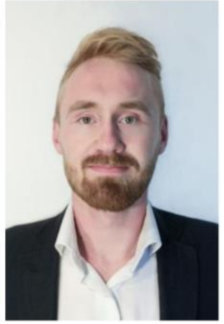
FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

Advanced Business Analytics Seminar
Winter Semester 23/24

Analysis of Continuous Manufacturing Sensor data with REHAU

TEAM

Our Advisor



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Analysis of continuous manufacturing polymer extrusion sensor data with REHAU

The shift towards Industry 4.0 entails a gradual rise in the intricacy of system operations and the management of production processes. Concurrently, emerging technologies present opportunities for enhancing services and cutting costs. With machines becoming more digitized, substantial amounts of data are now being collected. Utilizing data-driven methods becomes a viable solution to address the growing complexity and unlock potential benefits.

Objectives

- Identify polymer extrusion process dependencies and causalities.
- How do sensor parameters influence each other?
- Building data-driven process-model from data
- Model to simulate „what-if" - scenarios

Figure only for representation

OVERVIEW

DATA OVERVIEW

RAW DATA

6.8 M rows X 93 columns

HOPPER SECTION

Total 5 Hoppers. For each hopper we have:

- Temperature
- Power
- Rotation Speed
- Weight
- Throughput

MAIN EXTRUDER SECTION

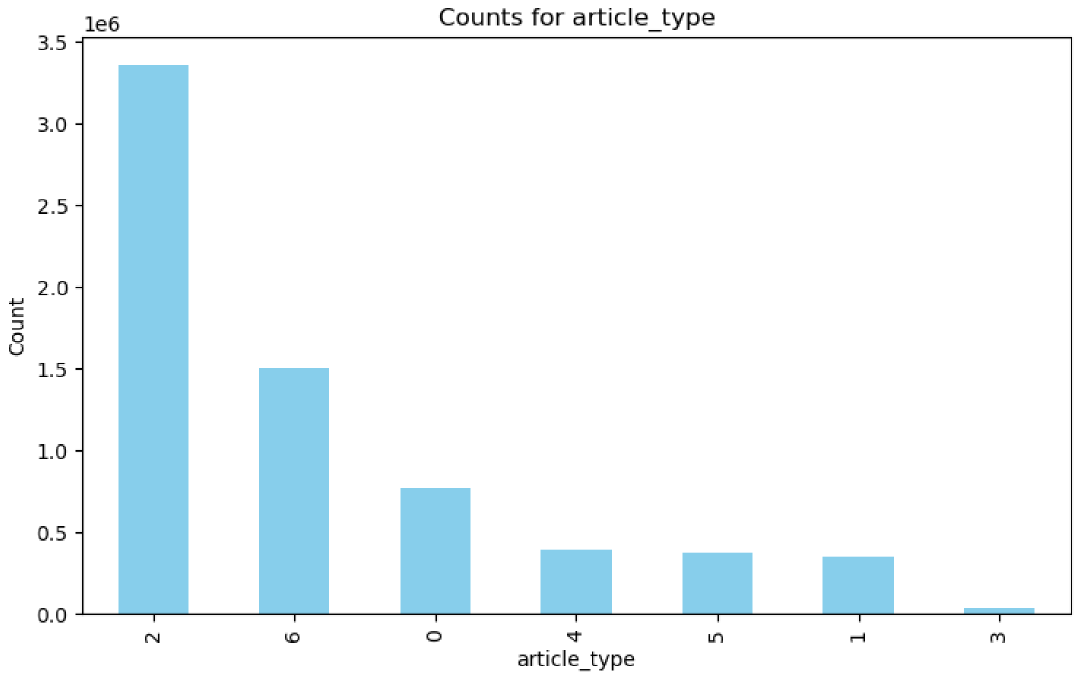
Main sensor parameters:

- Funnel Active
- Temperature
- Pressure
- Screw Load
- Screw Rotation speed
- Vacuum

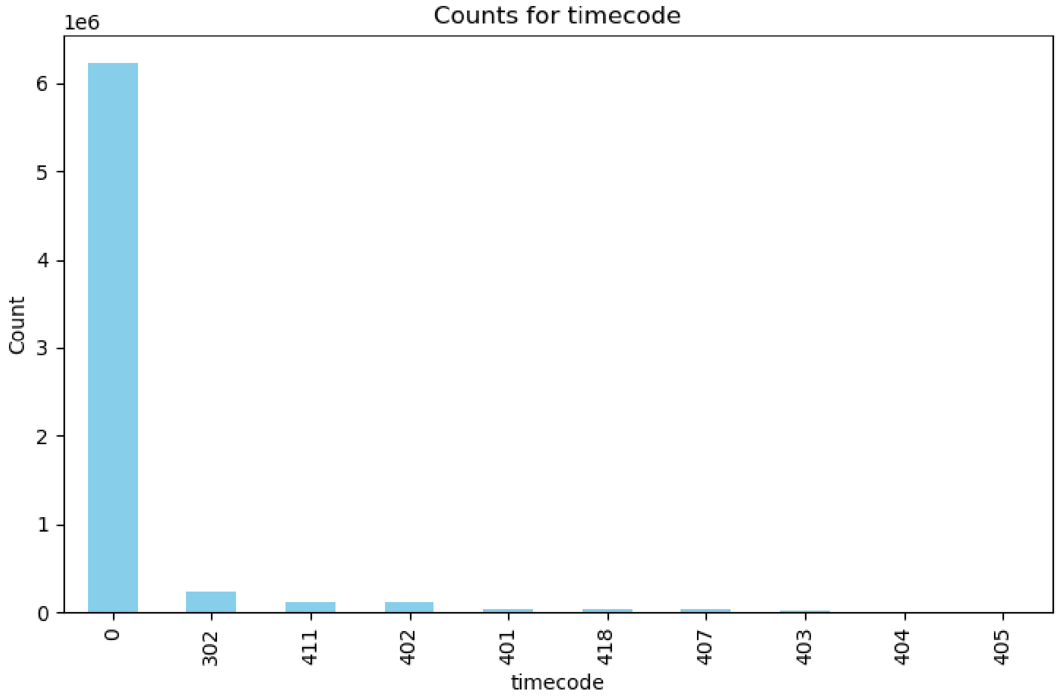
Total 16 zones. For each zone, we have:

- Control Point
- Temperature

INITIAL FINDINGS



50% of the observations represent Article type 2.



Timecode 0 represents production time in line with specifications and others represent machine/article failure time.

OVERVIEW

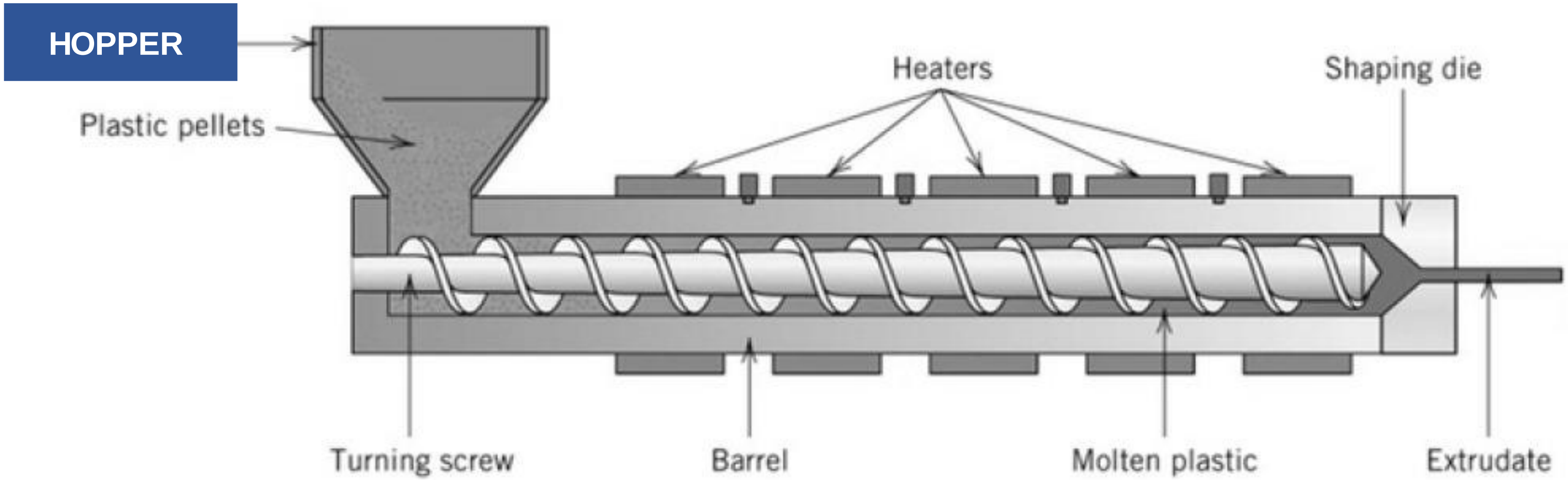
1. Data Overview & Initial Findings

2. Hopper Section
    I. Dependencies
    II. Model Building 1 & its What if Scenarios
    III. Model Building 2

3. Main Extruder
    I. Model Building 1 & What if Scenarios
    II. Dependencies
    III. Model Building 2
    IV. ADF Testing
    V. Granger Causality Test

4. Future Endeavours

HOPPER SECTION



HOPPER : DEPENDENCIES

Strong Correlation	Weak Correlation	No Correlation

Hopper 1-4	Temperature	Power / Throughput / Rotation speed	Weight
Temperature			
Power / Throughput / Rotation speed			
Weight			

- Hoppers 1-4 exhibit consistent correlation patterns among various sensor parameters.
- The high degree of similarity between Power, Throughput & Rotation speed suggests a cohesive behavior in the relationships between these sensors.

Hopper 5	Temperature	Power / Throughput / Rotation speed	Weight
Temperature			
Power / Throughput / Rotation speed			
Weight			

- Hopper 5 displays a slight deviation in correlation patterns compared to Hoppers 1-4.
- This distinct behavior in Hopper 5 may indicate unique operational characteristics or specific influences on the correlation between its sensor parameters.

HOPPER : MODEL BUILDING 1

Objective: Optimizing Hopper Parameter Coefficients for Precise Throughput Prediction

- Goal: Attain optimal coefficients for hopper parameters to predict throughput, closely aligning with predefined throughput standards.
- Striving for a model that ensures accurate throughput predictions based on specified hopper features.

Features and Target

- Parameters under consideration: Temperature, Power, Rotation Speed and Weight.
- Target variable for prediction: Throughput - the key performance indicator.

Model and Approach: Lasso Regression, but why Lasso?

- Lasso regression performs variable selection by imposing a penalty on the absolute size of the regression coefficients. This means that it tends to shrink the coefficients of less important variables towards zero, effectively selecting the most relevant variables. In the context of the hopper section, where various factors (e.g., temperature, pressure, screw speed) might affect the extrusion process, Lasso can help identify the most influential variables among a large set of potential predictors.

- Regularization: Lasso regression incorporates a regularization parameter that helps prevent overfitting by penalizing large coefficient values.

HOPPER : MODEL BUILDING 1

For simplicity of this presentation we have chosen Article Type 2 in this model since it covered 50% of the overall data.

```
Coefficients:
Feature 1: -0.0
Feature 2: -0.09
Feature 3: 0.33
Feature 4: 0.26
Feature 5: 0.09
Feature 6: 0.07
Feature 7: 0.12
Feature 8: -0.14
Feature 9: 0.0
Feature 10: 0.0
Feature 11: 0.04
Feature 12: -0.0
Feature 13: -0.0
Feature 14: 0.0
Feature 15: 0.13
Feature 16: -0.0
Feature 17: 0.38
Feature 18: 0.50
Feature 19: 0.08
Feature 20: 0.0004
```

→

```
Important Features and their Coefficients:
Hopper 1 Power: -0.09
Hopper 1 Rotation Speed: 0.33
Hopper 1 Weight: 0.26
Hopper 2 Temperature: 0.09
Hopper 2 Power: 0.07
Hopper 2 Rotation Speed: 0.12
Hopper 2 Weight: -0.14
Hopper 3 Rotation Speed: 0.04
Hopper 4 Rotation Speed: 0.13
Hopper 5 Temperature: 0.38
Hopper 5 Power: 0.50
Hopper 5 Rotation Speed: 0.08
Hopper 5 Weight: 0.0004
```

What does this coefficient signify?

Coefficient in a Machine Learning modelling represents the weight or magnitude of influence that a particular feature has on the predicted outcome.

In Mathematical terms for a 2 feature model,

$y = m_1x_1 + m_2x_2 + b$, where:

y = predicted outcome
x_1, x_2 = input / feature values
m_1, m_2 = coefficients associated with inputs

HOPPER : WHAT IF ANALYSIS FOR MODEL 1

What if we increase the Temperature of Hopper 5 by 5%

Feature	Value
Hopper 1 Temp	24.06
Hopper 1 Power	70.9
Hopper 1 Rotation Speed	34.24
Hopper 1 Weight	6.52
Hopper 2 Temp	26.32
Hopper 2 Power	0
Hopper 2 Rotation Speed	0
Hopper 2 Weight	3.11
Hopper 3 Temp	23.29
Hopper 3 Power	0
Hopper 3 Rotation Speed	0
Hopper 3 Weight	3.86
Hopper 4 Temp	22.31
Hopper 4 Power	0
Hopper 4 Rotation Speed	0
Hopper 4 Weight	4.15
Hopper 5 Temp	304.55
Hopper 5 Power	0
Hopper 5 Rotation Speed	0
Hopper 5 Weight	8.09

Result: Observing a 4.66% increase in the model's throughput prediction with the implemented Hopper 5 Temperature adjustment.

```
Predicted output before increase : 124.39 kg/h
Predicted output after increase : 130.18 kg/h
Percentage Change: 4.66 %
```

HOPPER : WHAT IF ANALYSIS FOR MODEL 1

What if we increase the Power of Hopper 1 by 20%

Feature	Value
Hopper 1 Temp	24.06
Hopper 1 Power	70.9
Hopper 1 Rotation Speed	34.24
Hopper 1 Weight	6.52
Hopper 2 Temp	26.32
Hopper 2 Power	0
Hopper 2 Rotation Speed	0
Hopper 2 Weight	3.11
Hopper 3 Temp	23.29
Hopper 3 Power	0
Hopper 3 Rotation Speed	0
Hopper 3 Weight	3.86
Hopper 4 Temp	22.31
Hopper 4 Power	0
Hopper 4 Rotation Speed	0
Hopper 4 Weight	4.15
Hopper 5 Temp	304.55
Hopper 5 Power	0
Hopper 5 Rotation Speed	0
Hopper 5 Weight	8.09

Result: Observing a 1.03% decrease in the model's throughput prediction with the implemented Hopper 1 Power adjustment.

```
Predicted output before increase: 124.38 kg/h
Predicted output after increase: 123.10 kg/h
Percentage change: -1.03%
```

HOPPER : WHAT IF ANALYSIS FOR MODEL 1

What if we decrease the Temperature of Hopper 3 by 5%

Result: Observing a no significant change in the model's throughput prediction with the implemented Hopper 3 Temperature adjustment.

```
Predicted output before decrease: 124.38 kg/h
Predicted output after decrease: 124.38 kg/h
Percentage change: 0%
```

Feature	Value
Hopper 1 Temp	24.06
Hopper 1 Power	70.9
Hopper 1 Rotation Speed	34.24
Hopper 1 Weight	6.52
Hopper 2 Temp	26.32
Hopper 2 Power	0
Hopper 2 Rotation Speed	0
Hopper 2 Weight	3.11
Hopper 3 Temp	23.29
Hopper 3 Power	0
Hopper 3 Rotation Speed	0
Hopper 3 Weight	3.86
Hopper 4 Temp	22.31
Hopper 4 Power	0
Hopper 4 Rotation Speed	0
Hopper 4 Weight	4.15
Hopper 5 Temp	304.55
Hopper 5 Power	0
Hopper 5 Rotation Speed	0
Hopper 5 Weight	8.09

HOPPER : MODEL BUILDING 2

Objective: Optimizing Hopper Parameter Coefficients for Precise Throughput Prediction

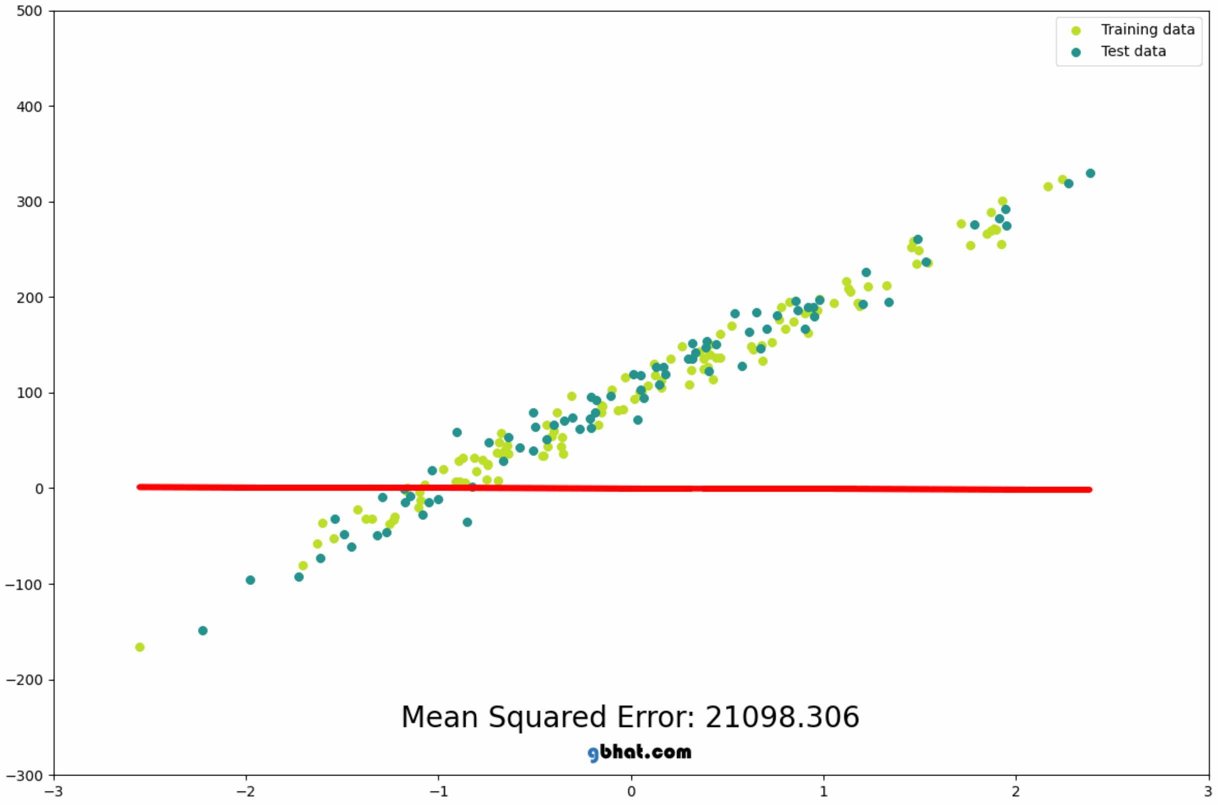
- Goal: Observe mathematical relation between throughput of each individual hopper.
- Striving for a model that ensures accurate throughput predictions based on specified hopper throughputs.

Features and Target

- Parameters under consideration: Throughput act of each hopper.
- Target variable for prediction: Throughput set.

Model and Approach: Linear Regression

- Linear regression is a statistical method used to model the relationship between a dependent variable and one or more independent variables by fitting a linear equation to observed data, aiming to predict the dependent variable's value based on the independent variable(s).



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HOPPER : MODEL BUILDING 2

Contribution of each Hopper Throughput towards the Final Throughput for each Article type

```
Article Type 1
Features Coefficients

Hopper 4 Throughput:: 0.07
```

Article Type 0 has only Hopper 4 contributing to the final Throughput

```
Article type 2
Feature Coefficients

Hopper 1 Throughput:-0.03
Hopper 2 Throughput: 0.05
Hopper 3 Throughput: 0.01
Hopper 4 Throughput: 0.23
Hopper 5 Throughput: 0.01
```

Article 2 is the only article type which has all the Hoppers from 1 to 5 contributing towards the final throughput.

HOPPER : MODEL BUILDING 2

Contribution of each Hopper Throughput towards the Final Throughput for each Article type

```
Article type 0
Feature Coefficients

Hopper 1 Throughput: 0.45
Hopper 2 Throughput: 3.23
Hopper 3 Throughput: 3.22
Hopper 5 Throughput: 0.10
```

```
Article Type 3
Features Coefficients

Hopper 1 Throughput: 0.05
Hopper 2 Throughput: 1.38
Hopper 3 Throughput:-0.08
Hopper 5 Throughput:-0.02
```

```
Article Type 4
Features Coefficients
Hopper 1 Throughput: 0.05
Hopper 2 Throughput: 2.77
Hopper 3 Throughput: 0.01
Hopper 5 Throughput: 0.08
```

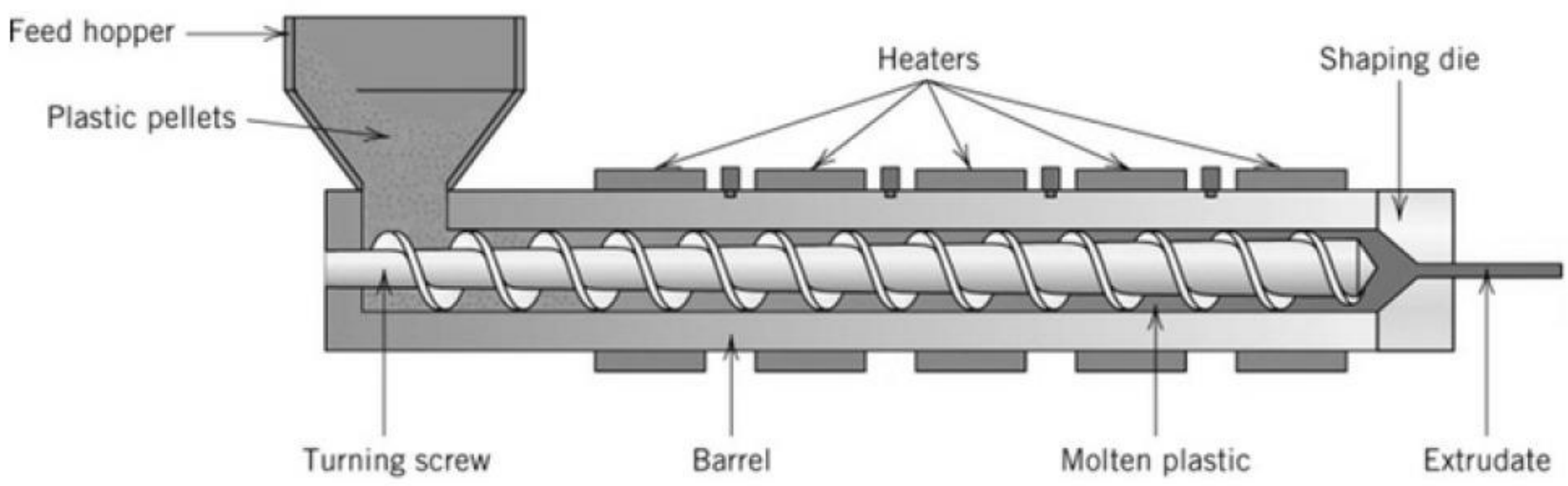
```
Article Type 5
Features Coefficients
Hopper 1 Throughput: 0.26
Hopper 2 Throughput: 0.00
Hopper 3 Throughput: 0.18
Hopper 5 Throughput: 0.07
```

```
Article Type 6
Features Coefficients
Hopper 1 Throughput: 0.60
Hopper 2 Throughput: 1.03
Hopper 3 Throughput: 1.07
Hopper 5 Throughput: 0.03
```

Each of the article type here does not have the contribution of Hopper 4's Throughput towards the final Throughput.

OVERVIEW

MAIN EXTRUDER SECTION



MAIN EXTRUDER

Objective: Optimizing Main extruder parameters Coefficients for Precise Throughput Prediction

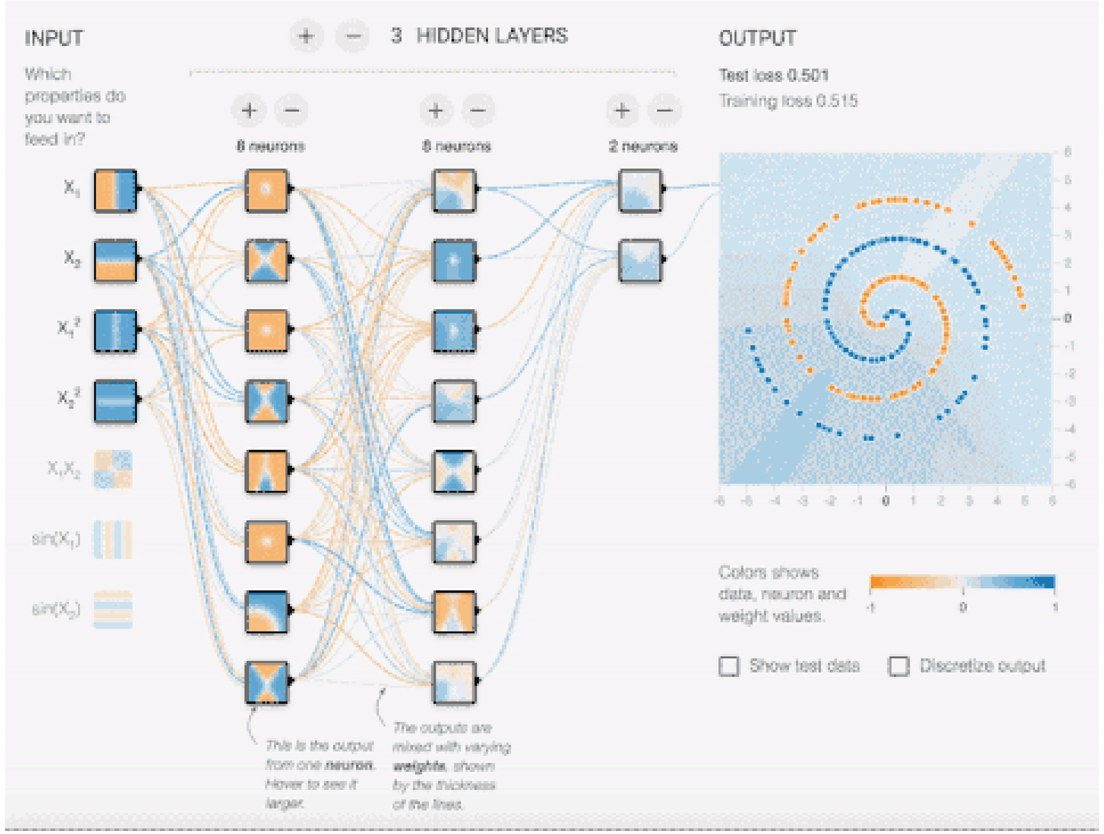
Goal: To understand the mathematical relation between main extruder sensor parameters.

Features and Target

- Parameters under consideration : Input Throughput, Funnel Active, Melt Temperature, Screw Load, Screw Rotation Speed, Vacuum.
- Target variable for prediction : Melt Temperature & Pressure.

Model and Approach: Neural Network, but why?

- Neural networks are adept at capturing and modeling the intricate nonlinear relationships inherent in polymer extrusion processes.
- Main extruder portion data is highly complex and non-linear in nature so that regular linear/ridge/lasso is not a good fit for this scenario. So in order to increase the model accuracy neural net is a good choice.



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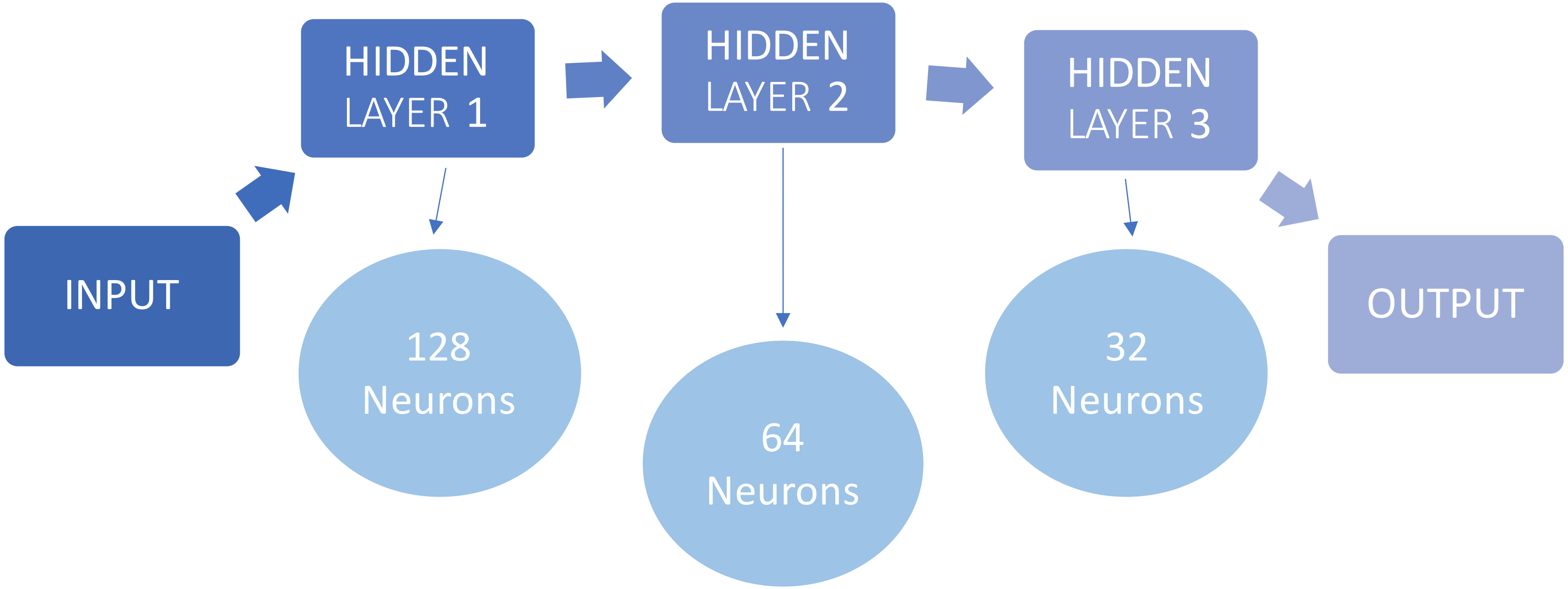
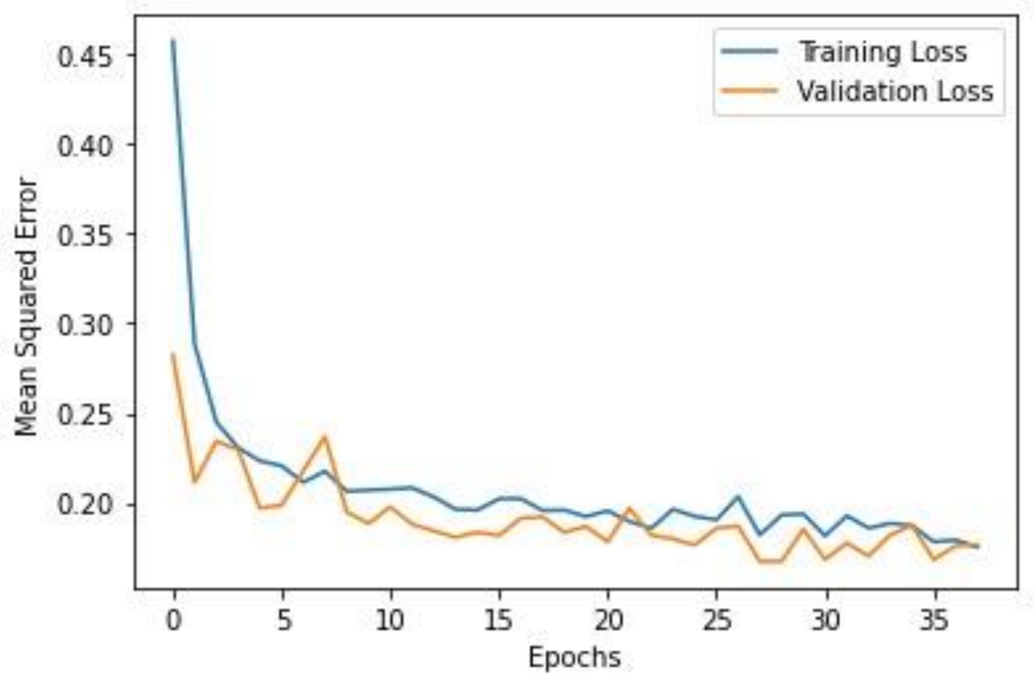
Neural Network Architecture



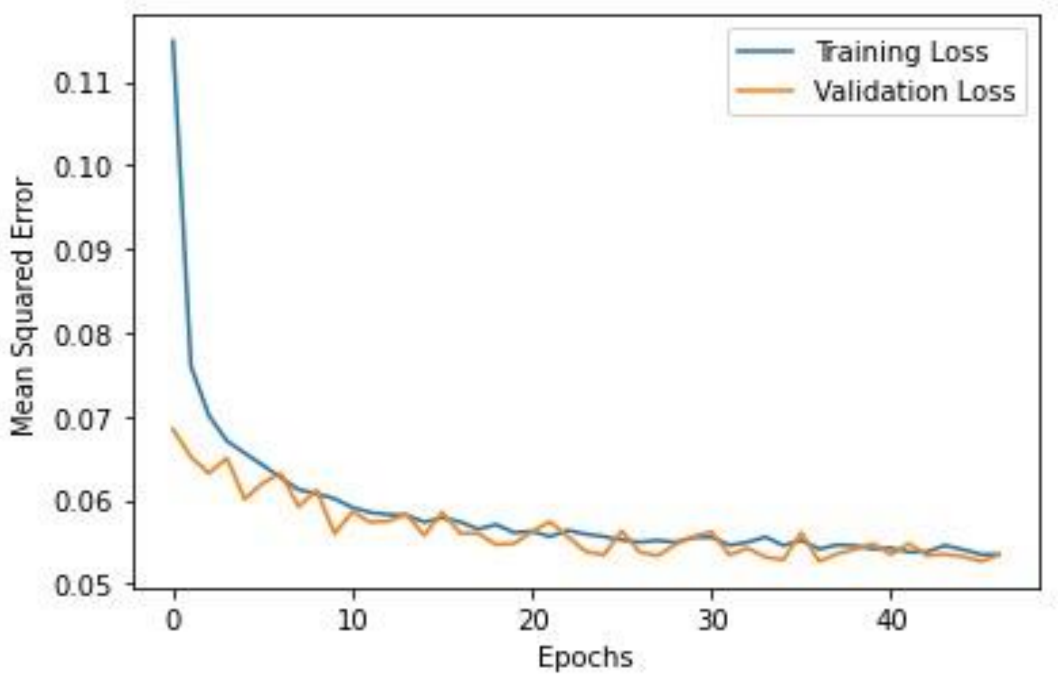
- We have passed the main extruder features to the input layer and then output is passed through the following consecutive hidden layers and finally output layer is responsible for the desired prediction.
- As we proceed through the hidden layers our model learns more abstract features gradually leading to a trustworthy accurate output.

MAIN EXTRUDER : MODEL BUILDING 1

Neural Network Training Visualization :



Loss curve for temperature as target column



Loss curve for pressure as target column

MAIN EXTRUDER : WHAT IF ANALYSIS FOR MODEL 1

What if we increase the Screw Rotation Speed by 5%, how will the Melt Pressure be affected?

Feature	Standardized Value
Total Throughput	0.13
Funnel Active	0
Melt Temperature	0.65
Screw Load	2.37
Screw Rotation Speed	0.24
Vacuum	-0.12

Result: Observing a 1.37% decrease in the model's Melt Pressure with the implemented Screw Rotation Speed adjustment.

```
Predicted output before increase (Standardized): 0.51 bar
Predicted output after increase (Standardized): 0.50 bar
Percentage Change: -1.37 %
```

MAIN EXTRUDER : WHAT IF ANALYSIS FOR MODEL 1

What if we increase the Screw Rotation Speed by 5%, how will the Melt Temperature be affected?

Feature	Standardized Value
Total Throughput	0.13
Funnel Active	0
Melt Pressure	-0.03
Screw Load	2.37
Screw Rotation Speed	0.24
Vacuum	-0.12

Result: Observing a 0.11% increase in the model's Melt Temperature with the implemented Screw Rotation Speed adjustment.

```
Predicted output before increase (Standardized): 1.256
Predicted output after increase (Standardized): 1.257
Percentage Change: 0.11 %
```

MAIN EXTRUDER ZONES 1-16 : DEPENDENCIES

Strong Correlation	Moderate Correlation	No Correlation

Zones 1-16	Temp Zones 1-12 & 15-16	Temp Zone 13	Temp Zone 14
Temp Zones 1-12 & 15-16			
Temp Zone 13			
Temp Zone 14			

- Zones 1-12 & 15-16 exhibit consistent strong correlation patterns among each other.
- Zone 13 has almost no correlation with other zones.
- Zone 14 has a moderate correlation with other zones.

MAIN EXTRUDER : MODEL BUILDING 2

Objective: Optimizing Zonal Parameter Coefficients for main extruder parameters prediction

- Goal: To understand the mathematical relation between main extruder and heating power & temperature zones 1-16.
- Striving for a model that ensures accurate main extruder parameters prediction based on specific zonal features.

Features and Target

- Parameters under consideration : Temperature & Control point.
- Target variable for prediction : Melt Temperature, Melt Pressure, Screw Load, Screw Rotation Speed, Vacuum.

Model and Approach: Lasso Regression, but why Lasso?

- Lasso regression performs variable selection by imposing a penalty on the absolute size of the regression coefficients. This means that it tends to shrink the coefficients of less important variables towards zero, effectively selecting the most relevant variables. In the context of the hopper section, where various factors (e.g., temperature, pressure, screw speed) might affect the extrusion process, Lasso can help identify the most influential variables among a large set of potential predictors.

- Regularization: Lasso regression incorporates a regularization parameter that helps prevent overfitting by penalizing large coefficient values.

MAIN EXTRUDER : MODEL BUILDING 2

Contribution of each Zones to Main extruder parameters

```
        Screw Load
   Feature Coefficients

Zone 5 Temperature :  2.01
Zone 7 Temperature : -0.56
Zone 9 Temperature : -0.52

Zone 2 Ctrl Point : -0.02
Zone 3 Ctrl Point : -0.23
Zone 4 Ctrl Point : -0.19
Zone 5 Ctrl Point : -0.81
Zone 8 Ctrl Point :  0.07
Zone 12 Ctrl Point: 0.006
```

Temp Zone 5 and Control Zone 5 contributes the most towards Screw Load positively and negatively based on the coefficient values.

```
          Pressure
    Feature Coefficients

 Zone 1 Temperature : 0.61
 Zone 3 Temperature : 0.02
 Zone 4 Temperature : 0.21
Zone 7 Temperature  : 0.006
Zone 10 Temperature :  0.13

 Zone 3 Ctrl Point :  0.05
 Zone 4 Ctrl Point :  0.02
 Zone 5 Ctrl Point : -0.95
 Zone 8 Ctrl Point :  0.04
Zone 12 Ctrl Point :  0.005
```

Temp Zone 1 and Control Zone 5 contributes the most towards Pressure positively and negatively based on the coefficient values.

MAIN EXTRUDER : MODEL BUILDING 2

Contribution of each Zones to Main extruder parameters

Temperature
Feature Coefficients

```
Zone 1 Temperature : 0.81
Zone 2 Temperature : 0.004
Zone 5 Temperature : 0.17

Zone 1 Ctrl Point : 0.05
Zone 4 Ctrl Point : -0.02
Zone 5 Ctrl Point : -0.85
Zone 8 Ctrl Point : 0.009
Zone 10 Ctrl Point : 0.03
Zone 11 Ctrl Point : 0.004
Zone 12 Ctrl Point : 0.046
```

Temp Zone 1 and Control Zone 5 contributes the most towards Temperature positively and negatively based on the coefficient values.

Screw Rotation speed
Feature Coefficients

```
Zone 1 Temperature :  0.96
Zone 2 Temperature :0.0009
Zone 4 Temperature :0.0001
Zone 5 Temperature :  0.03

Zone 1 Ctrl Point : 0.05
Zone 4 Ctrl Point :-0.005
Zone 5 Ctrl Point :-0.86
Zone 8 Ctrl Point : 0.01
Zone 10 Ctrl Point: 0.04
Zone 12 Ctrl Point: 0.05
```

Temp Zone 1 and Control Zone 5 contributes the most towards Screw Rotation Speed positively and negatively based on the coefficient values.

Vacuum
Feature Coefficients

```
Zone 1 Temperature : 0.59
Zone 4 Temperature : 0.08
Zone 5 Temperature : 0.17
Zone 7 Temperature : 0.05
Zone 14 Temperature:0.06

Zone 1 Ctrl Point : 0.03
Zone 4 Ctrl Point : -0.03
Zone 5 Ctrl Point : -0.85
Zone 10 Ctrl Point: 0.03
Zone 11 Ctrl Point: 0.01
Zone 12 Ctrl Point: 0.02
```

Temp Zone 1 and Control Zone 5 contributes the most towards Vacuum positively and negatively based on the coefficient values.

MAIN EXTRUDER : ADF TESTING

Why ADF Testing?

ADF test is a valuable tool for analyzing time series data, providing insights into the underlying properties of the data and guiding the selection of appropriate modeling techniques.

Stationary data refers to a time series dataset whose statistical properties such as mean, variance, and autocovariance remain constant over time.

Benefits:

- Detection of Structural Changes: Changes in the statistical properties of time series data, such as shifts in mean or variance, can signal structural changes in regulations or consumer preferences.
- Causal Inference: ADF testing can be used in conjunction with other econometric techniques to explore causal relationships between variables.
- Improved Decision-Making: Stationary time series data provides a stable foundation for analyzing historical trends and making informed decisions.

MAIN EXTRUDER : ADF TESTING RESULTS

Melt Pressure:

```
ADF Statistic: -7.55, p-value: 3.22e-11
Conclusion: Reject the null hypothesis, the time series is likely stationary.
```

Melt Temperature:

```
ADF Statistic: -8.33, p-value: 3.30e-13
Conclusion: Reject the null hypothesis, the time series is likely stationary.
```

Screw Load:

```
ADF Statistic: -7.17, p-value: 2.78e-10
Conclusion: Reject the null hypothesis, the time series is likely stationary.
```

Vacuum:

```
ADF Statistic: -12.17, p-value: 1.41e-22
Conclusion: Reject the null hypothesis, the time series is likely stationary.
```

Screw Rotation Speed:

```
ADF Statistic: -6.87, p-value: 1.53e-09
Conclusion: Reject the null hypothesis, the time series is likely stationary.
```

MAIN EXTRUDER : GRANGER CAUSALITY TEST

Objective

The main purpose of the Granger causality test is to determine whether one time series variable can reliably predict future values of another time series variable.

Approach

- We have taken 3 time lags here.
- "lag" refers to the number of past observations of a variable that are included in the model to predict the current value of another variable.
- Sensory data that are included in the test are Temperature, Pressure, Screw Load and Screw Rotation speed

MAIN EXTRUDER : GRANGER CAUSALITY TEST RESULTS

Melt Pressure

- Temperature causes changes in 'Pressure' at all tested lag lengths.
- Screw Load causes changes in 'Pressure' at all tested lag lengths.
- Screw Rotation speed does not Granger cause changes in 'Pressure' at lag lengths 1 and 2, but it does at lag length 3.

Temperature

- Pressure does not Granger cause changes in 'Temperature'.
- Both screw load and screw rotation speed do have a Granger causality relationship with Temperature.

Screw Load

- Both Temperature and screw rotation speed Granger cause changes in screw load, whereas pressure only shows significant evidence of causing changes in screw load at lag 2 and 3.

Screw Rotation Speed

- Pressure Granger cause changes in Screw rotation speed at lag 2 and 3.
- Temperature Granger cause changes in Screw rotation speed at all lag lengths.
- Screw Load influence changes in Screw rotation speed at lag 2 and 3.

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   II. Dependencies
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   IV. ADF Testing
   V. Granger Causality Test

4. **Future Endeavours**

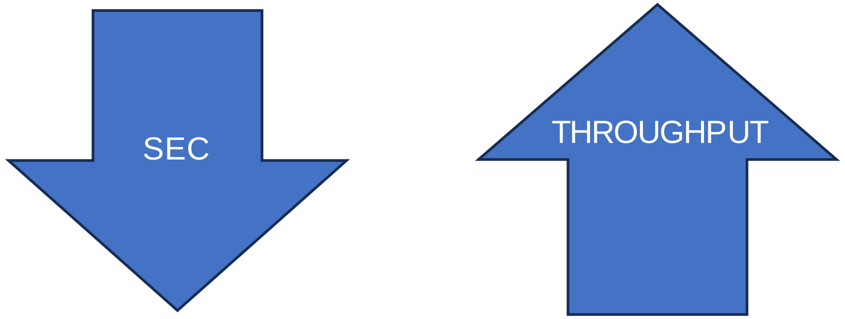
FUTURE ENDEAVORS

Specific energy consumption (SEC) of a hopper = power(kw) / throughput(kg/h)

Objective : Minimizing the SEC while maximizing throughput

Problem Statement : Multi objective optimization problem

Probable Solution : To solve a multi-objective optimization problem where we aim to minimize energy consumption while maximizing throughput, you can use techniques like Pareto optimization. One common approach is to use multi-objective evolutionary algorithms (MOEAs) such as NSGA-II (Non-dominated Sorting Genetic Algorithm II) or SPEA2 (Strength Pareto Evolutionary Algorithm).



Business Outcome

Cost Reduction: Optimizing energy consumption and maximizing throughput leads to lower operational expenses and increased profitability.

Increased Productivity: Maximizing throughput enables the business to produce more units in the same timeframe, enhancing overall productivity and output capacity.

Competitive Advantage: Efficiency improvements resulting from optimization provide a competitive edge, allowing the business to offer more competitive pricing or higher-quality products.

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Erlangen-Nürnberg

THANK YOU!