APPLICATIONS OF DIGITAL TWIN WIND TURBINES

Proposal Presentation

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Meet Our Team !

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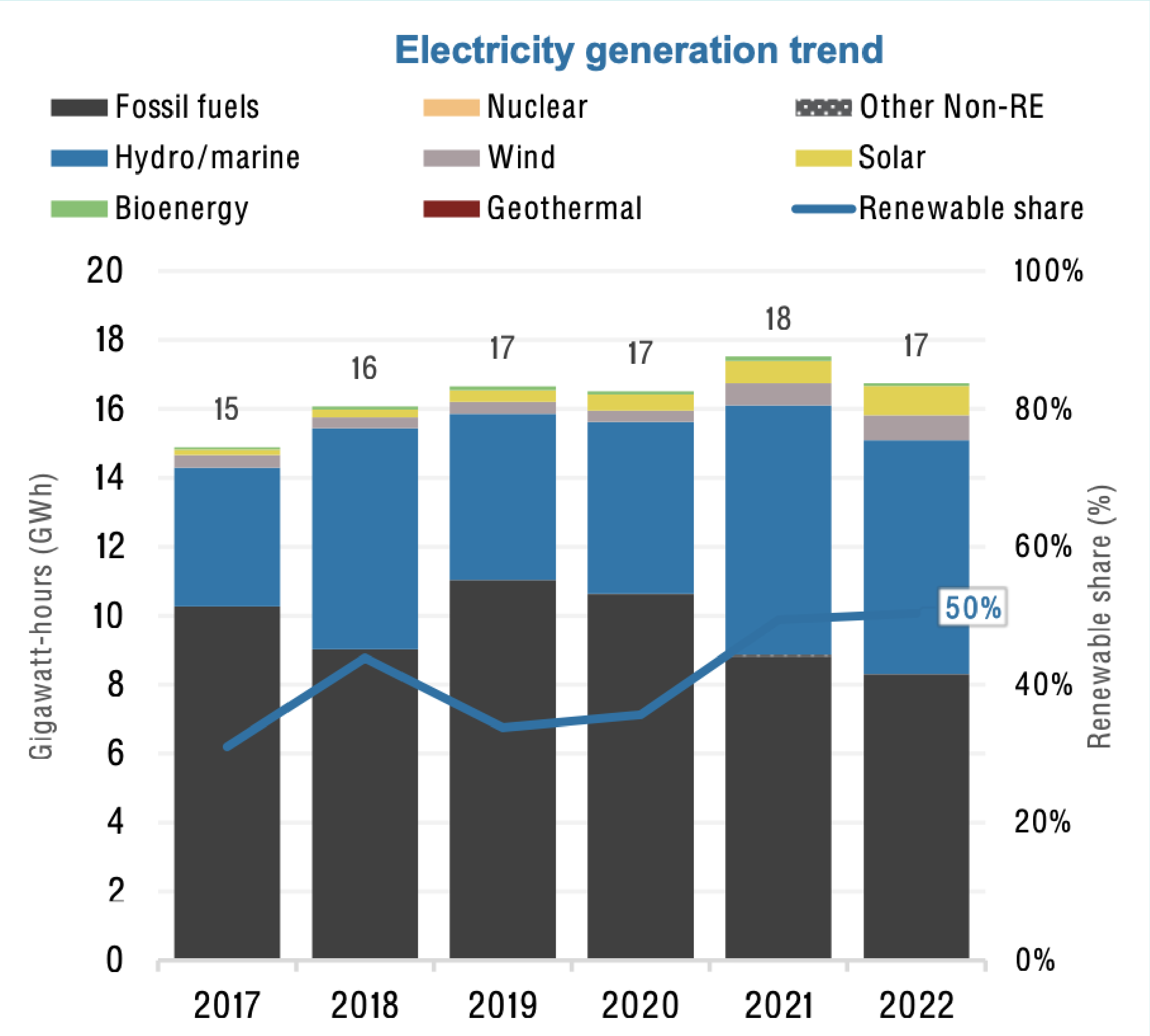
INTRODUCTION



- Sri Lanka is generating 40-45% of electricity from renewable resources

- **Total Electricity Generation (2022)**: ~15,942 GWh.
- Hydropower: ~40% in earlier years, slightly reduced recently.
- Wind Energy: ~10% of low-carbon electricity.
- Solar: Growing steadily.

Government Goal: 70% renewable energy by 2030, carbon neutrality by 2050.

RESEARCH QUESTION

1. How can digital twin technology improve wind turbine performance in Sri Lanka’s climate?

2. What weather factors can be simulated using digital twins to optimize turbine operations?

3. How can machine learning improve fault detection and failure prediction for turbines?

4. What strategies can reduce the impact of extreme weather on turbine performance?

5. How does digital twin-based maintenance compare to traditional methods in reducing costs and downtime?

OBJECTIVES

Main Objective

Real-Time Optimization and Maintenance of Wind Turbine Performance Using Digital Twin Technology.

Sub Objectives

1. Analyzing weather impacts on turbines.
2. Enhancing power generation efficiency.
3. Investigating noise effects in wind turbines.
4. Optimizing wind turbine maintenance strategies.

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Specialization : Software Engineering

Background

Analyze Weather Impacts on Wind Turbine Performance

- Weather Impacts on Wind Turbines
  - High Winds: Damage rotor blades and turbine structure, causing shutdowns.
  - Heavy Rains & Lightning: Lead to electrical short circuits and severe component damage.
  - Extreme Heat: Causes overheating, wear and tear, and critical component failures.
- Digital Twin Solution
  - Real-Time Monitoring: Track turbine performance using live weather data.
  - Predictive Maintenance: Anticipate damage and schedule repairs with AI.
  - Simulations: Test turbine resilience in virtual extreme weather scenarios.
  - Dynamic Adjustments: Optimize settings automatically to reduce weather stress.
  - Cost Efficiency: Minimize repair costs and downtime through proactive actions.

Research Gap

Research A

- IoT and predictive analytics for optimizing wind energy microgrids
- Gaps :
- No digital twin integration for real-time adjustments.
- Lacks focus on extreme weather impacts.

Research B

- Digital twin using machine learning for wind speed and energy prediction
- Gaps :
- Limited focus on specific weather factors.
- No adaptive operational strategies

Research C

- Predictive digital twin for maintenance and failure detection in offshore farms.
- Gaps :
- Minimal insights into environmental impacts.
- No operational simulations for extreme weather.

Comparison of existing systems

Research	Impact of Extreme Weather on Turbines	Adaptive Operational Strategies to Mitigate Damage	Use Digital Twin
Research A	✗	✗	✗
Research B	✗	✗	✓
Research C	✗	✗	✓
Our Project	✓	✓	✓

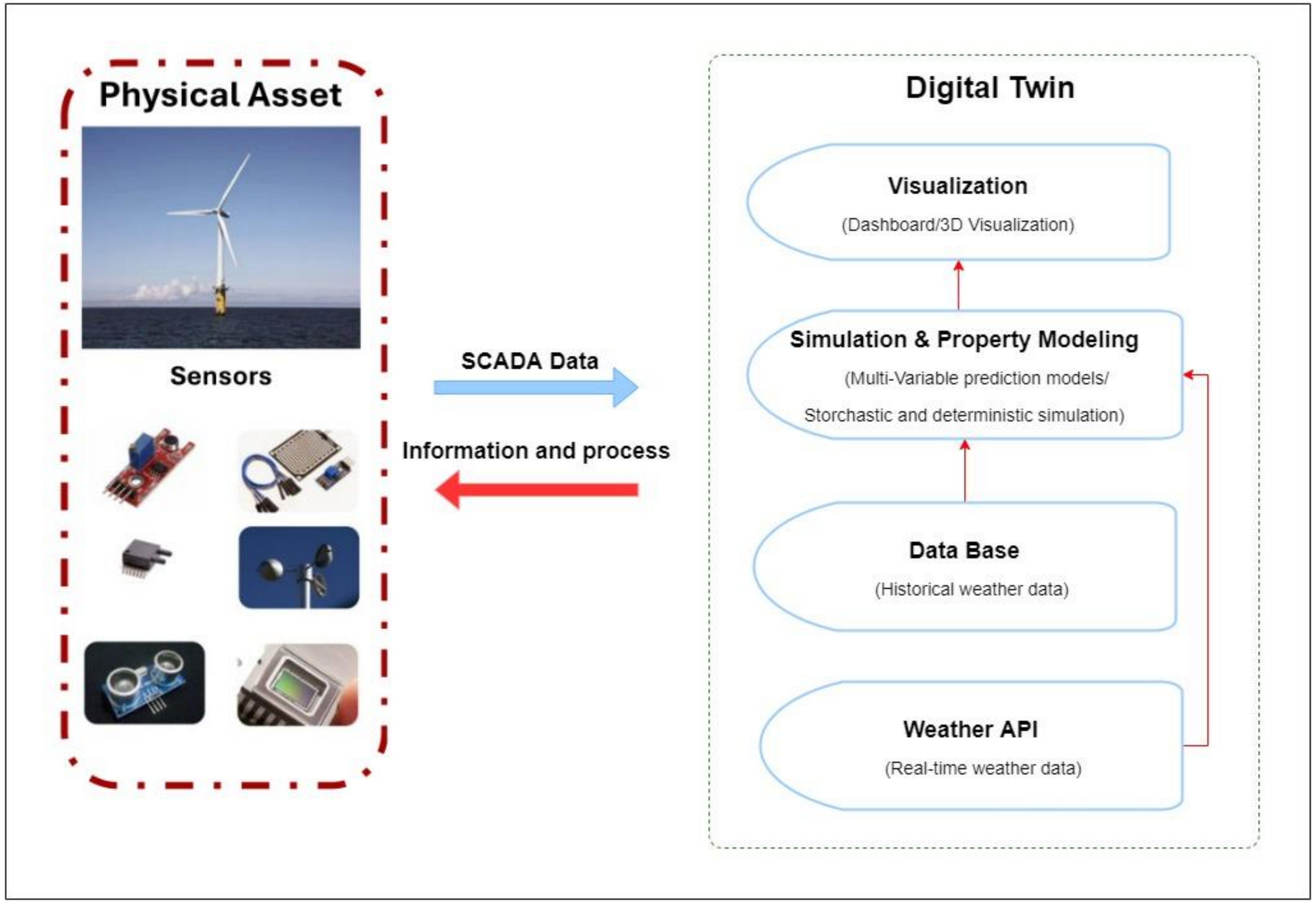
Research Question

How can we analyze the impacts of weather factors such as temperature, wind speed, rain, and lightning on wind turbine performance using digital twin ?

Specific and Sub Objective

- Analyze Weather Impacts on Wind Turbine Performance
- Develop a Digital Twin for Turbine Behavior Simulation
- Train and Integrate a Machine Learning Model
- Propose and Validate Adaptive Operational Strategies

Methodology
System Diagram



Methodology
System, Personnel, and Software Specification Requirements

Software Requirements

- OpenWeatherMap API
- Python
- VS code
- Plotly

Personnel Requirements

- Mr. Jeewaka Perera (AI & ML Senior Lecturer)
- Ceylon Electricity Board of Sri Lanka Wind Farm

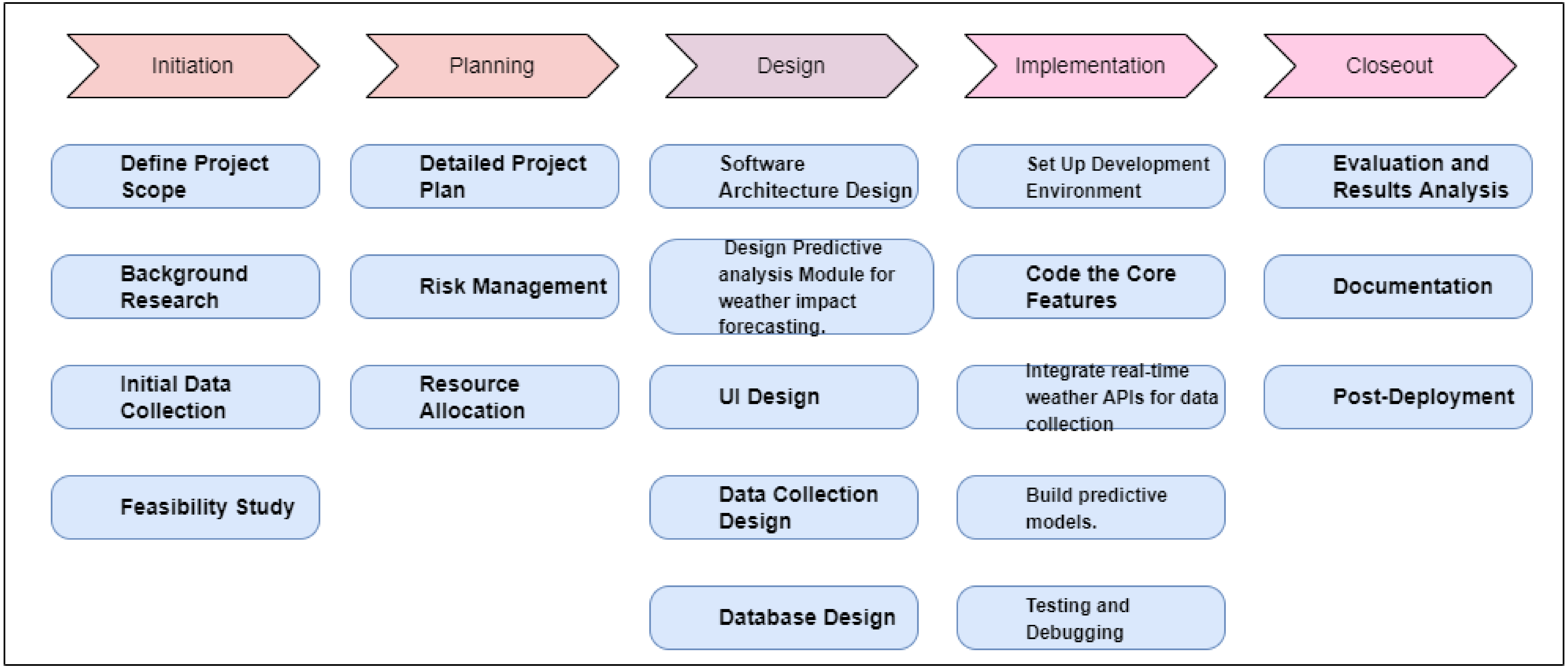
Functional Requirements

- **Collect real-time and historical weather and turbine data.**
- **Preprocess and merge data for machine learning input.**
- **Train a model to predict performance degradation and risks.**
- **Simulate weather impacts using a digital twin.**
- **Develop and test adaptive operational strategies**

Non-Functional Requirements

- **Real-time data processing with <5 seconds latency.**
- **Machine learning model accuracy ≥85%.**
- **Secure data with encryption and authentication**
- **User-friendly dashboards for simulations and strategies**

Work Breakdown Structure



References

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Intrduction

My Contribution:

- Focus on developing software solutions to analyze wind turbine noise using digital twin technology.

Key Objectives:

- Identify primary noise sources (aerodynamic and mechanical).
- Create a virtual model of noise generation under different operational and environmental conditions.
- Simulate and analyze the impact of various operational changes on noise levels.

Impact:

- Integrate sensor data with digital twin simulations.
- Provide real-time noise level predictions for better turbine operation and design.
- Support community and environmental concerns through effective noise reduction.

Research Gap

Research	Noise Source Identification	Noise Mitigation Techniques	Real-Time Noise Prediction	Digital Twin Use	Machine Learning Use
Bakker et al., 2012	✓	✓	✗	✗	✗
Feng et al., 2019	✗	✓	✗	✗	✗
Gao et al., 2019	✗	✗	✗	✓	✗
Our Project	✓	✓	✓	✓	✓

Research Question

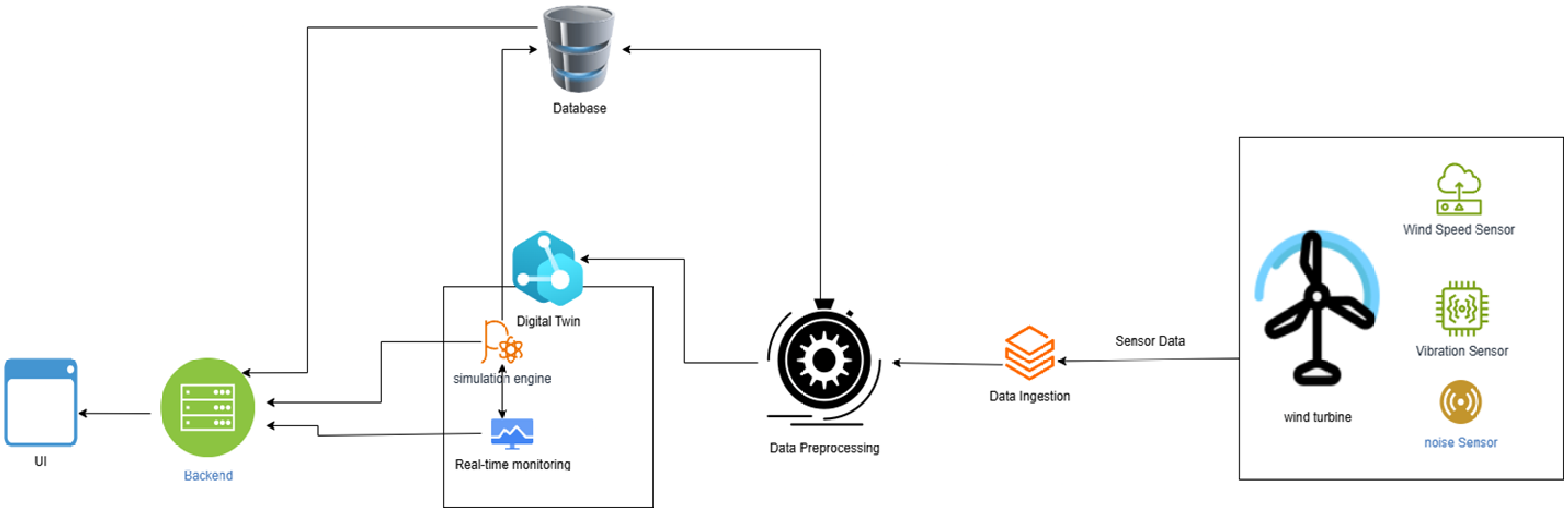
How can digital twins be utilized to predict and mitigate noise levels in wind turbines in real time?

Introduction

Specific Objective

- Identify Primary Noise Sources in Wind Turbines
- Develop a Digital Twin Model for Noise Simulation
- Analyze and Evaluate Noise Mitigation Techniques

Methodology
System Diagram



Technologies, Techniques, Algorithms

Technologies

- React.js
- Python
- Flask
- SQLite
- Plotly/D3.js
- Google Cloud
- Google Firebase

Algorithms & Architectures

- **Algorithms**:
  - Linear Regression: Noise level prediction.
  - Neural Networks: Complex noise pattern analysis.
  - Kalman Filter: Real-time sensor data smoothing.
  - Decision Trees: Noise mitigation strategy optimization.
- **Architectures**:
  - Digital Twin Framework: Virtual turbine with live sensor data.
  - Client-Server Model:
    - Client: React.js dashboard.
    - Server: Flask backend for data processing.
  - REST API: Data exchange between sensors, simulations, and the dashboard.

Techniques

- **Data Handling**:
.
- **Noise Mitigation**:
- **Dashboard Development**
:
- **Testing & Integration**

Software,Functional and Non-Functional Requirements

Software Requirements

- Languages: Python, JavaScript (React.js, Node.js)
- Libraries/Tools: Flask, Scikit-learn, OpenFOAM, Plotly, Apache Kafka, SQLite
- Database: SQLite or Google Firebase
- Cloud: Google Cloud Platform (Free Tier)
- Web Development: React.js

Functional Requirements

- **Noise Prediction**: Predict noise levels using machine learning.
- **Data Collection**: Real-time sensor data (wind speed, turbine speed, etc.).
- **Noise Mitigation**: Simulate noise reduction techniques.
- **Real-Time Adjustments**: Dynamic operational changes for noise reduction.
- **Data Visualization**: Dashboard for real-time noise levels.
- **Data Storage**: Store sensor data and results.
- **Reporting**: Generate reports on noise mitigation.

Non-Functional Requirements

- **Performance**: Real-time processing with minimal delay.
- **Scalability**: Handle increasing data and predictions.
- **Usability**: Intuitive user interface for stakeholders.
- **Reliability**: Accurate predictions and data collection.
- **Security**: Secure data storage and transmission.
- **Maintainability**: Easy to maintain and extend.
- **Portability**: Platform-independent (Windows, Linux, macOS).
- **Data Integrity**: Ensure data accuracy.

Work Breakdown Structure

Initiation	Planning	Design	Implementation	Closeout
Define Project Scope	Detailed Project Plan	Software Architecture Design	Set Up Development Environment	Evaluation and Results Analysis
Background Research	Risk Management	Noise Prediction Model Design	Code the Core Features	Documentation
Initial Data Collection	Resource Allocation	UI Design	Integrate Real-Time Data Collection	Post-Deployment
Feasibility Study		Data Collection Design	Develop Noise Mitigation Simulations	
		Database Design	Testing and Debugging	

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Specialization : Software Engineering

INTRODUCTION

- Renewable energy sources, particularly wind energy, are crucial for sustainable development.
- However, optimizing wind turbine performance remains a challenge due to variable environmental conditions and operational inefficiencies.
- A digital twin can be used to enable predictive analysis, performance optimization, and maintenance planning.
- Enhancing energy production efficiency is key to meeting global renewable energy goals.
- Leveraging Digital Twin technology offers a data-driven approach to maximize power generation.

Research Question

How can Digital Twin technology be utilized to optimize wind turbine performance, maximize energy output, and improve energy forecasting accuracy?

Comparison of former researches

Application Reference	Use of Digital twin simulations	Real-time energy forecasting	integration of power curve analysis	Optimization of Control Strategies	Use of machine learning
Research A[1]	✓	✓	✗	✗	✓
Research B[2]	✗	✗	✗	✓	✓
Research C[3]	✗	✗	✓	✓	✓
Proposed System	✓	✓	✓	✓	✓

Specific and Sub Objective

Specific Objective

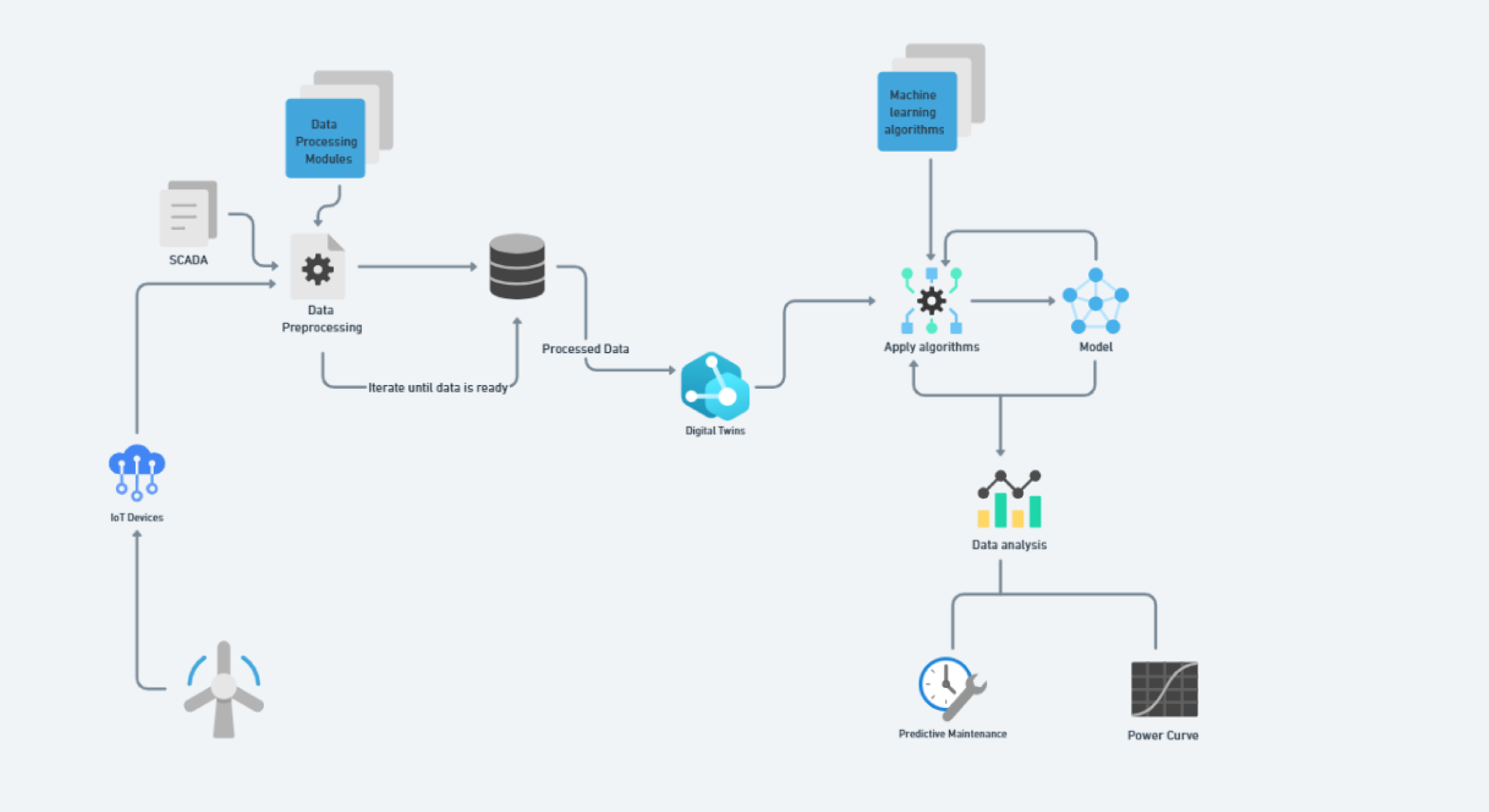
To develop a Digital Twin system that integrates real-time monitoring, control strategy optimization, and energy forecasting to maximize wind turbine energy production.

Real-Time Performance Monitoring

Control Strategy Optimization:

To Energy Forecasting

System Diagram



Technologies, algorithms to be used

Technologies

- Python
- React.js
- VS code
- Flask/FastAPI
- TensorFlow
- PostgreSQL
- Google cloud
- OpenWeather API

Techniques

- Simulation Modeling
- Machine Learning

Algorithms & Architectures

Algorithms

- K Means
- CNN

Architecture

Digital Twin Framework

System Requirements

Functional Requirements

- Collect real-time data from wind turbine sensors and weather APIs.
- Compare real-time sensor data against the power curve to detect inefficiencies.
- Simulate and recommend optimal operational parameters
- Predict energy output based on weather and turbine data.
- Provide real-time dashboards for performance monitoring and energy forecasting results

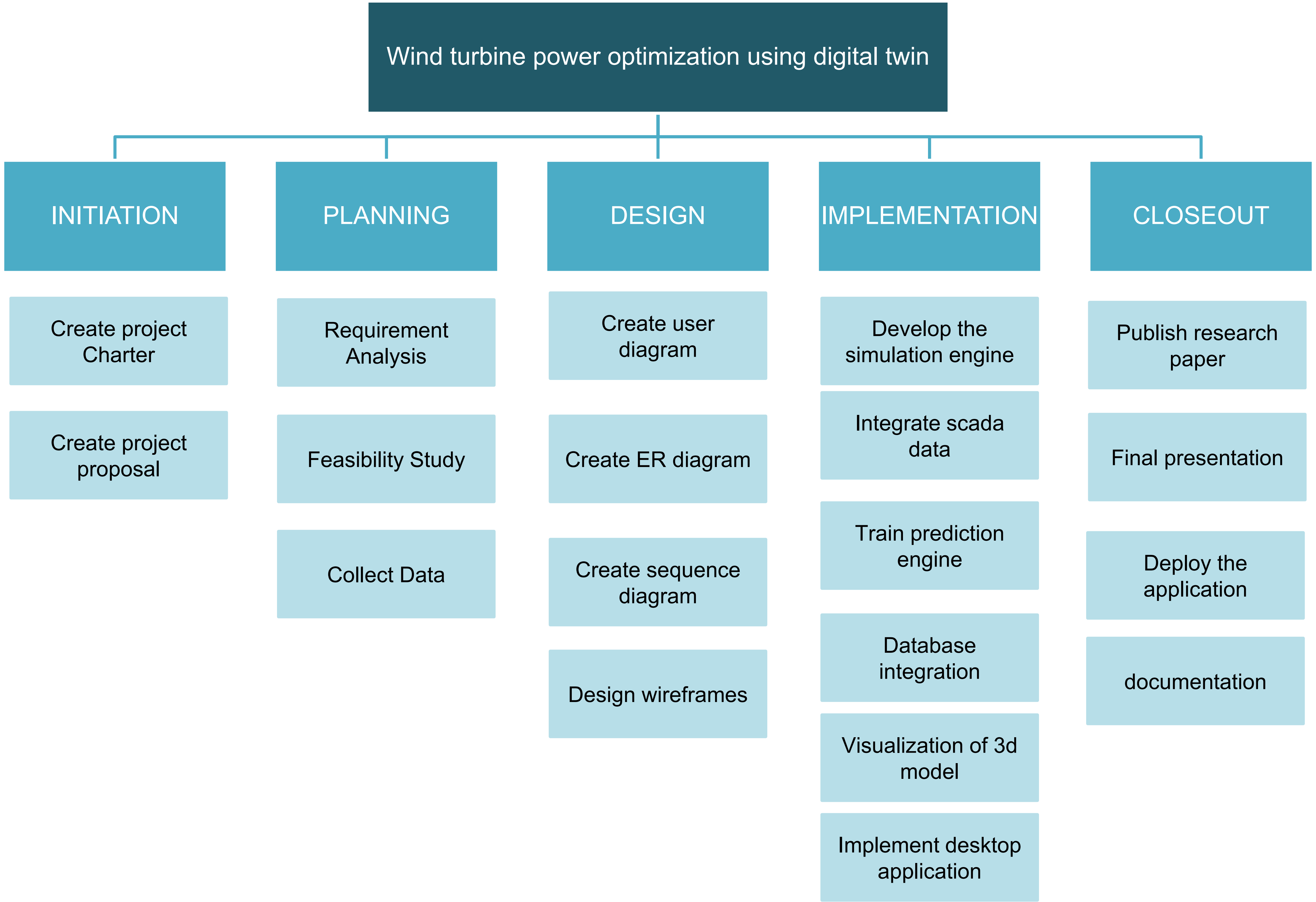
Non-Functional Requirements

- High availability and fault tolerance for continuous operation.
- Low latency for real-time processing.
- Scalability for multiple turbines.
- Secure data communication.

Personnel Requirements

Ceylon Electricity Board of Sri Lanka
Wind Farm

Work Breakdown Structure



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Specialization : Software Engineering

Background

Wind turbines face challenges like extreme weather, mechanical failures, and unplanned downtime

Digital Twin Technology: A revolutionary tool for real-time monitoring, simulations, and predictive maintenance.

Sri Lanka's unique tropical climate demands adaptive and advanced maintenance strategies.

Enhance turbine performance, reduce costs, and minimize downtime using digital twin technology.

Research Gap

Research A

Hybrid-Model-Based Digital Twin of the Drivetrain of a Wind Turbine (Pujana et al., 2023)

Primarily centered on drivetrain-specific failures and synthetic data generation for failure prediction.

Research B

intelligent Monitoring and Maintenance of Wind Turbine Blades Driven by Digital Twin Technology (Luo et al., 2023)

Concentrated on turbine blade maintenance using digital twin technology.

Research C

Digital Twins in Wind Energy: Emerging Technologies and Industry-Informed Future Directions (Castellani et al., 2023)

Explores general applications of digital twins in wind energy, with emerging technologies and challenges.

Comparison of existing systems

Feature	R[1]	R[2]	R[3]	Proposed System
Focus on drivetrain-specific failures	✔	✘	✘	✔
Blade monitoring maintenance strategies	✘	✔	✘	✔
Real-time weather data integration	✘	✘	✘	✔
Comprehensive turbine health monitoring	✘	✘	✔	✔
Adaptation to Sri Lanka’s tropical climate	✘	✘	✘	✔

Research Question

How can digital twin technology be utilized to enhance the reliability, efficiency, and cost-effectiveness of wind turbine maintenance in Sri Lanka’s unique tropical climate?

Specific and Sub Objectives

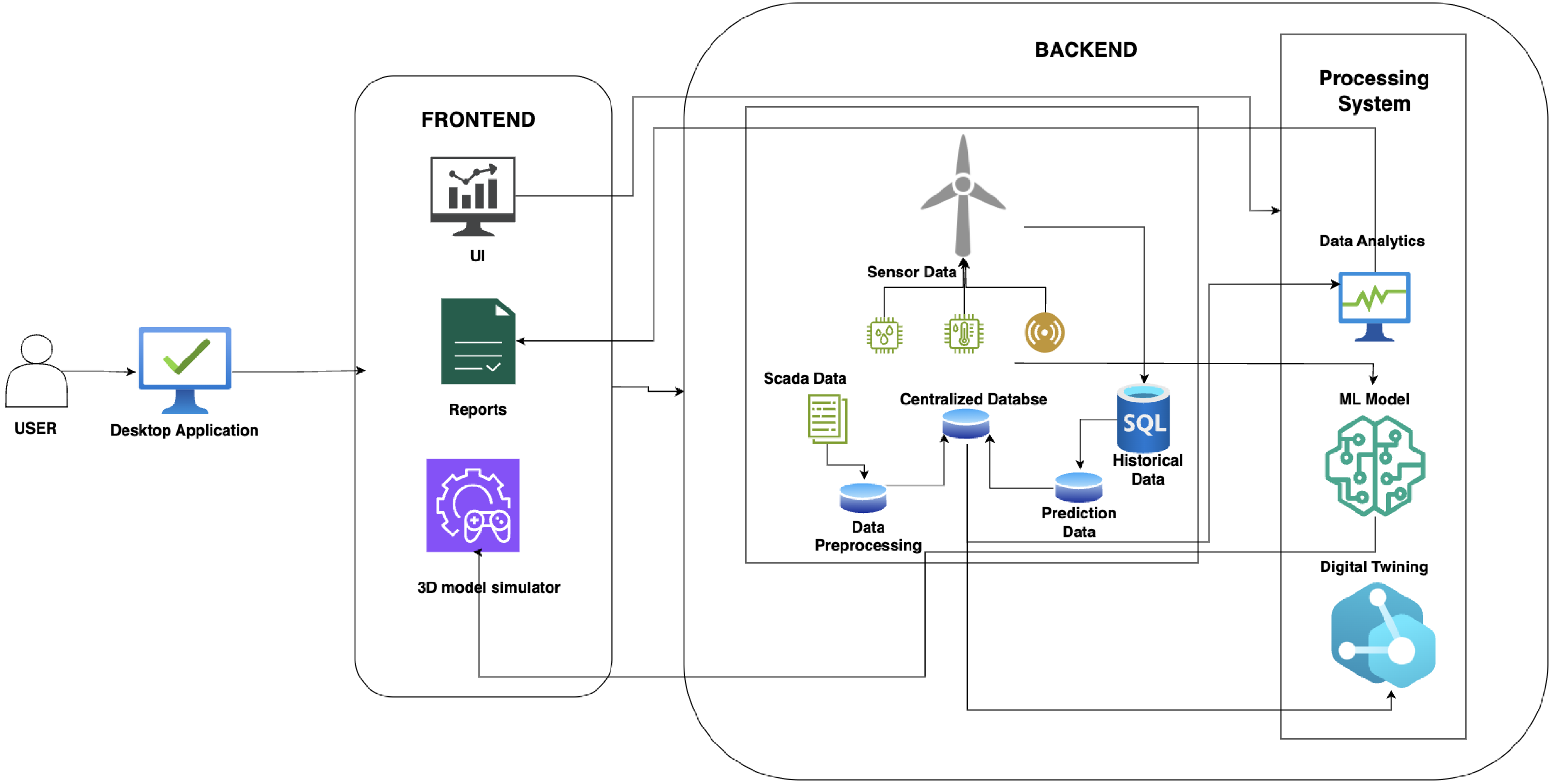
Sub Objectives

- Collect and integrate real-time sensor data into a centralized system for continuous turbine performance monitoring.
- Use digital twin simulations to model turbine behavior under different weather conditions and analyze impacts.
- Develop machine learning models to predict failures and identify early signs of wear or degradation.
- Create weather-specific protocols like speed adjustments and optimize operations dynamically.
- Build dashboards to display turbine health and generate maintenance reports.
- Evaluate cost savings and tailor solutions to Sri Lanka's climatic challenges.

Specific Objective

To design and implement a digital twin-driven maintenance strategy for wind turbines that enhances their reliability, optimizes performance, and minimizes downtime while adapting to Sri Lanka's tropical climate.

Methodology
System Diagram



System,Personnel and Software Specification Requirements

Software Requirements

- Python
- PyBullet(Simulation Engine)/Gazebo
- VS code
- Flask/FastAPI (Backend RestAPIs)
- MQTT Broker
- TensorFlow/Pytorch (Prediction Engine
- PostgreSQL
- OPC-UA/Modbus libraries

Personnel Requirements

- Mr. Jeewaka Perera (AI & ML Senior Lecturer)
- Ceylon Electricity Board of Sri Lanka Wind Farm

System Requirements

The system should simulate real-world physics for robotics and machine systems in real time.

The simulator should send and receive real-time telemetry data using MQTT.

The backend should perform predictions based on simulator data, SCADA data, or historical data from the database.

The system should ingest SCADA data using protocols like OPC-UA or Modbus.

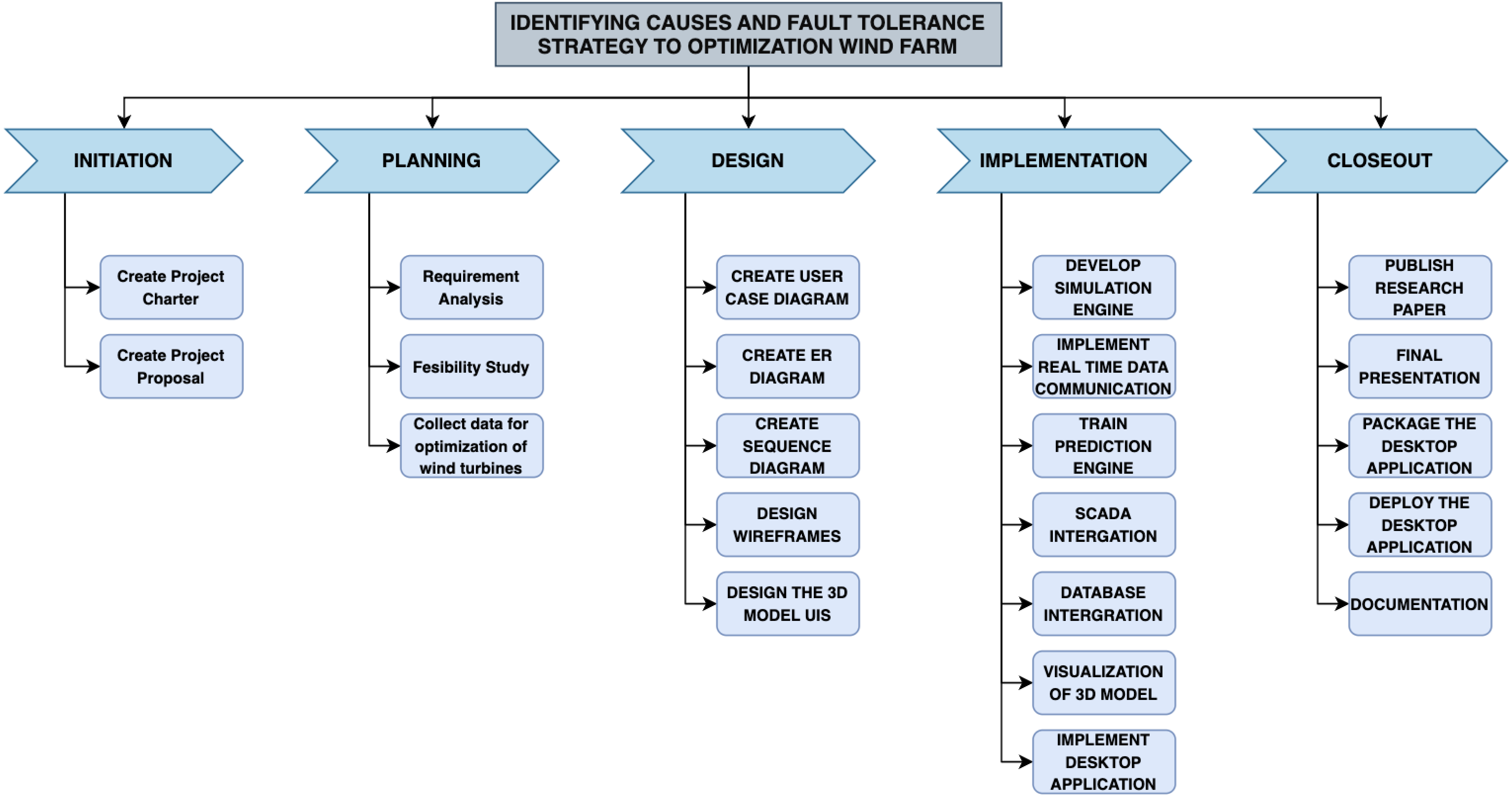
The backend should support REST APIs for system configuration, logging, and prediction results.

The system should provide visualization and analytics for simulation and prediction results.

Non-Functional Requirements

- Should handle real-time data with low latency.
- Must ensure data security in MQTT communication and REST API endpoints.
- Should be cross-platform compatible for simulator deployment.
- The application must be reliable and fault-tolerant for long simulation runs.

Work Breakdown



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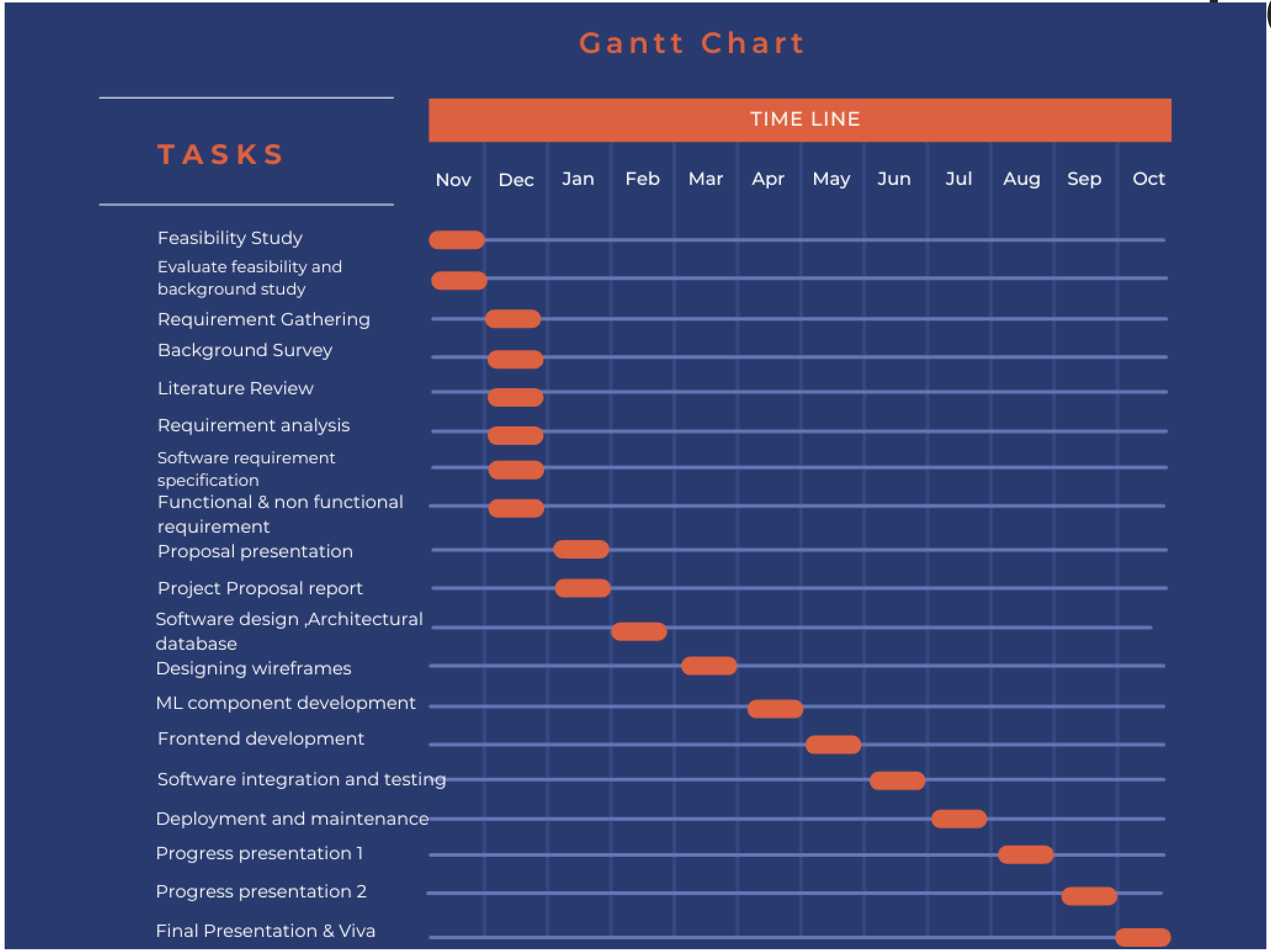
Supportive Information Commerlization



Thank You !