# Analysis of Regression Models for estimating the main bearing loads of wind turbines

Master Thesis
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Aachen, 12.08.2022

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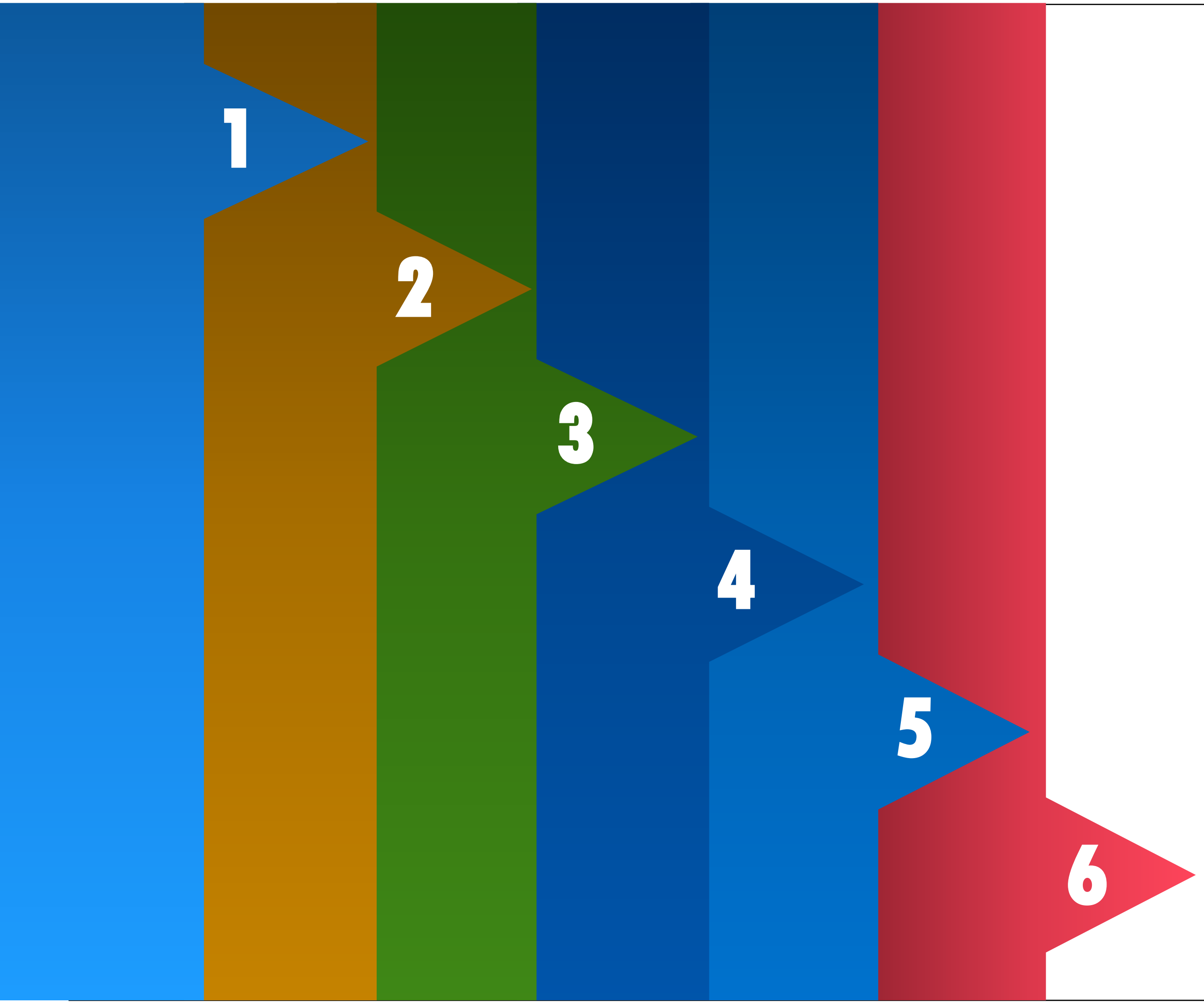
# Structure

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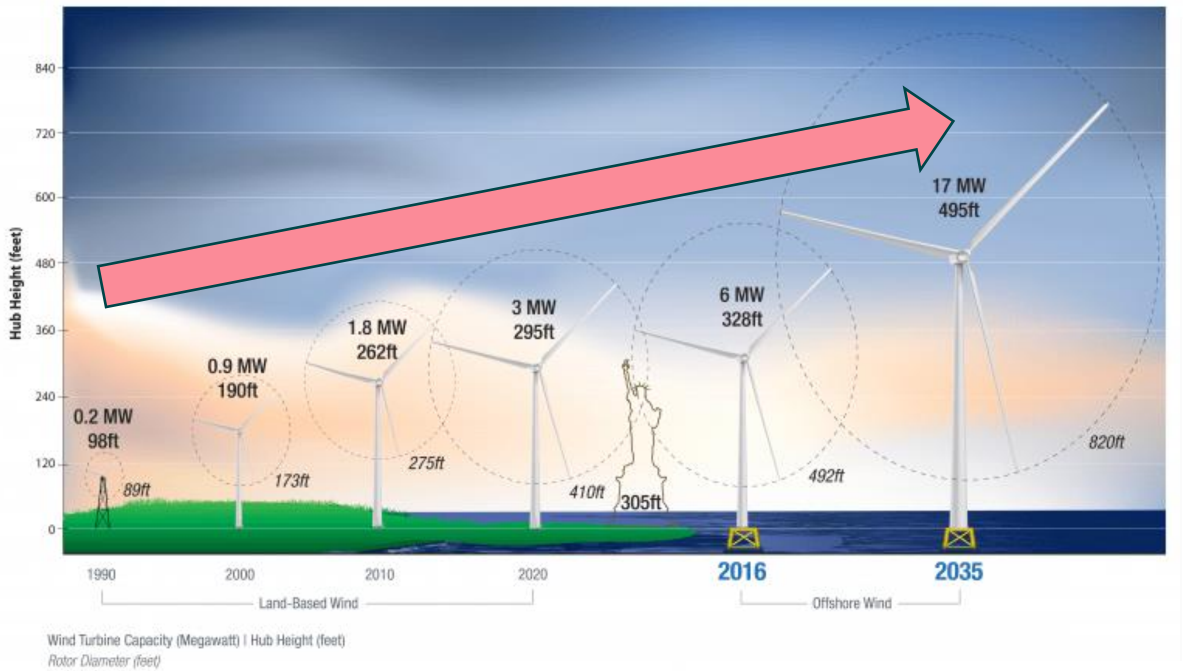
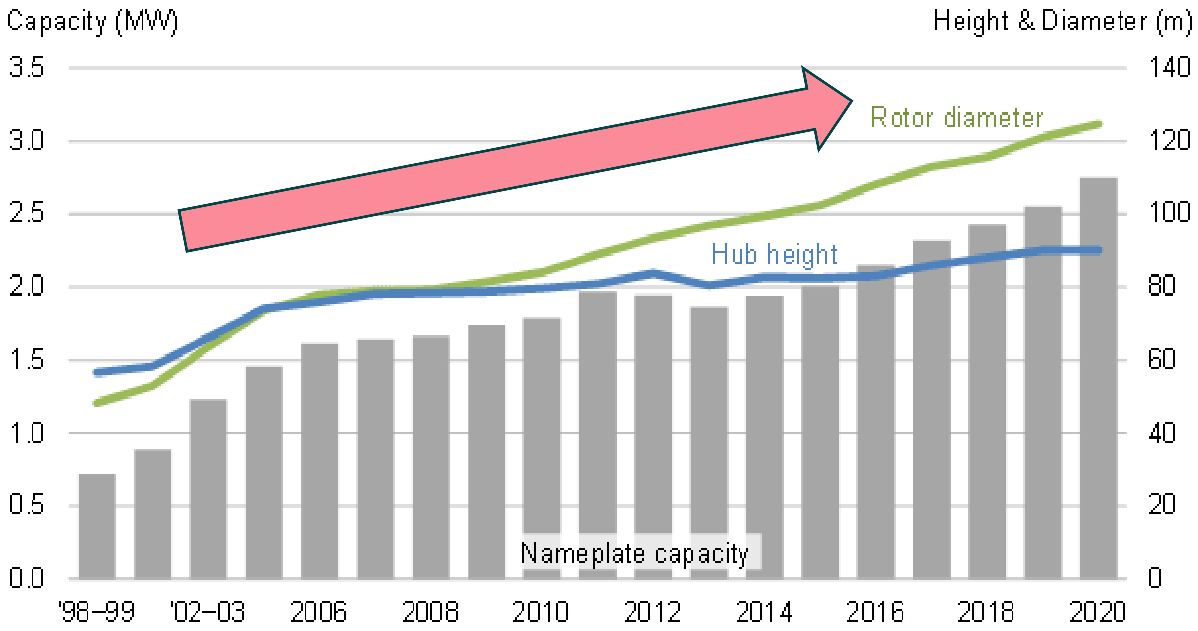
# MOTIVATION

# Motivation




- Wind is set for largest increase in renewable energy generation growing by 275TW by 2021.
- The trend shows that there is substantial increase in diameter of turbine blades and size of hub every decade by an amount of 40 percent every decade.
- This increased size has significantly increased the torque and non torque loads.

Source : Office of energy efficiency and renewable energy



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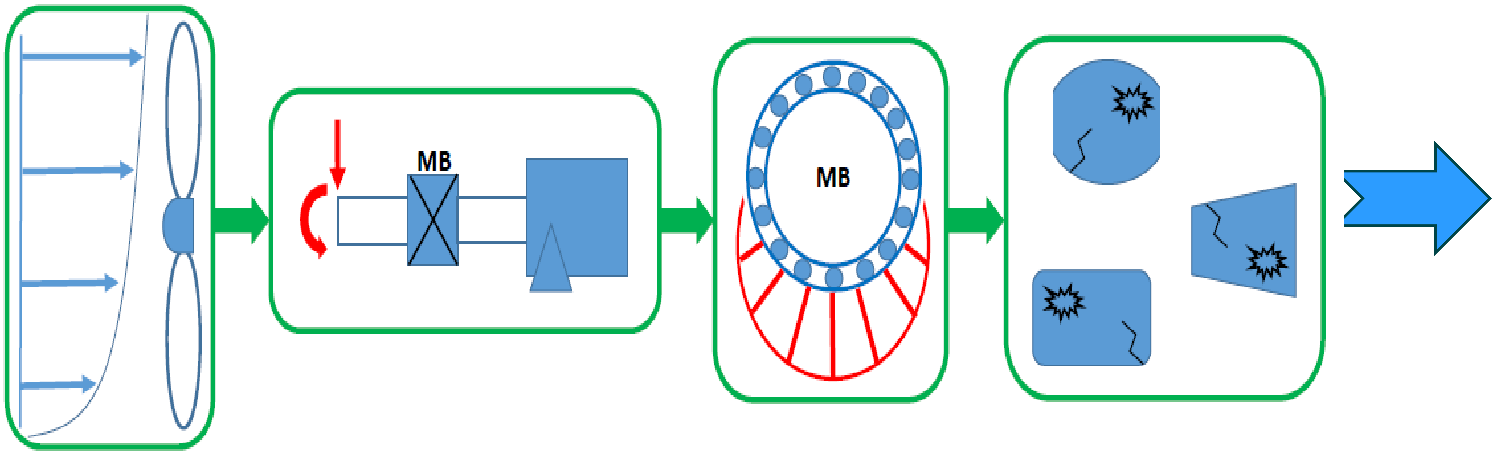
# Motivation




**High Operation cost and less reliability**

- Under ideal conditions, lifespan of wind turbine is around 20 years[#].
- In actual , the wind turbine lasts for about 6 years[#].

**Reason[#]:**

- Wear and tear due to bearing misalignment
- Bearing unseating, skewing and sliding due to high axial to radial loads.

**Solution:**

Load monitoring system to monitor loads and send signals prior to observed failures.

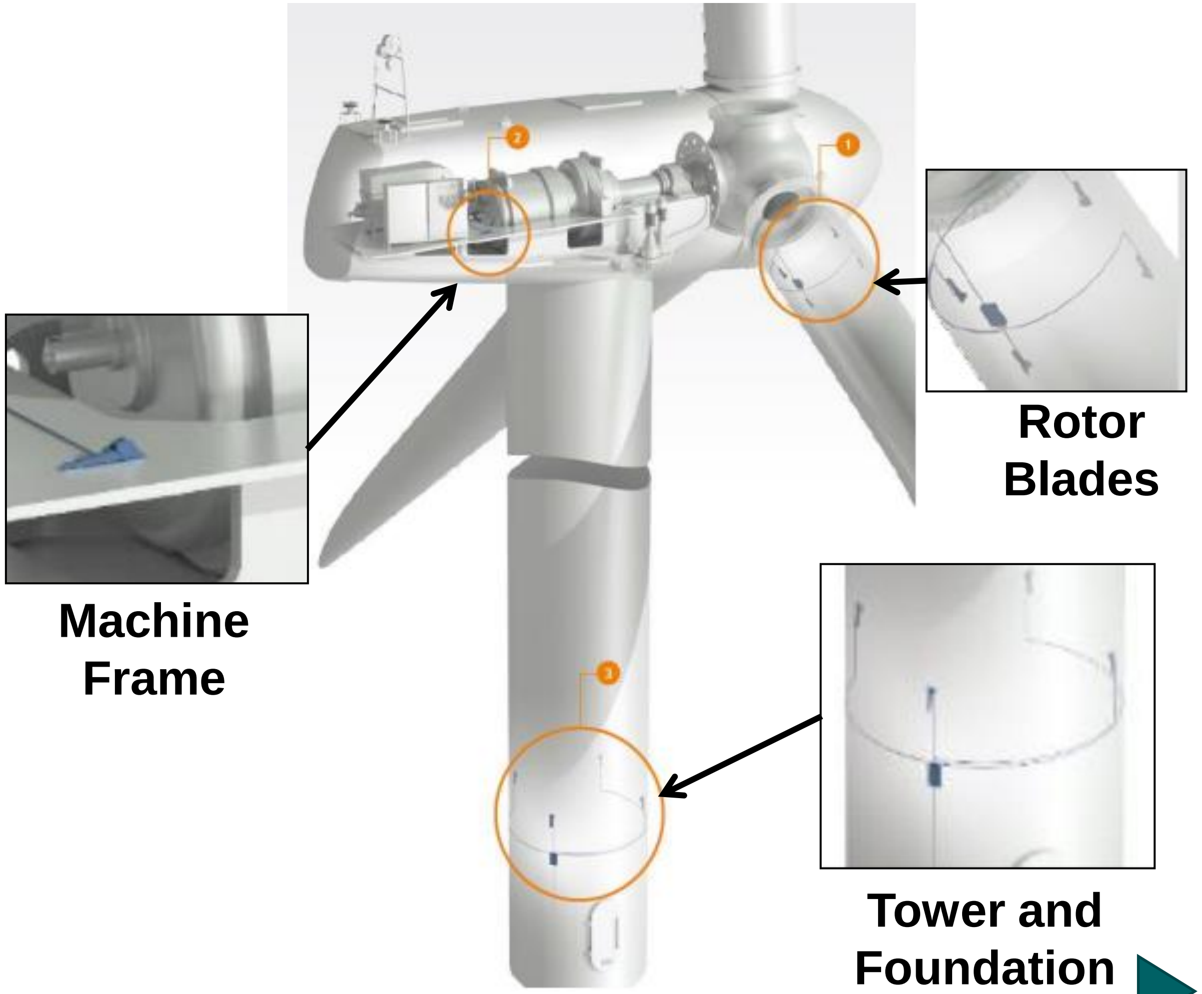
# Source: Wind turbine main-bearing loading and wind field characteristics, Edward Hart

# BACKGROUND

# Background

Strains → **Strain Gauge** → loads

- Currently **strain based load estimation** is used.
- Measurement based on linear relationship between strains and loads.
- Vulnerable to calibration error and signal drift#.
- Limited lifetime typically 1 to 3 years#.
- A better technology is necessary which is **long-lasting** and **robust.**



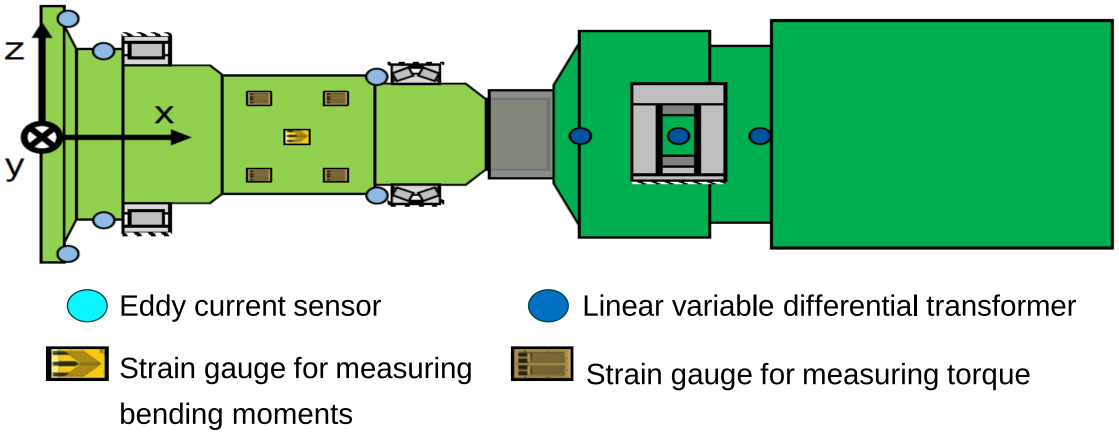

# Source:Fibre Optic Blade Monitoring for optimisation of offshore wind farm O&M, TW Verbruggen

Source : Leine Linde Systems

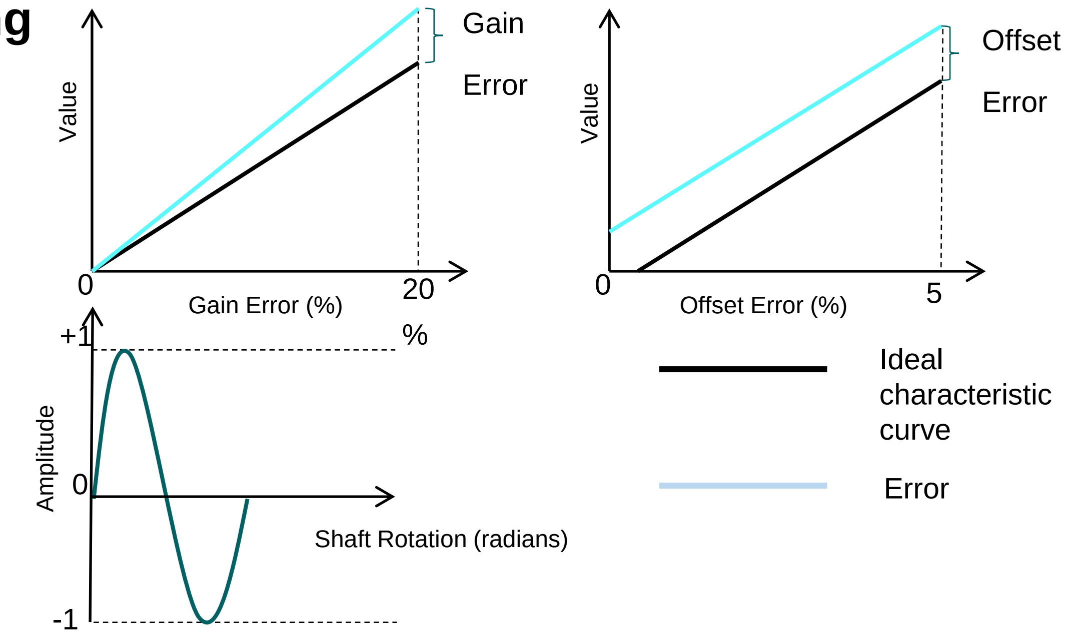
# OBJECTIVE

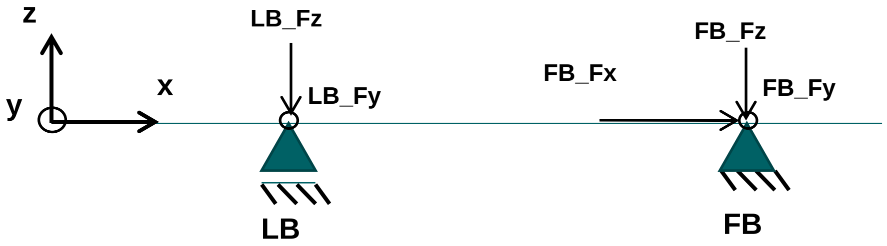
# Objective

**Displacements** → **ML Model** → **Main Bearing loads**




## Model Robustness

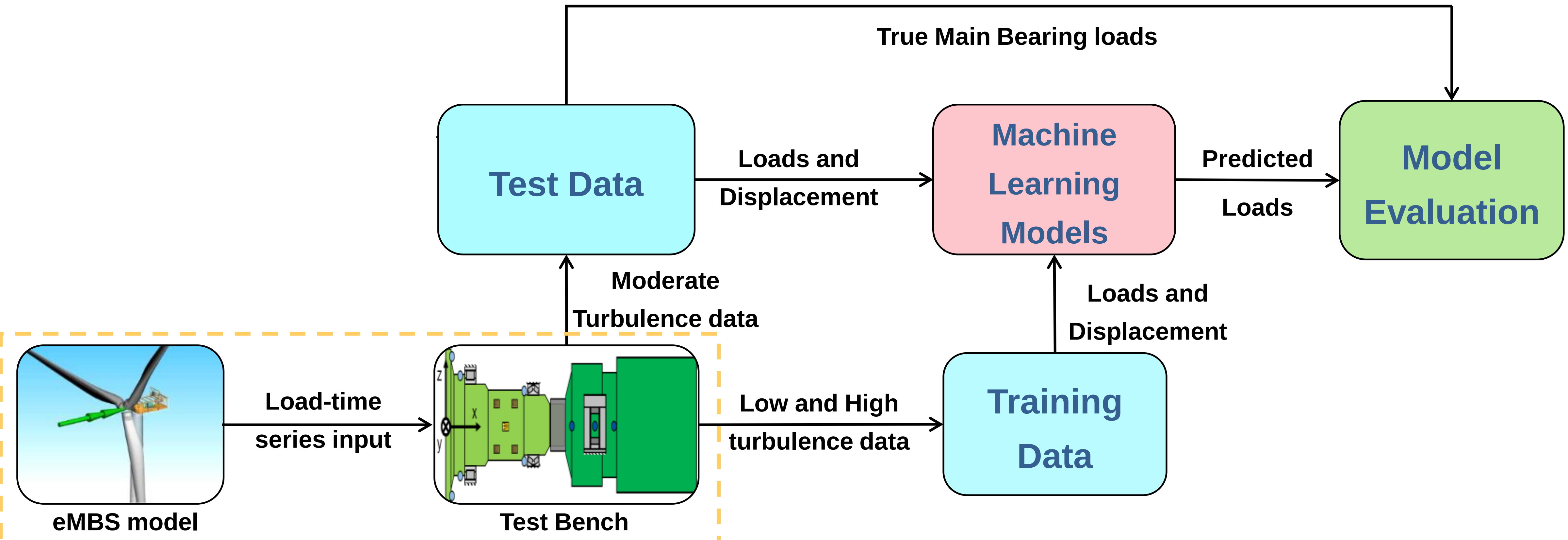



- Training, building and testing the models from displacement signals recorded by Eddy current sensors to predict loads.
- Checking robustness of models to errors like **Gain error, Offset error and sinewave error.**

# METHODOLOGY

# Methodology



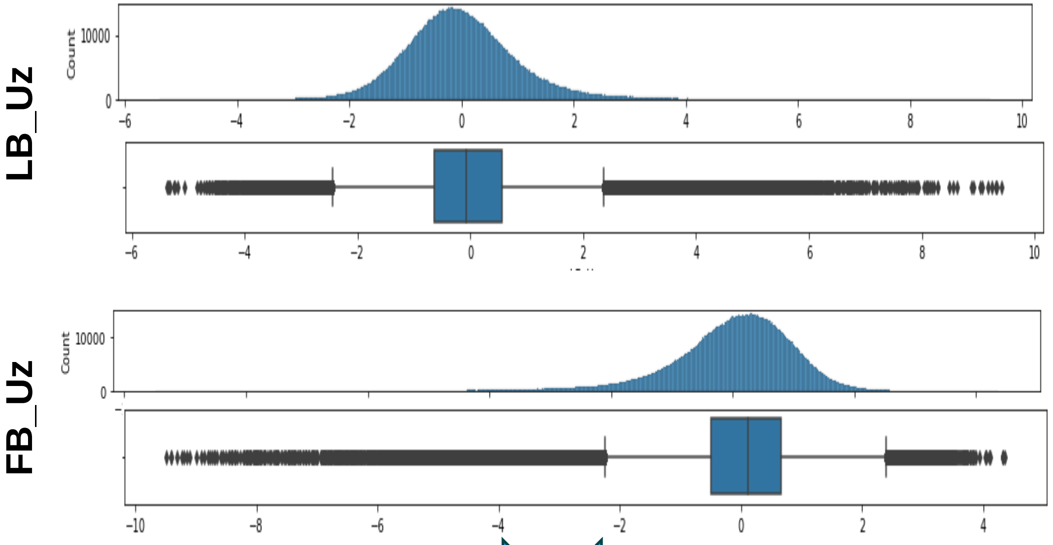

**From previous study at CWD, the eMBS model was built and subjected to different wind fields.**

# EDA and Feature Engineering

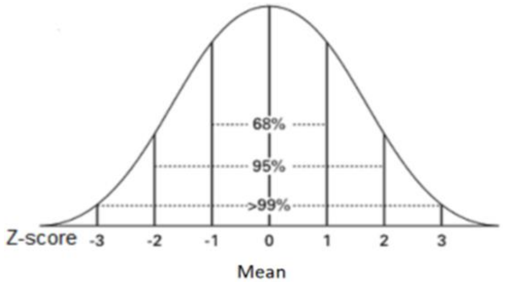
## Variables study

| Independent Variables | | Response Variable |
|---|---|---|
| Fixed Bearing (FB) | Loose Bearing (LB) | Main Bearing Loads |
| Linear Displacements | Linear Displacements | Fixed Bearing Loads |
| x direction - FB_Ux<br>y direction - FB_Uy<br>z direction - FB_Uz | x direction - LB_Ux<br>y direction - LB_Uy<br>z direction - LB_Uz | x direction - FB_Fx<br>y direction - FB_Fy<br>z direction - FB_Fz |
| Angular Displacements | Angular Displacements | Loose Bearing Loads |
| y axis - FB_PHIy<br>z axis - FB_PHIz | y axis - LB_PHIy<br>z axis - LB_PHIz | y direction - FB_Fy<br>z direction - FB_Fz |

## Outlier Detection




## Normalization




$$z = \frac{x - \mu}{\sigma}$$

$\mu$ = Mean
$\sigma$ = Standard Deviation

- Performance of regression models depend on quality of data and outliers can lead to high variance.
- The training data was split in **80% for training** and **20 % for validation**.
- The data was normalized using **Z-score** method.



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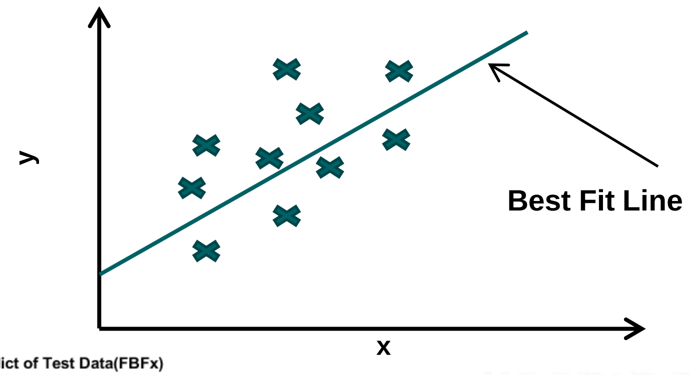
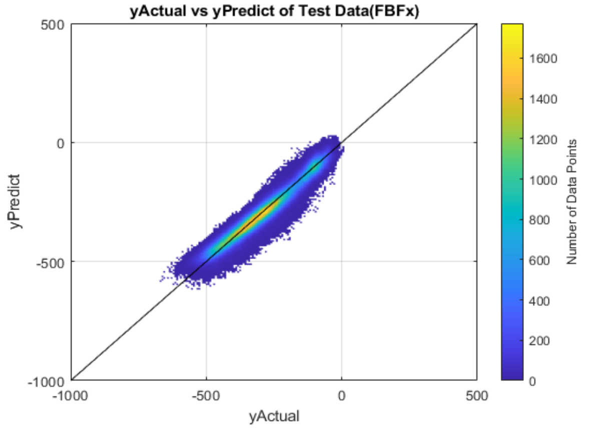
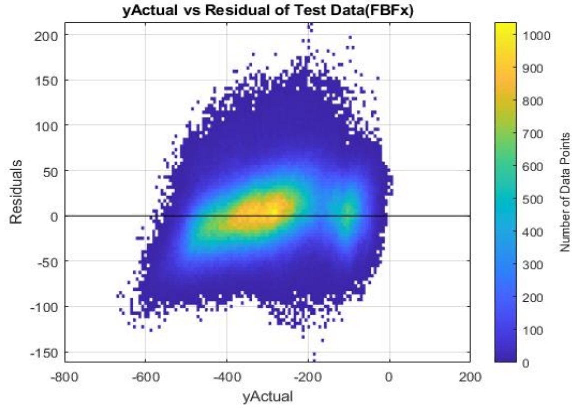
# Linear and Polynomial Regression

## Linear Regression for FB_Fx



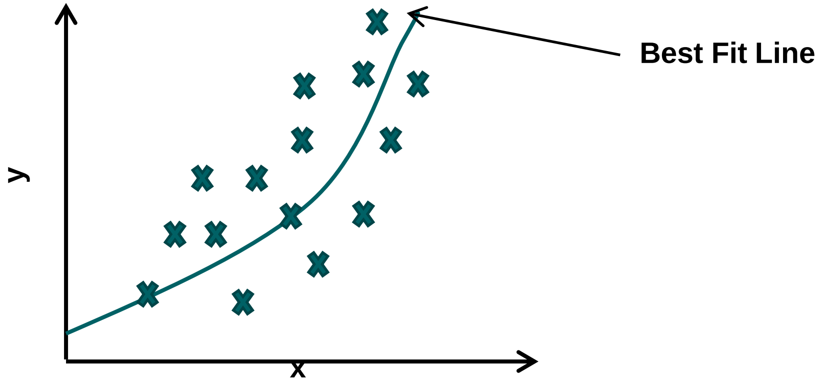



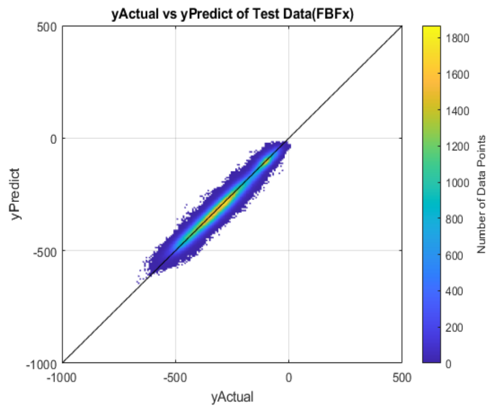



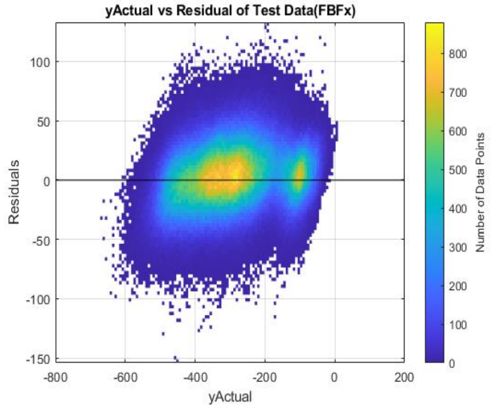

| MAE | MSE | RMSE | R2 |
|---|---|---|---|
| 22.7565 | 856.9163 | 29.2731 | 0.9392 |

- Simple model and used as reference.
- Residual error range
- **-120kN to +180kN**.

## Polynomial Regression for FB_Fx



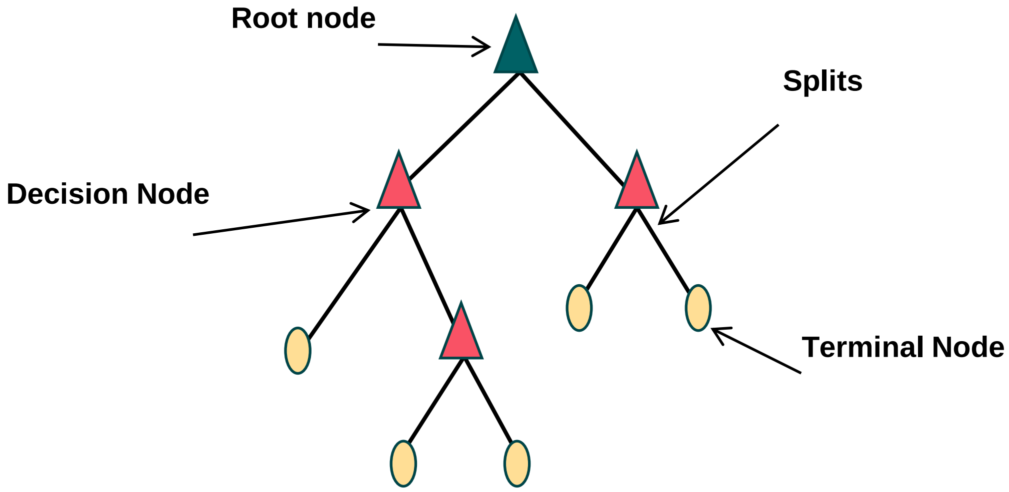



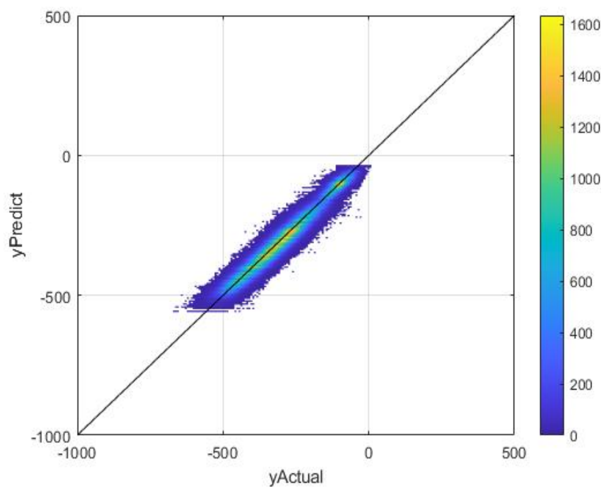



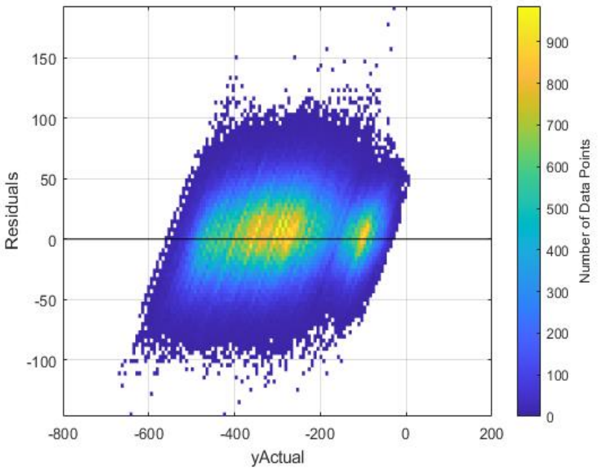

| MAE | MSE | RMSE | R2 |
|---|---|---|---|
| 18.9258 | 574.4274 | 23.9672 | 0.9593 |

- Degree is **2**.
- Residual error range **-100kN to +100kN**.

# Regression Tree Model



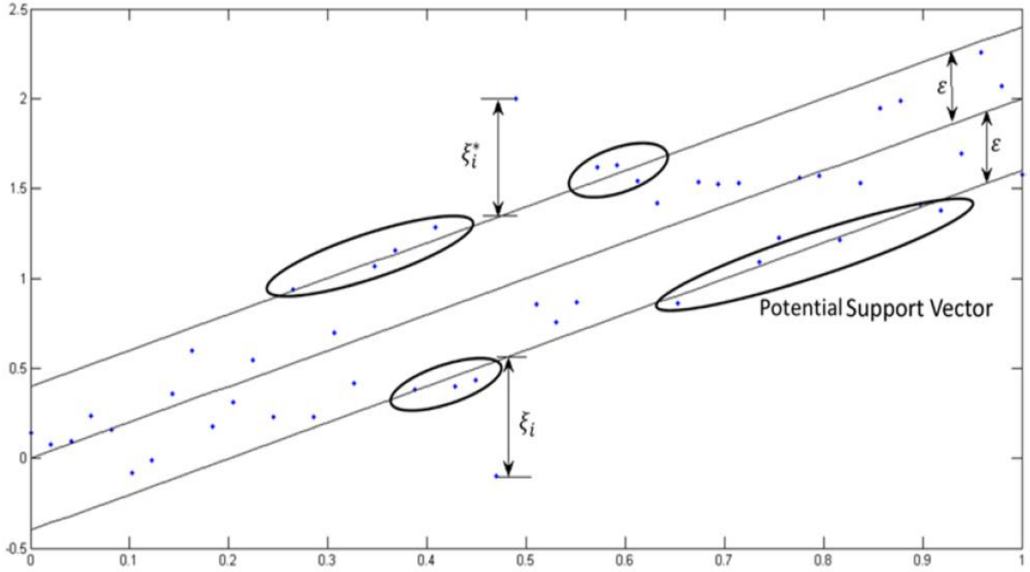



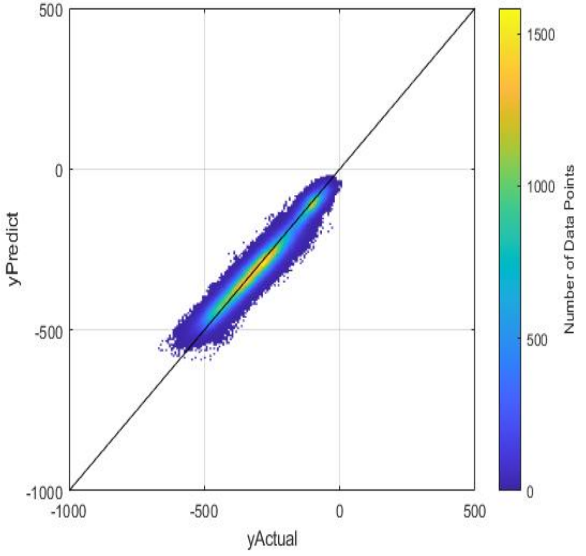



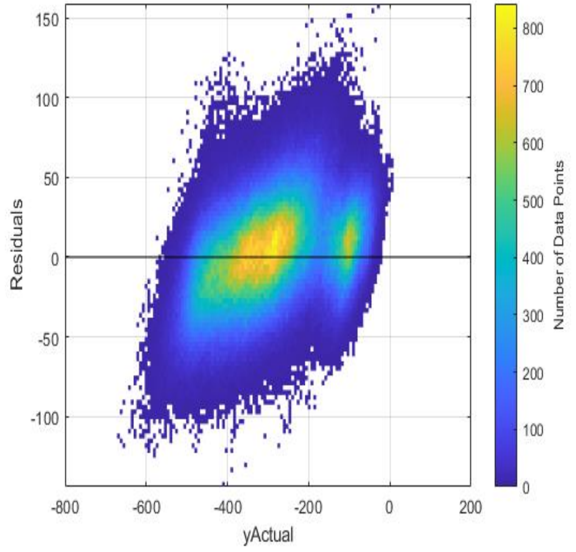

- Flexibility to capture nonlinear predictor-response relationship.
- Minimum leaf size set at 35 to 40 for balanced fit.
- Residual error varying between **±110kN** with high density points found at around **±25kN**

| MAE | MSE | RMSE | R2 |
|---|---|---|---|
| 20.6247 | 681.8551 | 26.1124 | 0.9516 |

# Support Vector Regressor




- Consists of Є tube which reformulates the optimization problem to find best tube that approximates continuous valued function.
- The kernel was set as polynomial of order 2.
- The residual error varied between **±120kN** with high density of points seen around **±35kN**.

| MAE | MSE | RMSE | R2 |
|---|---|---|---|
| 22.3663 | 796.6266 | 28.2246 | 0.9435 |



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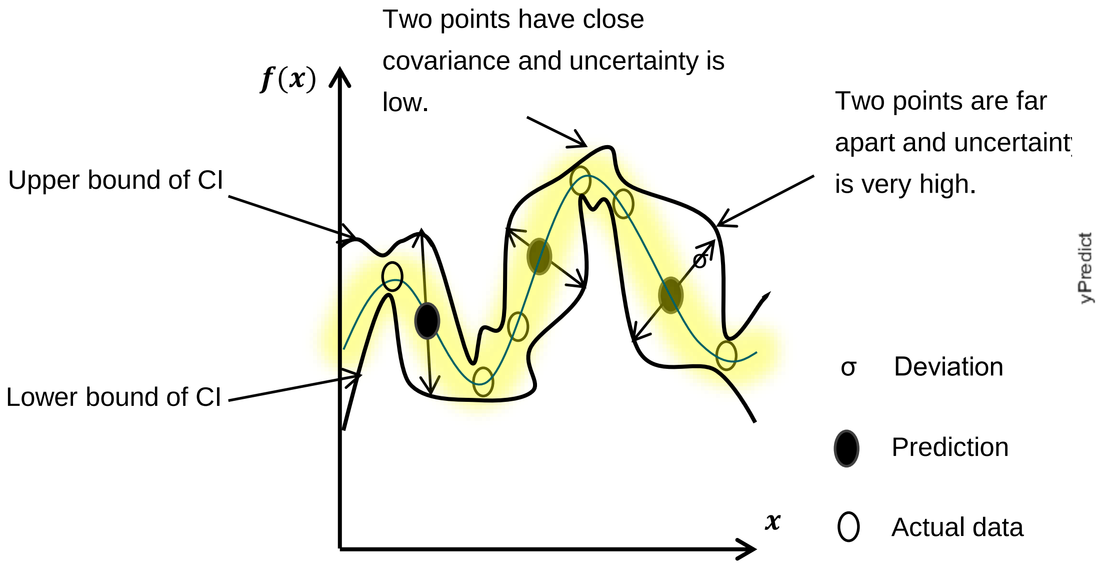
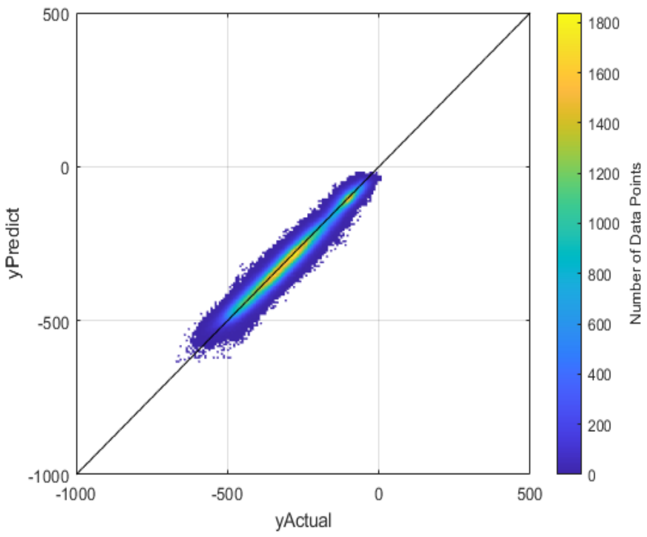
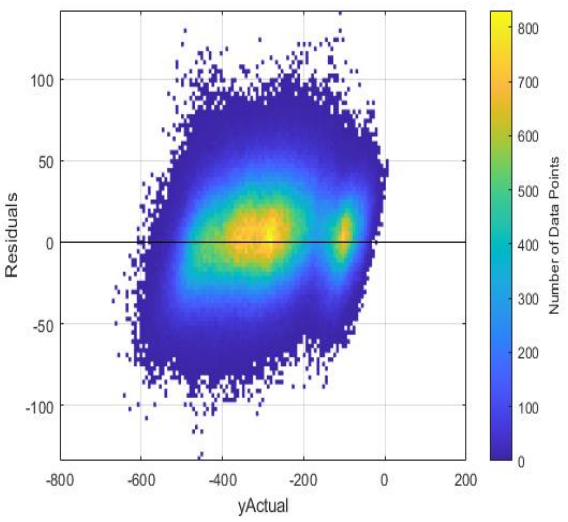
# Gaussian Process Regressor



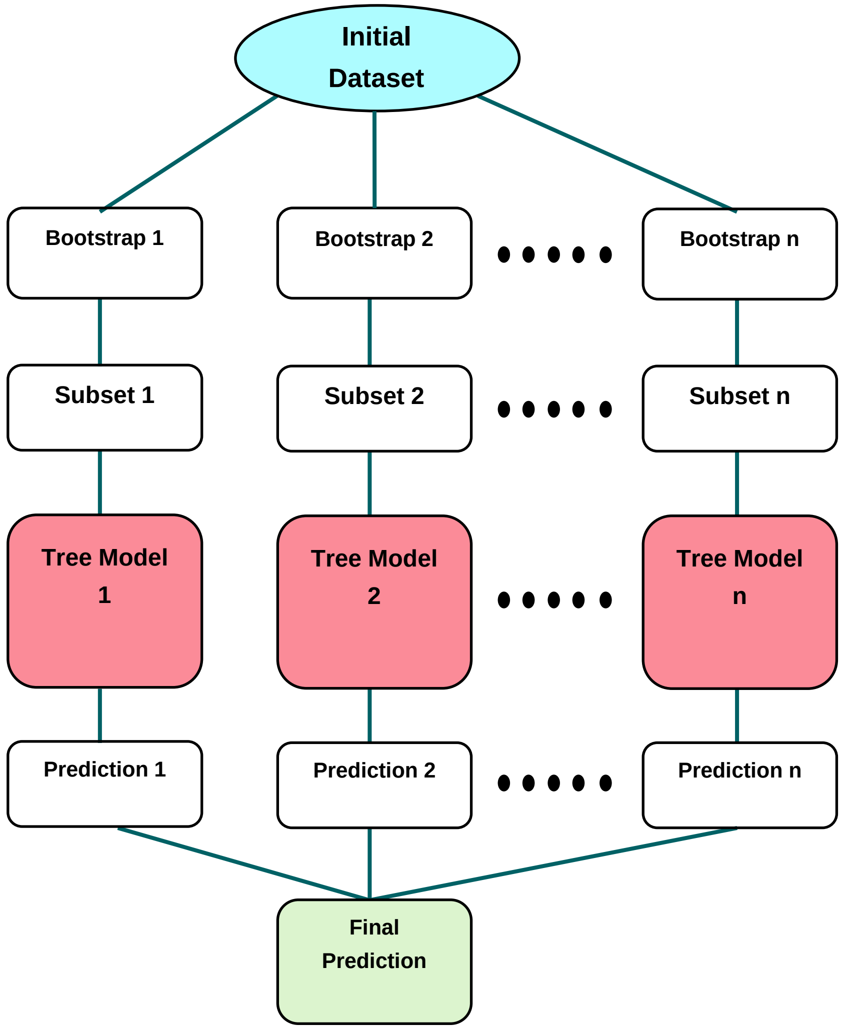



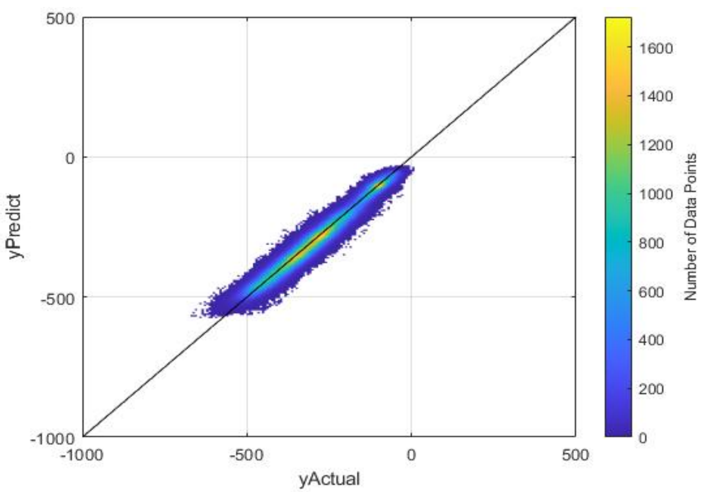



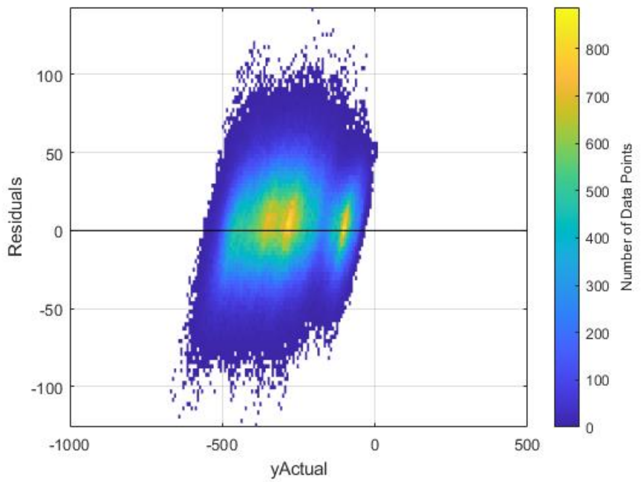

- Gaussian process regression (GPR) models are nonparametric kernel based probabilistic models.
- Kernel function used is squared exponential based on the data distribution.
- The residual error varies between **±95kN** with high density of points seen around **±25kN**.

| MAE | MSE | RMSE | Rsq |
|---|---|---|---|
| 18.5603 | 553.0644 | 23.5173 | 0.9608 |

# Ensemble Bagged Tree




| MAE | MSE | RMSE | R2 |
|---|---|---|---|
| 19.2415 | 594.3141 | 24.3786 | 0.9579 |

- A bagged ensemble tree is a machine learning algorithm where multiple tree models are trained to solve the same problem and combined to get better results.
- Bagged ensembles help to avoid the problem of overfitting.
- The model becomes resilient to generating errors.
- Residual error varying between **±90kN** with high density of points seen around **±20kN** .



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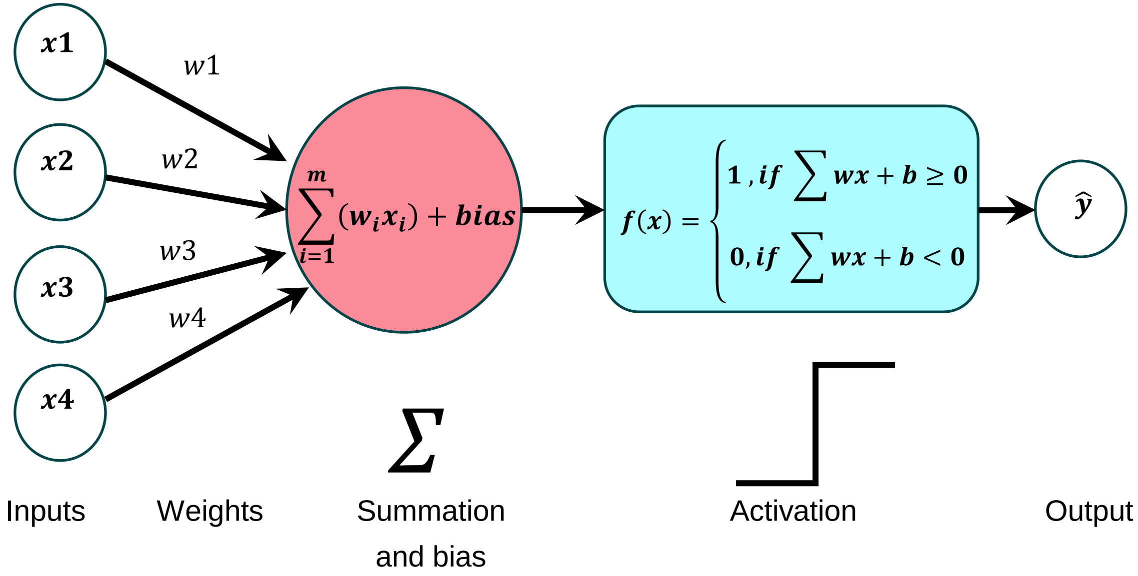
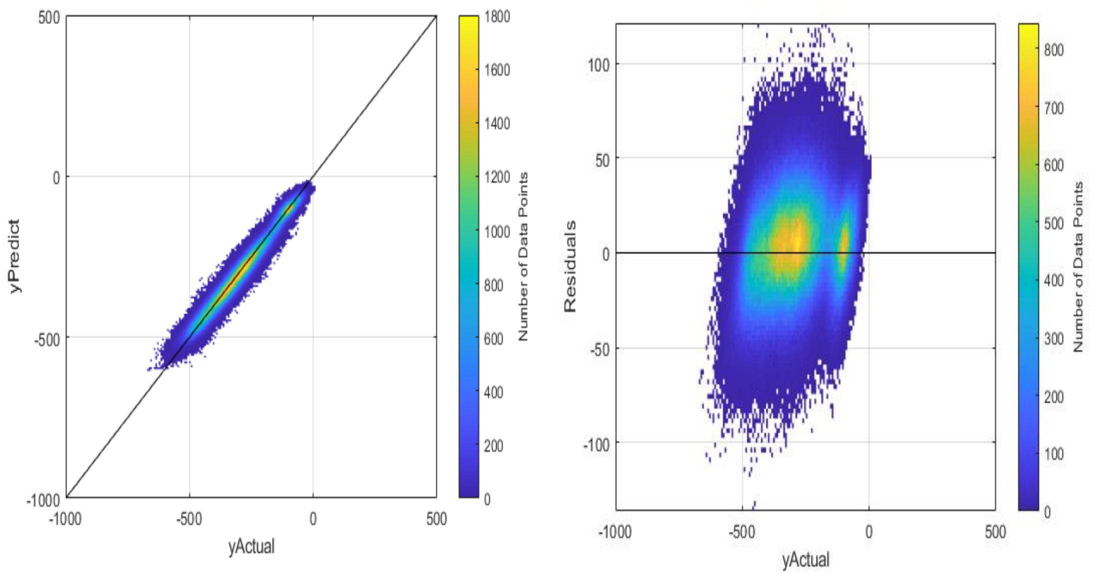
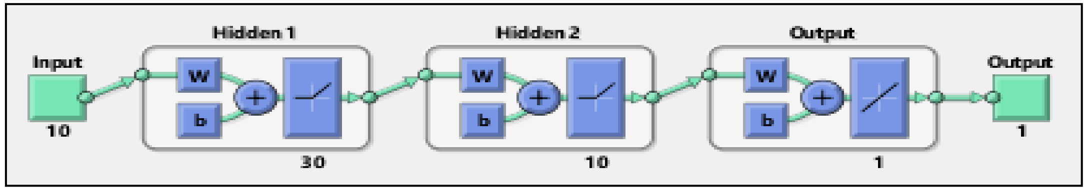
# Artificial Neural Network




| MAE | MSE | RMSE | R2 |
|---|---|---|---|
| 18.1189 | 527.1320 | 22.9594 | 0.9626 |

- To model a better nonlinear correlation between the displacements and the loads.
- The model was built with 2 hidden layers with RELU as activation function.

- Residual error varying between **±80kN** with high density of points seen around **±20kN** .



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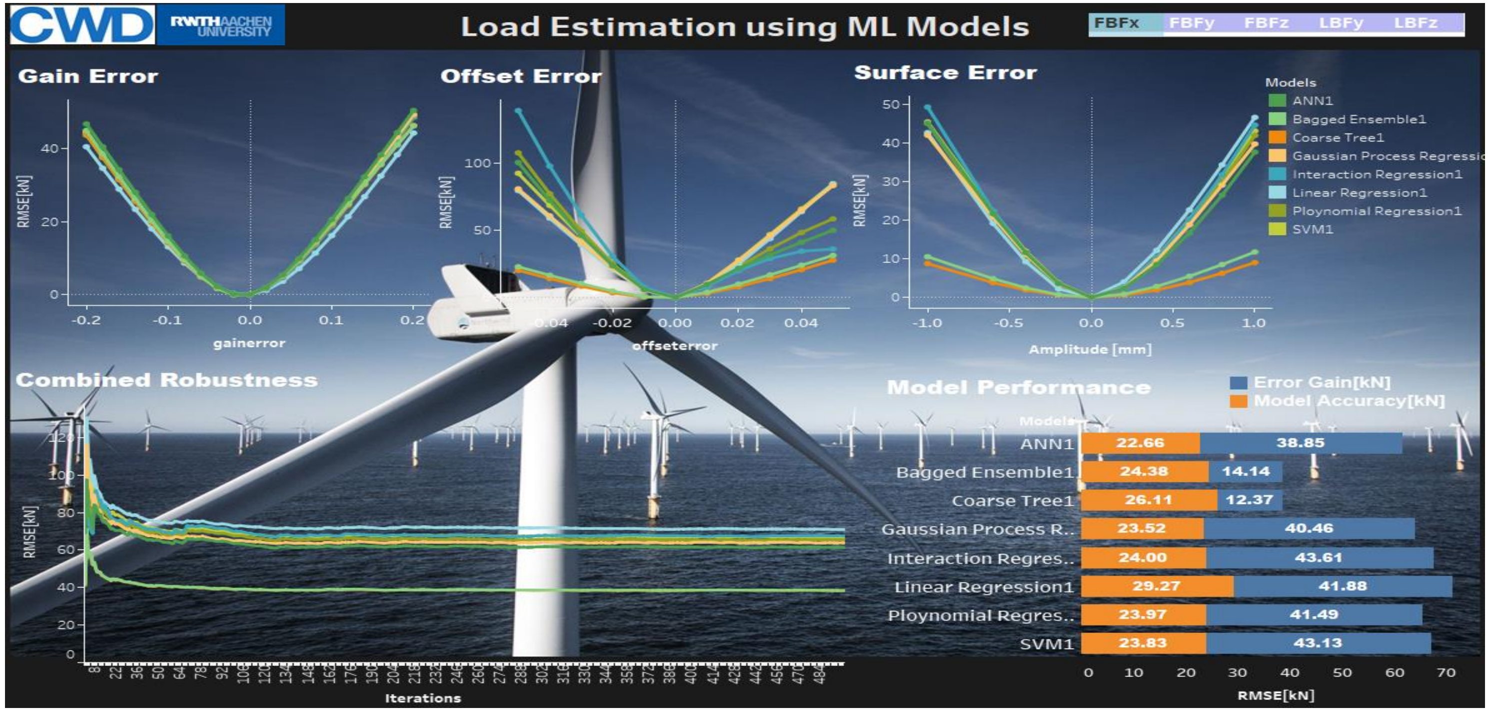
# RESULT STUDY

# Result Study




The results of each model and its performance for each main bearing loads is discussed in dashboard which can be accessed using below link.

https://public.tableau.com/views/Thesisresults_dashboard_v4/Dashboard12?:language=en-US&publish=yes&:display_count=n&:origin=viz_share_link

# Summary and Outlook

# Summary and Outlook

**Summary:**

- With approach presented in thesis, Regression models can estimate main bearing loads from displacement values with certain degree of error.
- Apart from linear model, all models could capture nonlinearity due to bearing surface and clearance with Bagged ensemble showing highest robustness.
- Bagged Tree ensemble model consistently showed strong robustness for all main bearing loads.
- ANN model showed good performance with original dataset and captured nonlinearity but was inconsistent in robustness test.
- Compromise made between the accuracy and robustness.

**Outlook:**

- Models can be further trained with dataset consisting all kinds of error for better performance to capture nonlinearities.
- Further study is needed on the minimum threshold for accuracy and robustness required to be implemented in real world.

# Thank you for your attention.

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