Predictive Maintenance for

Single Stage Air Compressors Using Advanced Machine Learning

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# List of Abbreviations

Below table (Table1) shows the list of abbreviations used in this proposal.

|  |  |
| --- | --- |
| Abbreviations | Description |
| ML | Machine Learning |
| MSE | Mean Squared Error |
| RMSE | Root Mean Squared Error |
| GPU | Graphics Processing Units |
| KPI | Key Performance Indicator |
| RF | Random Forest |
| RPM | Rotation Per Minute |
| KPI | Key Performance indicators |
| RM | Reactive Maintenance |
| PM | Preventive Maintenance |
| PdM | Predictive Maintenance |
| AI | Artificial Intelligence |
| IIOT | Industrial Internet of Things |
| IDE | Integrated Development Environment |
| EDA | Exploratory Data Analysis |
| RUL | Remaining Useful Life |
| CUDA | Compute Unified Device Architecture |

Table 1 - List of Abbreviations

# Abstract

Predictive Maintenance using ML algorithms is critical for analyzing the vast amounts of data generated by equipment to predict potential failures. By leveraging historical and real-time data, along with the power of Machine Learning, this approach enables maintenance activities to be precisely timed, ensuring equipment is serviced only when necessary.

This paper will research on Predictive Maintenance and anomaly detection of an industrial Single stage screw compressor with the use ML algorithms to analyze historical operational data and predict failures and also monitor and visualize real-time equipment data to detect anomalies for an industrial Single Stage Compressor. The study will focus on having an end-to-end solution that can be implemented across the shop floor. Predictive Maintenance of Compressor prevents unplanned downtime, prevents costly capital expenditure, and improves the overall efficiency of the equipment.

An industrial air compressor is a powerful mechanical device designed to convert power (using an electric motor, diesel, or gasoline engine) into potential energy stored in compressed air. This compressed air is then used to power various industrial tools and processes.

Currently, in any manufacturing industry, maintenance adopted is based on periodic and corrective maintenance policies. There are many research papers written on predictive maintenance of industrial equipment, but actual implementation of these on the shop floor is very limited.

Proposed research will predict key parameters, including discharge pressure, discharge temperature, and flow rate, using Random Forest regression models. Anomalies will be detected based on deviations between predicted and actual values and will be flagged, which will be visualized over the simple user interface.

The results obtained from the experimental tests will allow us to conclude on innovative techniques based on machine learning that can be applied to twin screw compressors, which are widely used in the industry, being able to perform predictive maintenance policies replacing the currently adopted periodic and corrective maintenance policies.

Additionally, the conclusion of this research can scale to other many other equipment and instruments in an industrial ecosystem, we can ensure the scalability, the integration, and the real-time processing capabilities.

# Background

Predictive maintenance is a preventative approach that forecasts the probability of industrial equipment failure using data and algorithms. ML models can predict possible problems before they arise by examining patterns in data gathered from sensors and other sources. Understanding Operational Efficiency and the reliability of all industrial systems in a manufacturing domain are very important to minimize downtime and improve efficiency and quality of production.

Research and understanding of these critical parameters and the relation of these parameters with overall efficiency and health of equipment is the key in predicting the performance of any equipment, and with this will help maintenance engineers to maintain the equipment and improve RUL (Remaining Useful Life).

This research will focus on predictive maintenance and anomaly detection of an industrial Single stage screw compressor with the use ML algorithms.

**What is Industrial Single Stage Screw Compressor?**

As referred in ([Shivansh Sabhadiya](https://www.theengineeringchoice.com/author/shivansh/),2021), An air compressor is a pneumatic device that converts power (using an electric motor, diesel, or gasoline engine, etc.) into potential energy stored in pressurized air (i.e., compressed air). An air compressor forces more and more air into a storage tank, increasing the pressure. This compressed air is then used to power various industrial tools and processes.

In this research we will be focusing on Industrial Single Stage Screw Compressor. A screw compressor works according to the positive displacement mechanism. It uses two spiral rotors (male and female rotors) for the compression of air or gas. These rotors mesh in such a way that the concave cavity of the female rotor meshes with the convex blade of the male rotor.

The female rotor has a more significant number of blades than the male rotor blades. Due to this reason, the female rotor rotates more slowly than the male rotor. The male rotor is connected to an electric motor via a shaft.

A diagram of a mechanical part

AI-generated content may be incorrect.

Figure 1-Screw Compressor Working Diagram

Above figure (Figure 1) shows the working principal of screw compressor(figure taken for reference from cited as: Nikhil Technochem (2024)

**Schematic Block Diagram of Screw Air Compressor Unit**

Below figure (Figure 2) shows Schematic block diagram of Screw Air Compressor unit figure taken for reference from cited as: Mechstudies (2021)

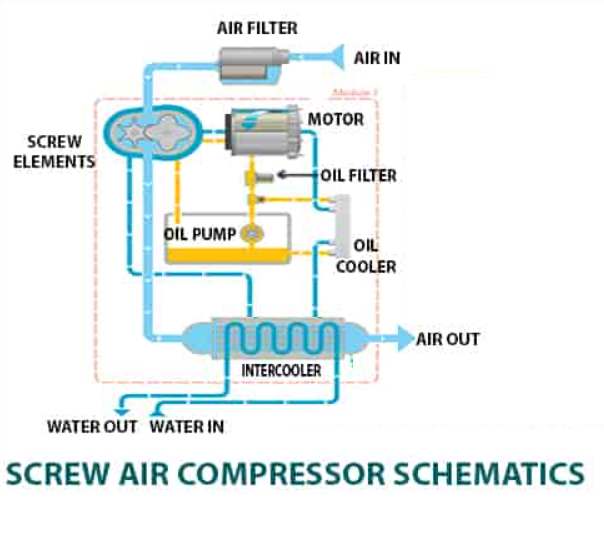


Figure 2 -Single Stage Screw Compressor Block Diagram

Screw Air Compressor consists of following Major parts which direct quotation from website (Engineer Waqar, 2020)

* **Air In**

Air is taken into the compressor from this Inlet. Air taken in from the outside environment is passed to the Inlet Air filter

* **Air Filter @ Inlet**

Air contains dust, mist, or pollutants, and it is required to be removed from the air. Filters are provided to clean the air.

Filters need to be cleaned frequently or requirement basis, based on the climatic conditions. An alarm is synchronized in case filter cleaning is required.

* **Screw Element**

The screw compressor has an air end that compresses the air. It is equipped with two screws.

* The bigger screw is known as female, while the other one is known as male.
* The female screw comes into rotary motion due to the electric motor.
* The female screw is comparatively more robust than the male screw.
* Here the two screws need oil treatment that is necessary for preventing or decreasing the abrasion on screws.

The primary purpose of the air end is to compress the oil and air mixture.

* **Motor**

One of the essential parts of the screw compressor is its electric motor. It is the power source of the compressor.

* **Oil Filters**

Oil is used for the lubrication system. In the compression system, due to rotating parts, oil is necessary. Oil filters are used to filter out the contamination from the oil.

* **Oil Pump & Oil Coolers**

Oil Pumps are used for pump oil to Screw Element and Oil Coolers are used to cool down oil which is pumped again to Screw Element

* **Bearings**

In screw compressor, anti-friction roller and ball Bearings are used,

* Due to rotation of screws, bearings are provided.
* It helps to balance properly.
* It reduces frictional forces as well as losses.
* It also helps to rotate the screw freely.

The bearing used may be,

* radial bearings
* axial bearings /thrust bearing

Some other conditions which might indicate a problem with your single-stage screw air compressor include:

1. A higher-than-normal level of noise.
2. Leaks in the air system.
3. The pressure cannot be reached at the desired level.
4. Overheating of the compressor motor.
5. Excessive vibration of the compressor.
6. Unusual smells or smoke from the compressor.
7. Corrosion or damage to the compressor can cause.
8. Difficulty in starting the compressor motor.
9. Improper performance of the compressor.

# Problem Statement & Related Research

Unplanned Downtime is a big issue for any manufacturing industry, there is a huge cost burden for each unplanned downtime. Direct Quotation from Doug White, Emerson Industry Expert – Based on current refinery economics, says every 1% gain in availability is worth $84 million of additional margin capture per year in a typical 200,000 bpd refinery. Studies carried out recently also show that machine downtime, which is unplanned or has occurred at the last minute due to some faults, costs industrial manufacturing organizations an estimated $50 billion each year.

With time, we saw a revolution in maintenance of equipment like Author in (Punam J Et al,2025) details out the evolution of maintenance in Industrial Systems - reflects a transition of maintenance strategies from Reactive Maintenance (RM) to Preventive Maintenance (PM) to Predictive Maintenance (PdM)

Predictive maintenance is not a new concept. However, technological advancements have enabled various applications for predictive maintenance across several industries and use cases. Predictive maintenance (PdM) uses condition monitoring tools and machine learning (ML) algorithms to predict potential failures, faults, and deterioration for assets and equipment. Timely handling of these causes, which can lead to unplanned downtime, is a game-changer in equipment maintenance.

Authors (João Barataa and Ina Kayserb,2023) talks about Industry 5.0 as a humanized vision of technological transformations in industry, balancing the current and future needs of the workers and society with the sustainable optimization of energy consumption, materials processing, and product lifecycles and author in (Daniel A Et al,2025) talks about adoption, expansion, and implementation of Artificial Intelligence (AI)-enabled hardware, tools, methods, and semiconductor technologies in the journey towards Industry5.0.

In this world of Industry 5.0, sustainability is top of everyone’s mind and [13] adopting predictive practices not only helps improve operational efficiency and reduce maintenance costs, adopting predictive practices also favors sustainability. Detecting and correcting inefficient operating conditions contributes to energy efficiency, extends the useful life of equipment, and reduces the need for replacements and disposal. The author in (Philip Stahmann Et al,2025) talks about how IIOT has enabled capabilities to perceive and communicate real-time data. This development enhances the monitoring of states and processes in industrial engineering, how things that were not connected are connected now and how these data can be used in predicting useful insights.

All these technical advancements have opened new doors for smart manufacturing practices, and every industry is focusing on ways to be more sustainable, efficient, and lean ways to manufacturing goods. Artificial Intelligence, with Machine learning and other subsets, are playing a key role in this advancement

The author in (S. Arena Et al,2022) mentioned that Predictive Maintenance (PdM) based on Machine Learning (ML) is one of the most prominent data-driven analytical approaches for monitoring industrial systems, aiming to maximize reliability and efficiency.

Another author, (Falsk Raja,2023) talks about the importance of AI-driven predictive maintenance and how this will revolutionize the field of maintenance and ensure increased equipment uptime, enhanced operational efficiency, and improved asset management.

Also, authors (Lei Y Et al,2020), emphasized the effectiveness of ML in processing multi-parameter data for fault detection, where the authors also mentioned that the integration of ML not only improves diagnostic accuracy but also enables predictive maintenance, reducing downtime and enhancing the overall reliability and efficiency of industrial processes.

Anomaly detection in predictive maintenance identifies unusual patterns in equipment behavior that may indicate potential failures. It works by analyzing sensor data (like temperature, vibration, or pressure) to establish a baseline of normal operation and flag deviations from it.

Pratanjit and Prithwiraj talk about the importance of real-time anomaly detection mechanisms in research (Parthajit Bisal and Prithwiraj Jana,2025), In this paper author also talks about an interesting way to maintain the health status of a compressor using a scoring mechanism.

Authors (Yuvraj Jivan Jadavi and Dr. Bhagya,2024) mentions similar approach in his papers and talks about how we can use the threshold approach for anomaly detection in the research paper.

Author (Ahmad Et al, 2024) also explores the computational challenges associated with deploying ML algorithms in real-time systems, discussing the trade-offs between computational demands and real-time performance requirements.

(Pooja Kamat and Rekha Sugandhi Zope.2024)talk about common issues in anomaly detection, which need to be taken care of, data containing noise that could be alerted as an anomaly, the characteristics of anomalous or normal may frequently change, and the anomaly pattern is mostly based on seasonality. All such issues need to be taken care of to have a robust anomaly detection system. Another paper's authors (David Valdivieso López Et al,2024) talk about a common issue where identifying anomalies is not perfect and may produce many false positives, which label standard data as anomalous. In this context, false positive mitigation is the task of reducing the number of false positives tagged by the anomaly detector. Author in

With the above references it is very evident that Predictive Maintenance is an important area of research in manufacturing for Industrial systems, and their big opportunity in research and innovation, which will add value to this field

Most of the studies in this area of Predictive Maintenance systems operate on historical data but fail to implement real-time monitoring and anomaly detection mechanisms and provide a minimum required user interface to visualize & monitor critical parameters & anomalies.

Also, there is very little research available that focuses on cost effectiveness, which is very important in the real adoption of such systems in Industrial floors.

# Research Questions

This thesis tries to answer the following questions:

* Can a Random Forest Regressor be effective in predicting key parameters of an Air compressor?
* How can model help with real-time monitoring of Compressor sensor inputs and detect anomalies (based on threshold values)? This will help the maintenance team take immediate action.
* How and what information related to condition monitoring and anomaly detection can be visually provided to the Maintenance team? so that they can root cause the issue relatively faster with minimum skills required.
* Can the research conducted on the Compressor be easily scaled to other industrial equipment on a plant floor(theoretical analysis)?

# Significance of the Study

In this study I am trying to address issue of unplanned downtime for industrial single stage air screw compressor. There is a huge cost burden for manufacturers with each unplanned downtime. As I mentioned in the related research section, Doug White, Emerson Industry Expert – Based on current refinery economics, says Every 1% gain in availability is worth $84 million of additional margin capture per year in a typical 200,000 bpd refinery. Studies carried out recently also show that machine downtime, which is unplanned or has occurred at the last minute due to some faults, costs industrial manufacturing organizations an estimated $50 billion each year.

This study will help manufacturers visualize forecasted values for key parameters and detect anomalies in real time, which will be used by Maintenance engineers to take appropriate actions and avoid unplanned downtime.

Output of this research can be used by any manufacturing industry to monitor and visualize detected anomalies, parameter prediction and condition monitoring parameters for any industrial single stage air screw compressor

# Aim and Objectives

**Aim:** of this research is topredict key parameters and detect anomalies for Single Stage Screw Air Compressor using advanced machine learning algorithm

**Objectives:**

* To conduct a comprehensive review of available literature regarding Anomaly Detection and Predictive Maintenance in Industrial Compressors.
* To predict critical features of Industrial Single stage Screw Compressor for predictive Maintenance.
* To detect anomalies using a machine learning algorithm by monitoring data in real-time.
* To provide an optimized value-driven driven User-Interface to maintenance engineers for real-time monitoring of parameters and detected anomalies.

# Scope of the Study

The scope of this thesis work is defined as follows:

* The thesis work is to be completed within 17 weeks after submission of the research proposal.
* The experiment will be conducted using open-source software and models.
* The experimentation will be conducted using a publicly available GPU such as Google-Colab.
* Human evaluation of the generated story is not a part of this thesis work. The evaluation will only focus on automated metrics.
* Human evaluation of the generated story is not a part of this thesis work. The evaluation will only focus on automated metrics.

# Proposed Structure

Machine learning is a powerful tool that provides the possibility to utilize structured, large-scale data for classification and regression purposes.

Below is the architecture diagram of the proposed system for Predictive Maintenance & Realtime Anomaly Detection.

Architecture diagram for proposed system is given below in figure (Figure 3)

A diagram of model building

AI-generated content may be incorrect.

Figure 3 -Architecture Diagram for proposed system

# Research Methodology

Here, for this research, we will employ multiple Random Forest Regression models to predict key air compressor parameters based on historical values

In the context of anomaly detection, Random Forest can identify anomalies

by evaluating how individual decision trees classify data points.  Anomalies are typically classified with lower consensus among the trees, allowing for the identification of outliers and irregularities

Architecture diagram for proposed Research Structure is given below in figure (Figure 4)

A diagram of a software development process

AI-generated content may be incorrect.

Figure 4 - Architecture diagram on Proposed Research Structure

# Gather Dataset

Data for any industrial compressor is collected from multiple sensors available with the compressor unit. These parameters are captured and stored in a time series fashion. For this research we will be using open-source data available in .csv for an industrial Screw Compressor

[https://www.neuraldesigner.com/wp-content/uploads/2023/10/aircompressor.csv](https://www.neuraldesigner.com/wp-content/uploads/2023/10/aircompressor.csv%20%20%20%20%20)

Data Preparation techniques like handling missing values, Noise Reduction, Outlier detection, Feature Scaling etc., will be used.

The dataset contains 1000 records captured at a defined period or when any major event happened.

We will be reusing the existing data for testing real-time data-related workflows.

List of parameters from data set is given below in table (Table2).

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter Name | Data Type | Unit Of Measure | Description |
| RPM | Numerical | r/min | Motor speed refers to the number of rotations or revolutions a motor’s shaft completes in each amount of time. It is usually expressed in RPM (Revolutions Per Minute). Motor speed determines how fast the motor is turning and is a critical factor in its operation, as it affects the performance of the system or machine it powers. |
| Motor Power | Numerical | kW(Kilo Watt) | Motor power represents the energy converted by the motor per unit time and is an important indicator of the motor’s working ability. The motor current determines both the input power and the output power of the motor |
| Outlet Pressure | Numerical | bar | In a compressor, the outlet pressure (also called discharge pressure) refers to the pressure of the gas or air after it has been compressed and exits the compressor |
| Outlet Temperature | Numerical | Degrees Celsius (°C) | The outlet temperature in a compressor refers to the temperature of the gas or air after it has been compressed and exits the compressor. |
| Air Flow | Numerical | CFM – Cubic Feet per Minute | In a compressor, air flow refers to the volume or mass of air that the compressor moves or processes over a given period of time |
| Noise | Numerical | decibel (dB). | In a compressor, noise refers to the unwanted sound produced during its operation. This noise can come from various sources such as:  **Mechanical vibrations** (from moving parts like pistons or rotors)  **Air turbulence** (especially at the intake and exhaust)  **Motor or engine noise**  **Structural resonance** of the compressor housing |
| Water Pump, Inlet Pressure | Numerical | bar | Water Pump’s Inlet pressure. |
| Water Pump, Inlet Pressure | Numerical | bar | Water Pump’s Outlet pressure. |
| Vibration Acceleration | Numerical | g (acceleration due to gravity) | Compressor, vibration parameters are critical indicators of mechanical health and performance. Monitoring these helps detect issues like imbalance, misalignment, bearing wear, or looseness before they lead to failure.  **Vibration Acceleration at X Axis** = Measures how quickly the vibration speed changes in x axis  **Vibration Acceleration at Y Axis** = Measures how quickly the vibration speed changes in Y axis |
| Bearing Fault | Categorical | Bool | Bearing Fault is the categorical value where 1 means bearing fault and 0 means no fault |
| Water Pump Fault | Categorical | Bool | Water Pump Fault is a categorical value where 1 means Water Pump fault and 0 means no fault |

Table 2 - List of Dataset Parameters

# EDA (Data Processing & Feature Selection)

# Data Processing:

Every dataset entry represents data collected at a defined period when any major event happened in the compressor, providing a detailed and comprehensive view of the compressor's operational status over time.

The following steps were taken to clean, transform, and prepare data before performing deeper analysis

* **Data Cleaning** of the raw dataset will be done to take care of missing values, duplicate data, and fix inconsistencies like formatting, typos, etc.
* **Data Transformation**- Normalization/Standardization of data is done for the required parameters. We will create new derived parameters like differential air pressure.
* **Treat Outliers**: Identify unusual values that may skew analysis and take appropriate action to handle outliers.

# Data Analysis:

In this phase, we will explore, summarize, and visualize the data to uncover patterns, trends, relationships, and potential issues. It helps you understand the structure and meaning of the data before applying any modeling or machine learning.

* + **Multivariate Analysis**: Examining interactions among three or more variables. The tools used here will be Pair plots, heatmaps etc.
  + **Correlation Analysis**: Measures the strength and direction of relationships between numeric variables.
  + **Trend and Pattern Detection**: Time series plots, moving averages, seasonality analysis (for time-based data)

# Feature Selection:

Feature selection is the process of identifying and eliminating irrelevant or redundant features, which plays a crucial role in enhancing the performance and interpretability of ML models.

The feature Selection process will be conducted to identify the most relevant predictors for the model. This process will involve techniques like correlation analysis, feature importance evaluation, etc.

# Model Selection

Based on the best understanding of Initial data validation and literature review, we will employ multiple Random Forest Regression models to predict key air compressor parameters based on historical values

In the context of anomaly detection, Random Forest can identify anomalies

by evaluating how individual decision trees classify data points. Anomalies are typically classified with lower consensus among the trees, allowing for the identification of outliers and irregularities

**Random Forest**

Random Forest is the most popular machine learning algorithm used for predictive maintenance. It can be used for both classification and regression problems in machine learning. It is based on concept of ensemble learning method which combines multiple classifiers to solve a complex problem and to improve the performance of the model. Random Forest is a classifier that contains a number of decision trees on various subsets of the given dataset and takes the average to improve the predictive accuracy of that dataset." Instead of relying on one decision tree, the random forest takes the prediction from each tree and based on the majority votes of predictions, and it predicts the final output. The greater number of trees in the forest leads to higher accuracy and prevents the problem of over fitting.

# Model Evaluation

The models will be assessed using key performance metrics like:

**MSE - Mean Squared Error:** It measures the average of the squares of the errors comparing the actual and the predicted values. Lower mean-squared Error values indicate better performance.

Formula for MSE in given below in figure (Figure 5)

A mathematical equation with numbers and symbols

AI-generated content may be incorrect.

Figure 5 - Mean Squared Error Formula

**RMSE - Root Mean Squared Error:** It is calculated as the square root of MSE and provides an error metric in the same units as the target variable, making it easier to interpret. Lower Root Mean Squared Error values reflect better predictive accuracy.

Formula for RMSE in given below in figure (Figure 5)

A math equations with numbers and symbols

AI-generated content may be incorrect.

Figure 6 - Root mean Squared Error Formula

**MAE - Mean Absolute Error**: It represents the average absolute difference between the predicted and the actual values. It is a parameter with a more direct measure of average model error.

Formula for MAE in given below in figure (Figure 5)

A mathematical equation with numbers and symbols

AI-generated content may be incorrect.

Figure 7 - Mean Absolute Error Formula

**R²- R Squared**: It calculates the ratio of the variance in the dependent variable that is predictable from the independent variables. It delivers an insight into how well the model fits the data, with values closer to one indicating a better fit

Formula for R Squared in given below in figure (Figure 5)

A mathematical equation with numbers and symbols

AI-generated content may be incorrect.

Figure 8 - R Squared Formula

All above figures in this section is taken for reference from ([Akshita Chugh](https://medium.com/@akshita-chugh024?source=post_page---byline--cd0326a5697e---------------------------------------),2020)

# Visualization & Monitoring

Anomaly Detection: The predicted values are compared against actual values, and anomalies are flagged if deviations exceed predefined thresholds

Also, this research will focus on the minimum required user interface to visualize & monitor critical parameters & anomalies.

We will be having the following as part of the visualization:

* **Raw Data Visualization**: Visualization of real-time and historical data
* **Predicted Values**: Forecast of predicted values for key selected features
* **Anomaly Detection**: An Anomaly was detected for key features annotated over a line trend.

# Resource Requirements

# Hardware Requirements

The following hardware requirements must be met for this research work:

* A laptop/desktop computer with internet access capable of browsing, doc-writing and compiling/executing code.
* Access to GPUs to execute CUDA-based deep-learning model training/inference.

# Software Requirements

The following software requirements must be met for this research work:

* Web-browser
* Code IDE
* Python 3.7+
* NVIDIA - CUDA libraries
* Deep Learning libraries such as TensorFlow, PyTorch
* Other python libraries required for working with data, e.g., Pandas, Numpy, NLTK, etc.

# Data Management Plan

All Data required for this research will be collected and stored in most ethical manner.

|  |  |  |
| --- | --- | --- |
| Artifact | Collection | Storage |
| Dataset  (csv format) | We will be using an Opensource dataset for this research paper | github |
| Py Files | All Py artifacts and its contents will be a developed my me and without any plagiarism | github |
| Research Proposal | All artifacts and its contents will be a developed my me and without any plagiarism | github |
| Research Paper | All artifacts and its contents will be a developed my me and without any plagiarism | github |

Table 3 - Data Management Plan

# Research Plan

# Research Project Plan

Research Project plan from topic selection to final completion is planned and documents as Project plan/schedule with Gant chart

A screenshot of a graph

AI-generated content may be incorrect.

Figure 9 - Project Plan Gant Chart

**Note:** 1 Period = 1 Calendar Week

# Risk Mitigation and Contingency Plan

The potential risks to the completion of the thesis work and corresponding contingencies are listed below:

|  |  |
| --- | --- |
| Risk | Contingency |
| Candidate is unable to perform research work due to health issues or personal problems and it affects timelines. | Plan for buffer time in project management.  Inform University/Upgrad administration and ask for extension. |
| Unavailability of specialized hardware such as GPUs. | Use cloud GPUs. |

Table 4 - Risks & Contingency

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