, and silicon content. Comparison of the two graphs shows that the gear oil viscosity decreased after one year, while the moisture and iron content increased significantly, among which the iron content of fans No. 7, 24, and 26 was abnormally high, increasing to 132, 119, and 118 mg/kg from 21, 29, and 21 one year ago. The decrease in phosphorus content indicates that there is a change in the transfer of phosphorus from the additive to the particulate matter after one year of operation.

As shown in Fig. 9, 'plot()' function was mainly used to visualise the changing trends in gear oil, followed by the 'text()', 'lines()', and 'grid()' functions, which are used to assist in completing the beautification of the diagrams. The last two lines of code in Fig. 9 implement the visualisation by 'ggpair()' function with installation of GGally package in Fig. 10, where the two-by-two relationship of the six

```r
library(shiny)
library(stringr)
library(readr)
library(ggplot2)
library(plotly)
library(gridExtra)
library(DT)

# Setting the csv file path
file_path <- "D:/Owindrealtimedataafterscreening-001.csv"

# Read data functions
read_data <- function(file_path) {
  data <- read_csv(file_path, col_names = FALSE, locale = locale(encoding = "UTF-8"))
  col_names <- as.character(data[2, ])
  data <- data[-c(1, 2), ]
  data <- as.data.frame(data, stringsAsFactors = FALSE)
  colnames(data) <- col_names
  return(data)
}
shinyUI<-fluidPage(
  tags$h2(style = "text-align: center; color:white", "Wind Turbine Main Gearbox Lubrication
                  Healthy Life Management Software"),
  tags$style(HTML("
        body {
            background-color: #031f41;
        }
```

Figure 6. Starting segment code of the software.

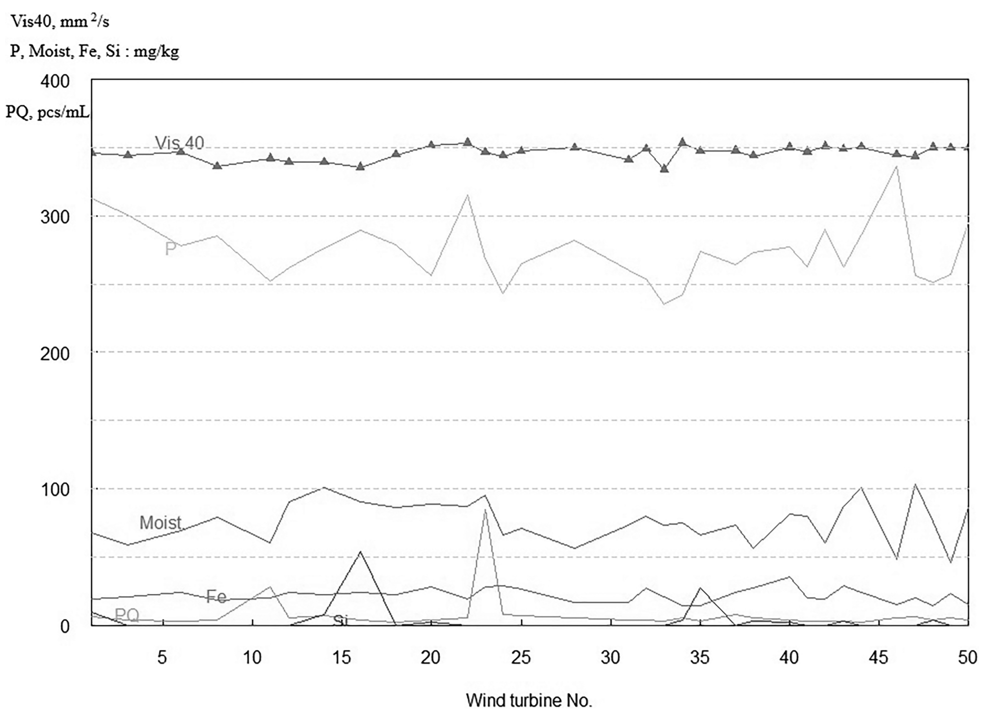


Figure 7. Distribution trend for performance data of main gear oil in December 2022.

key indicators of gear oil is shown. As shown in the code parameter 'ggplot2::aes(colour=Results)' in Fig. 9, the colour display of the data points in Fig. 10 is set according to the final evaluation result variable of this wind turbine, for example, in the correspondence subplot of silicon and phosphorus content, there exists an abnormal state point of (54, 289), which is marked in red, indicating that this wind turbine is in the state of 'Warning', so that it can be found in a similar method by quickly locate turbines with similar characteristics to provide an accurate judgement. Correlation scatter plots can display the correlation between six main factors pairwise, which provides strong analytical capability in the visualisation process with the application of the function of 'ggpair()'.

3.3 Gear Wear Evaluation

There are notable variations in gear oil variables during wind turbine operation, which is a huge distraction to modelling. Data heterogeneity is commonly found in comprehensive fault analysis tasks. A normalisation function must be used to scale each variable in the input datasets in order to remove differences in numerical values and the influence of units among different variables [6]. The minimum–maximum normalisation method is mostly used for data normalisation process, which maps the data uniformly onto the [**??**], [1] interval for all variable [29], [30]. In the real-time monitoring system for gear wear evaluation, minimum–maximum normalisation

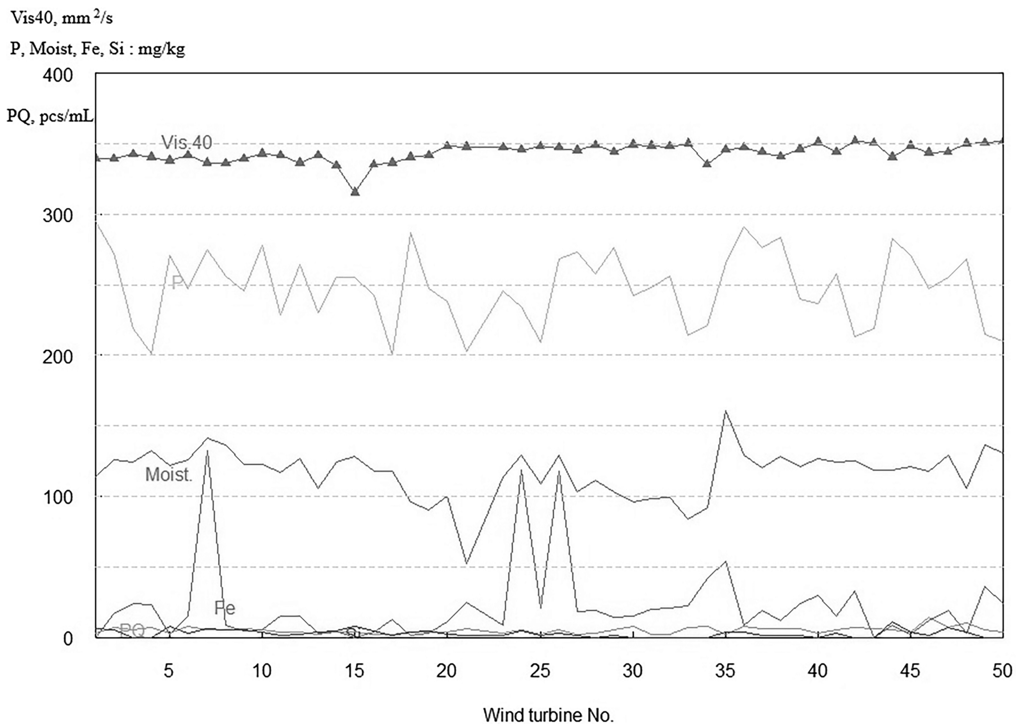


Figure 8. Distribution trend for performance data of main gear oil in December 2023.

```
par(las=1,tck=0.01)
plot(cc[1:32,2],cc[1:32,4],col=2,type='o',pch=17,ylim=c(0,400),ylab='',xlab='Wind turbine No.',
     xaxt="n",xaxs="i",yaxs="i")
axis(side=1, at=seq(0, 50, by=5))
text(x=6, y=mean(cc[1:32,4])+9, label=names(cc)[4],col=2)
lines(cc[1:32,2],cc[1:32,6],col=2);text(x=5, y=mean(cc[1:32,6]), label=names(cc)[6],col=2)
lines(cc[1:32,2],cc[1:32,7],col=3);text(x=3, y=mean(cc[1:32,7]), label=names(cc)[7],col=3)
lines(cc[1:32,2],cc[1:32,16],col=4);text(x=8, y=mean(cc[1:32,16]), label=names(cc)[16],col=4)
lines(cc[1:32,2],cc[1:32,27],col=6);text(x=15, y=mean(cc[1:32,27]), label=names(cc)[27],col=6)
lines(cc[1:32,2],cc[1:32,24],col=7);text(x=5.5, y=mean(cc[1:32,24])+4, label=names(cc)[24],col=7)
grid(nx=NA,ny=8,lwd=1,lty=2,col="lightgray")

library(GGally)
ggpairs(cc[,c(4,6,7,16,27,24)],ggplot2::aes(colour = Results))
```

Figure 9. Script code for visualisation process of gear oil datasets.

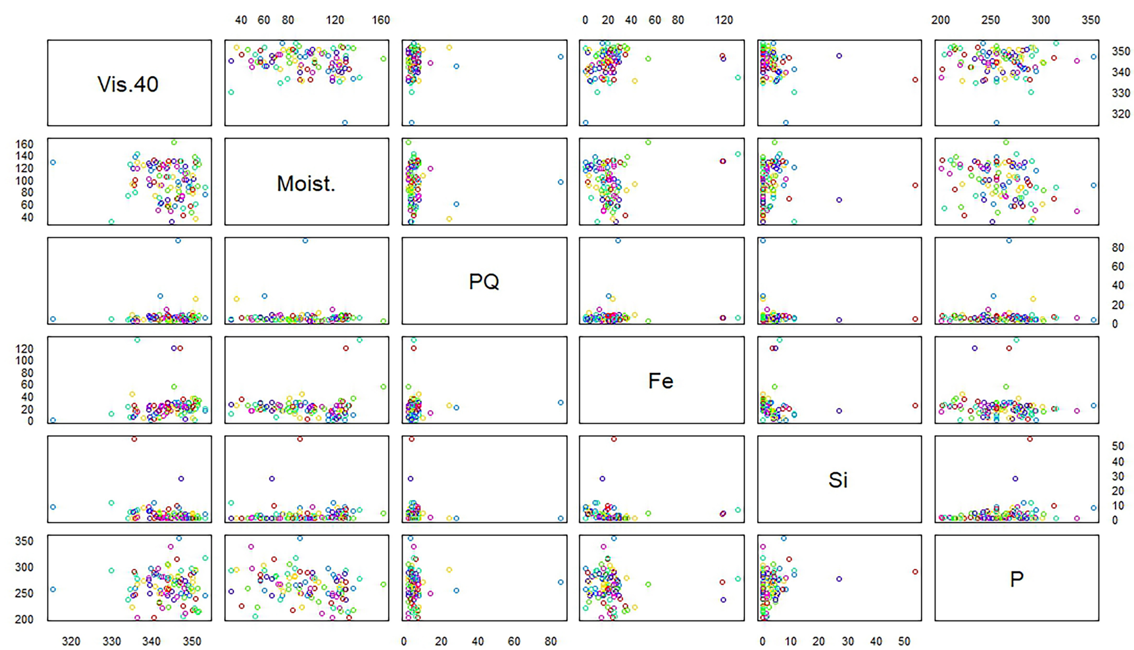


Figure 10. Relationship scheme of the six key indicators of gear oil.

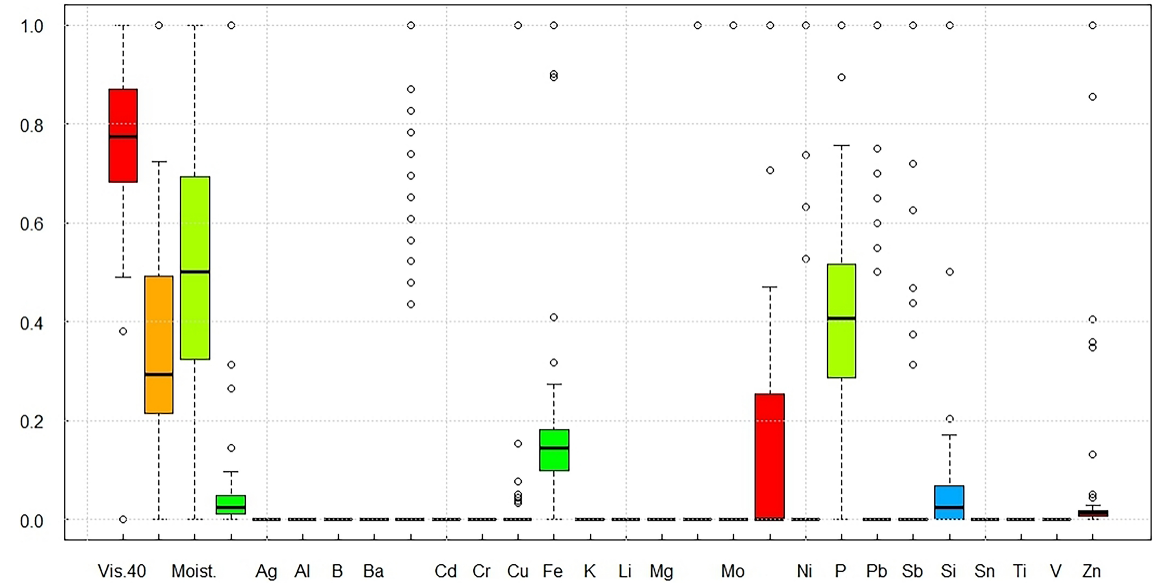


Figure 11. Statistical distribution with boxplot analysis for the values of the indicator variables after the normalisation process.

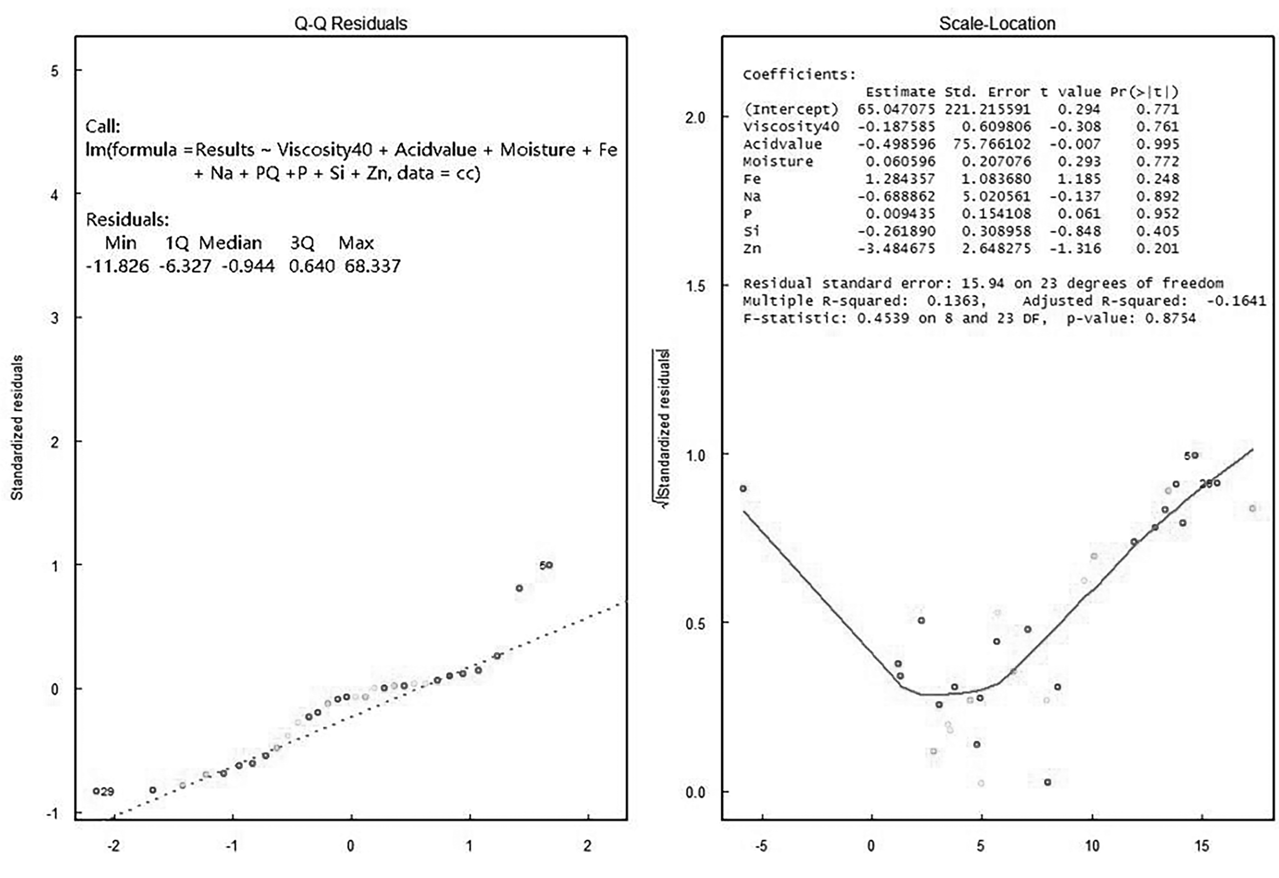


Figure 12. Model analysis of gear wear evaluation.

is realised by custom function based on a simple mathematical treatment, and the statistical distribution of the values of the indicator variables after the normalisation process is shown in Fig. 11 with the support of 'boxplot()' function.

Gear wear evaluation must be based gear oil performance datasets, and it is a multivariate modelling process after the normalisation process of raw gear oil values. According to database of existing cases, viscosity (40 °C), acid value, moisture, PQ value, Fe, Na, P, Si, and Zn are the critical variables for gear wear evaluation model. Additionally, dependent variables, results, can be set as variable 'Y', which reflects the evaluation of gear wear. Code of 'model4 <- lm(Results~Viscosity40

+ Acidvalue + Moisture + PQ + Fe + Na + P + Si +Zn, data = cc)' can realise multivariate modelling for gear wear evaluation. Due to existance of uncertainty, evaluation model should be continuously optimised and improved to meet the wear evaluation of more fans [31]–[34]. Figure 12 shows the parameter values and statistical distribution information for the generated model, and analytical evaluation information of the model comprising Q–Q residuals and scale-location plot. Q–Q residuals plot demonstrates that the residuals of the model conform to the state distribution, which indicates the model is reasonable and sound; scale-location plot checks that the uniformity of the residual distribution is good and the model is not considered to be heteroscedastic by the Breusch–Pagan test. On the basis of this model, validation tests in cooperative company demonstrated it can quickly determine whether or not the main gear wear is in an alarm state by acquiring the values of the gear oil indicators.

4. Conclusion

This study developed a real-time gear wear monitoring software system, which consists of data processing, data visualisation and modelling evaluation. Data screening and UI design with shiny package were important factors for developing the real-time gear wear monitoring system of wind turbine. The key indicators of gear oils included viscosity (40 °C), elemental phosphorus, moisture, iron content, PQ value, and silicon content. 'plot()' function was mainly used to visualise the changing trends in gear oil, and data heterogeneity was treated with minimum–maximum normalisation method for comprehensive analysis. Gear wear evaluation can be realised by a multivariate modelling process in gear wear monitoring system. Validation tests demonstrated that the system not only realised the automated conversion of discrete and sparse gear oil analysis data, but also monitored and evaluated the state of wind turbine main gear wear in real time and with high efficiency, thus substantially improving the level of wind turbine operational performance prediction and providing further technical guarantee for reliable and continuous operation of wind turbines.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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