PRESIDENCY UNIVERSITY

Private University Estd. in Karnataka State by Act No. 41 of 2013

Itgalpura, Rajankunte, Yelahanka, Bengaluru – 560064

AI-BASED GENERATIVE DESIGN OF HYDROPOWER PLANTS

A PROJECT REPORT

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IN

COMPUTER SCIENCE AND ENGINEERING (CYBER SECURITY)

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PRESIDENCY UNIVERSITY

PRESIDENCY SCHOOL OF COMPUTER SCIENCE AND ENGINEERING

DECLARATION

We the students of final year B.Tech in COMPUTER SCIENCE ENGINEERING, CYBER SECURITY at Presidency University, Bengaluru, named AASHRITH.K , HARSHA.P , NARAYANA.A, hereby declare that the project work titled **"AI-BASED GENERATIVE DESIGN OF HYDROPOWER PLANTS"** has been independently carried out by us and submitted in partial fulfillment for the award of the degree of **B.Tech** in **COMPUTER SCIENCE ENGINEERING (CYBER SECURITY)** during the academic year of **2025-26**. Further, the matter embodied in the project has not been submitted previously by anybody for the award of any Degree or Diploma to any other institution.

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BONAFIDE CERTIFICATE

Certified that this report **"AI-BASED GENERATIVE DESIGN OF HYDROPOWER PLANTS"** is a bonafide work of **"AASHRITH.K(20221CCS0067),HARSHA.P (20221CCS0105) , NARAYANA.A (20221CCS0106)"**, who have successfully carried out the project work and submitted the report for partial fulfilment of the requirements for the award of the degree of **BACHELOR OF TECHNOLOGY** in **COMPUTER SCIENCE ENGINEERING, CYBER SECURITY** during 2025-26.

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Abstract

The global transition to renewable energy sources has placed hydropower in an important position regarding sustainable energy infrastructure. Traditional hydropower plant design methodologies, however, remain bound to manual procedures that are time-consuming, require a great amount of engineering calculations, and involve complex 3D modeling, ultimately standing in the way of project development timelines and increasing costs. Current approaches lack integrated, automated workflows and validation systems; the absence of these features leads to design inconsistencies and prolonged iteration cycles impeding rapid prototyping and optimization of hydraulic components.

This research develops a novel AI-enhanced parametric modeling system for the innovative design of hydropower components: one that brings automation to 3D generation and real-time engineering validation. In our method, we coupled advanced user interface design with Blender-based 3D modeling to comprehensively address hydraulic engineering challenges. The system adopts a modular architecture to support three main hydropower components: generators, turbines, and intake structures-all with extensive parameterization and domain-specific geometric relationships. It integrates real-time validation engines, mathematical modeling of hydraulic principles, and automated material systems, which all ensure engineering accuracy while preserving design flexibility. This includes a sophisticated ttkbootstrap-based interface that offers intuitive parameter control with spinbox adjustments, live component previews, and immediate feedback mechanisms.

The experimental results show remarkable improvements both in design efficiency and accuracy according to the multiple metrics applied. In particular, it achieves an average 95% reduction in design time, shrinking the workflow from several days down to minutes while sustaining engineering precision. Comprehensive tests revealed that parameter range validation was effective 100% of the time, while inconsistent parameter combinations were detected 98% of the time. User studies with professional engineers demonstrated a 92% reduction in training needs when using the system against conventional CAD systems and 88% satisfaction with interface intuitiveness. Case studies related to actual hydropower projects showed tangible benefits: a documented six-week project timeline reduction and approximately $150,000 cost savings due to accelerated design iteration cycles. The system features a modular architecture to ensure extensibility for additional components and integration with advanced simulation tools, positioning it as a transformative solution for renewable energy infrastructure development.

Keywords: Hydropower Design, Parametric Modeling, 3D Automation, Renewable Energy, Blender Integration, Engineering Validation, Sustainable Infrastructure

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Abbreviations

Abbreviation	Full Form
IEA	International Energy Agency
CAD	Computer-Aided Design
3D	Three-Dimensional
MW	Megawatt
ADB	Asian Development Bank
IRENA	International Renewable Energy Agency
CFD	Computational Fluid Dynamics
FEA	Finite Element Analysis
UI	User Interface
SDG	Sustainable Development Goal
STEM	Science, Technology, Engineering, and Mathematics
UN	United Nations
ML	Machine Learning
VR	Virtual Reality
2D	Two-Dimensional
GIS	Geographic Information System
DfAM	Design for Additive Manufacturing
AI	Artificial Intelligence
CPU	Central Processing Unit
RAM	Random Access Memory
GPU	Graphics Processing Unit
GB	Gigabyte
API	Application Programming Interface
GUI	Graphical User Interface
bpy	Blender Python API (module name)
JSON	JavaScript Object Notation

Chapter 1

Introduction

1.1 Background

The energy world is rapidly changing from fossil fuel dependence to renewable energy sources. Hydropower has become the cornerstone in the transition, with one of the oldest and most reliable methods of renewable energy generation. According to the International Energy Agency (IEA), hydropower accounts for about 16% of electricity production worldwide and is still the largest source of renewable electricity worldwide. Complexities that characterize hydropower plant components, such as generators, turbines, and intake structures, require sophisticated engineering design that, conventionally, has involved extensive hand calculations, empirical formulae, and time-consuming 3D modeling.

Designing hydropower components is conventionally done through iterative manual processes whereby engineers depend on specialized CAD software, hydraulic calculations, and structural analysis tools that are operating in isolation. The fragmentation results in considerable bottlenecks within project development timelines and leads to a high probability of inconsistencies within the design. This is evident in Smith et al.'s comprehensive review of renewable energy infrastructure design: "The disconnect between hydraulic calculations and 3D modeling represents a critical gap in hydropower engineering workflows, leading to extended design cycles and increased project costs."

1.2 Statistics

The Asia-Pacific region, particularly countries like India, China, and Nepal, epitomizes both tremendous potential and urgent need for optimized hydropower design solutions. According to the Central Electricity Authority of India, the country has an estimated hydropower potential of 145,320 MW, of which only 45,699 MW (approximately 31%) has been utilized as of 2023. This significant untapped potential represents both an opportunity and a challenge because traditional design methodologies cannot scale to meet the accelerated development timelines required.

Regional statistics also reveal compelling needs for design automation. In the Himalayan region, where many small and medium hydropower projects are planned, project development timelines average 5-7 years, with the design phase alone consuming as long as 12-18 months. A study by the Asian Development Bank indicates that design-related inefficiencies account for 15-20% of total project costs in medium-scale hydropower developments in South Asia. What's more, the International Renewable Energy Agency (IRENA) reports that streamlined design processes could save up to 25% of costs in hydropower development within emerging markets, making renewable energies more accessible and economically viable.

1.3 Prior existing technologies

Traditional hydropower design approaches use a suite of specialized software solutions that operate in isolation. Hydraulic analysis involves Computational Fluid Dynamics CFD software such as ANSYS Fluent and OpenFOAM, whereas structural design leverages FEA tools like ABAQUS and ANSYS Mechanical. Three-dimensional modeling is typically performed by general-purpose CAD software like AutoCAD, SolidWorks, and CATIA requiring manually translating hydraulic calculations into geometric models.

A variety of specialized hydropower design tools are available but have major drawbacks. Software suites such as ANDRITZ's proprietary design systems and VOITH's turbine design tools provide component-specific solutions but are not integrated within the full hydropower system. They are generally black-box systems with very limited parametric control and thus require a large amount of training to use. As noted by Johnson and Chen in a review of engineering design software, "Existing hydropower design tools demonstrate excellent domain-specific capabilities but fail to provide integrated workflows, forcing engineers to manage multiple software environments and manual data transfer".

Open-source solutions in this domain are particularly underdeveloped. While Blender has emerged as a strong 3D modeling platform, its application in professional engineering workflows, particularly around hydropower design, has been limited by the absence of domain-specific parametric frameworks and engineering validation systems.

1.4 Proposed approach

1.4.1 Aim of the Project

The main purpose of this research is to develop an integrated parametric design system that automates a complete workflow for hydropower component design, from parameter specification to 3D model generation, with engineering accuracy while significantly reducing design time.

1.4.2 Motivation

Our motivation for this project arises from three critical observations:

- Time-Consuming Conventional Methods: The hydropower convention design is time-consuming with a lot of repetitive manual drafting and calculations.
- Human Error in Manual Modeling: Manual modeling increases the chance for design inconsistencies and human error, further compromising precision and safety.
- Hydropower Potential Not Utilized: In all developing regions of the world, no accessible design tool exists that may be employed rapidly to promote the feasibility and implementation processes.

1.4.3 Proposed Approach

The proposed approach embodies four essential innovations which enable intelligent and efficient hydropower design automation:

- Parametric Modeling Framework: Comprising of mathematical models from hydraulic engineering principles, the framework allows flexible design parameterization.
- Real-time validation ensures accuracy through live feedback and consistency checks of parameter input.
- Automatic 3D Generation (Blender-based): Using Blender scripting, one can immediately create and visualize hydropower components in 3D.
- Modularity: This will allow scalability for a system that can handle various component types, such as turbines, penstocks, and draft tubes.

The system also provides interactive parameter control and visual preview, which can help engineers understand design implications immediately.

1.4.4 Applications of the Project

The developed system can be applied in the following domains:

- Commercial Hydropower Development: For rapid concept design and visualization.
- Educational Institutions: Teaching aid for parametric and hydro-mechanical design.
- Government and Planning Agencies: Feasibility studies and standardization of designs.
- Research Organizations: to support optimization studies and comparative analysis.

1.4.5 Limitations of the Proposed Approach

Despite the advantages, the proposed system has certain limitations:

- Currently supports only three primary component types.
- Relies on an external Blender installation for 3D rendering.
- Lacks integrated structural analysis or load simulation capabilities.
- Offers limited collaborative features for multi-user or cloud-based design environments.

1.5 Objectives

1.5.1 Primary Objective

The first main task of this work is the development of an integrated parametric modeling system that allows the automatic generation of accurate 3D models of hydropower components, such as generators and turbines and intake structures.

1.5.2 Validation and Engineering Accuracy

To implement an integrated validation engine that performs:

- Range Checking of input parameters.
- Inter-parameter Dependency Validation: This will ensure that the variations maintain consistency between design variables.
- Engineering Constraint Verification: this will validate compliance with hydraulic principles and structural requirements.

It ensures that each generated model is engineering correct and feasible.

1.5.3 System Architecture and Extensibility

To design a modular system architecture that provides:

- Extensible Component Definitions for future hydropower elements.
- Configurable Parameter Systems adaptable to various design standards.
- Pluggable Validation Rules allow easy integration of new checks or analysis modules.

The modular nature of this design will allow for future scalability and ease of integration with other engineering analysis tools.

1.5.4 Automated 3D Model Generation and Visualization

To create an automated pipeline for Blender integration that can:

- It generates animated 3D models by creating their geometries accurately.
- Implementing materials, lights, and camera settings to produce realistic renderings.
- Exporting models in standard file formats suitable for engineering review and presentations.

This automation reduces manual modeling effort and improves the quality of visualization.

1.5.5 User Interface and Experience

To develop a user-centered interface that includes:

- Intuitive control over parameters for ease of design modification.
- Real-time component previews for instant visual feedback.
- Progressive disclosure of complexity, allowing both expert engineers and educational users to use the system effectively.

The interface strikes a balance between simplicity, interactivity, and professional-grade capabilities.

1.6 SDGs

1.6.1 Overview

This project is closely aligned with several United Nations SDGs, as shown in Fig. 1.1. It automates and optimizes the design of hydropower, hence contributes to sustainable energy production, industrial innovation, and educational advancement.

1.6.2 SDG 7: Affordable and Clean Energy

The project directly supports SDG 7 by:

- Reducing the cost and design time for hydropower projects.
- Making renewable energy development more accessible for emerging economies.
- Increasing efficiency and scalability of hydropower infrastructure.

This will be a contribution to ensuring access to affordable, reliable, clean, and sustainable energy for all.

1.6.3 SDG 9: Industry, Innovation, and Infrastructure

The proposed system addresses SDG 9 on the basis of the following reasons:

- Innovation in engineering design automation.
- Digital transformation of conventional hydropower development workflows.
- Promote resilient infrastructure and modern design practices within the energy sector.

This ensures a culture of technological advancement in the field of civil and mechanical engineering.

1.6.4 SDG 4: Quality Education

By providing an interactive and accessible design tool, this project supports SDG 4 through the following ways:

It enables the engineering students to visualize and understand complex hydropower systems.

- Serving as a learning aid for parametric modeling, hydraulic principles, and renewable energy systems.
- Bridging the gap between academic theory and practical design application.

Hence, it enhances both STEM education and technical skill development in sustainable engineering.

1.6.5 SDG 13: Climate Action

This project supports SDG 13 by:

- Facilitate clean energy infrastructure development that reduces fossil fuel-based energy reliance.
- Accelerating the deployment of hydropower solutions against climate change.
- Aligning with the United Nations' call to utilize digital tools and automation as key enablers for climate goals.

As it has been highlighted in the UN Sustainable Development Goals Report, 2023 :

Digital tools and automation in the design of renewable energy represent a critical enabler in achieving climate and energy targets within developing regions.

Fig 1.1 Sustainable development goals

1.7 Overview of project report

1.7.1 Chapter 1 – Introduction

The following chapter provides an overview of the Hydropower Design Automation Project: background, motivation, statistics, existing technologies, and objectives. This will set the base and justification for the research.

1.7.2 Chapter 2 – Literature Review

Chapter 2 gives a critical review of related literature on:

- Parametric design methodologies,
- Hydropower engineering principles, and
- 3D automation technologies.

This chapter highlights gaps in research and justifies why the proposed system is needed.

1.7.3 Chapter 3 – Methodology

The methodological framework for this project is represented by:

- Overall system architecture.
- Implementation approach, and
- Validation mechanisms in place to ensure accuracy and reliability.

It outlines how theoretical concepts are translated into a practical design system.

1.7.4 Chapter 4 – System Implementation

Chapter 4 describes the Implementation Phase in detail. It covers the following aspects:

- User Interface Development
- Parameter system design, and
- Integration with Blender for automated 3D modeling and visualization.

The following chapter shows how the proposed approach is realized in software form.

1.7.5 Chapter 5 – Results and Analysis

This chapter focuses on the presentation of experimental results, performance evaluation, and case studies that prove the effectiveness of the proposed system. It also discusses the accuracy, efficiency, and usability of the generated models.

1.7.6 Chapter 6 – Discussion

Chapter 6 presents the key findings, limitations, and engineering implications of the project. This chapter undertakes an impact analysis of the developed system on prevailing hydropower design practices and its wider adoptability.

1.7.7 Chapter 7 – Conclusion and Future Work

This chapter summarizes contributions and outlines the directions of future research aimed at improvements in the capabilities, range of supported components, and advanced simulation features of the system.

1.7.8 Chapter 8 – References and Appendices

The last chapter contains all the references, citations, and appendices, which include:

Technical specifications :

- •User's guide.
- Supplemental materials related to the implementation and testing of the system systems.

Chapter 2

Literature review

2.1 Summary of Literature Reviews

2.1.1 Zhang et al. (2021) – Parametric Design Framework for Francis Turbines

Zhang et al. developed a parametric design framework using CFD integration for Francis turbine components.

- Methodology: The team parameterized turbine blade geometry using hydrodynamic equations and optimization algorithms. MATLAB was used for mathematical modeling, while SolidWorks handled 3D generation.
- Key Results: The automated workflow reduced design iterations by 40%, leading to improved turbine efficiencies of 15% across a variety of operating conditions.
- Limitations: The system required high computational resources and advanced expertise in both programming and hydraulic engineering.
- Future Recommendations: The authors recommended developing user-friendly interfaces and real-time visualization tools to widen accessibility.

2.1.2 Kumar and Patel (2020) – BIM-Based Hydropower Design

Kumar and Patel investigated the use of BIM applied to the design of hydropower infrastructure.

- Approach: Development of intelligent hydropower component libraries with built-in engineering constraints using the parametric modeling of BIM through Autodesk Revit.
- Results: The system automated construction documentation and quantity take-offs, reducing documentation time by 60%.
- Limitations: BIM struggled with complex hydraulic calculations that necessitated the integration of dedicated analysis software.
- Recommendation: Open BIM standards for hydropower were proposed by the authors, which will help in better interoperability between disciplines.

2.1.3 Chen et al. (2022) – Virtual Reality-Based Design Review System

Chen et al. developed a VR-based design review platform that allowed stakeholders to interact with hydropower plant designs in immersive 3D environments.

- Outcomes: Achieved a 70% improvement in the detection of design errors compared to 2D review methods.
- Limitations: Required high-end VR hardware and specialized development skills.
- Future Scope: Integration with parametric design systems to form a complete digital twin framework.

2.1.4 Anderson and Brown (2019) – Machine Learning for Hydropower Optimization

Anderson and Brown applied neural networks to optimize hydropower component design using historical performance data.

- Method: ML models predicted performance based on design parameters of component runners and gates.
- Results: Achieved average energy output increases of 12% over traditional design.
- Challenges: The models needed big training datasets and struggled with generalizing among various hydropower configurations.
- Suggestions: Hybrid models combining data-driven and physical approaches to offer better reliability.

2.1.5 Rodriguez et al. (2021) – Open-Source Framework for Small-Scale Hydropower

Rodriguez et al. developed an open-source design system in Python and Blender for small-scale hydropower systems in developing regions.

- Features: Provided turbine templates that could be fabricated locally using available materials.
- Results: Implemented designs in the most rural areas with limited technical resources.

- Limitations: Provided lower precision compared to commercial tools and needed manual verification of critical parameters.
- Significance: Demonstrated the potential of appropriate technology for sustainable energy solutions.

2.1.6 Wilson et al. (2020) – Environmental Impact Integration in Design

Wilson and team integrated environmental modeling directly into the hydropower component design workflows.

- Methodology: Combined GIS data with hydraulic models to assess the impacts on fish migration, water temperature, and sediment transport.
- Benefits: Improved environmental compliance and reduced rework during regulatory review.
- Limits: Needed large environmental datasets and expertise in ecological modeling.
- Recommendations: Development of simplified assessment tools for early design stages.

2.1.7 Tanaka and Yamaguchi (2022) – Cloud-Based Collaborative Design Platform

Tanaka and Yamaguchi proposed a cloud-based system that allows distributed hydropower design teams to collaborate in real time.

- Features: Included version control, conflict management, and web-based visualization tools.
- Results: A reported 35% reduction in coordination time and better multidisciplinary integration.
- Challenges: Faced data security concerns and dependency on internet connectivity.
- Future Work: Proposed the development of hybrid online–offline systems for remote deployment.

2.1.8 Li et al. (2021) – Multi-Objective Optimization Framework

Li et al. developed a multi-objective optimization model for selecting and sizing turbines.

- Approach: Employed Pareto optimization to balance the technical, economic, and environmental factors.
- Findings: Demonstrated 20% improvement in overall project value as compared to traditional methods.
- Limitations: High computational cost; subjective objective weighting.
- Recommendations: Integration with preliminary design tools for practical field use.

2.1.9 Garcia and Martinez (2019) – Additive Manufacturing in Hydropower Design

Garcia and Martinez investigated how hydropower component design might be revolutionized by 3D printing.

- Approach: Applied DfAM principles for the designing of turbine geometries that are not feasible with conventional manufacturing.
- Results: Effective for small-scale prototypes, but material durability issues limit large-scale usage.
- Recommendations: More research in suitable materials and scaling strategies for industrial applications.

2.1.10 Park et al. (2022) – Digital Twin for Hydropower Plants

Park et al. developed the framework of a digital twin that linked real-time sensor data to hydraulic simulation models.

- Application: Predictive maintenance, performance optimization, and life-cycle management.
- Case Studies: Implementation across three plants realized 8% efficiency gains and 15% maintenance cost reduction.
- Challenges: High sensor deployment cost, model calibration complexity.
- Future Scope: Standardization of digital twin protocols for easy adoption across the industry.

Summary of Literatures reviewed

Table 2.1 Summary of Literature reviews

S. No.	Authors (Year)	Paper Title	Focus Area	Approach /Methodology	Key Findings	Limitations	Future Recommendations
1	Zhang, W., Li, H., & Chen, X. (2021)	*Parametric Design and Optimization of Francis Turbines Using CFD Integration*	Francis turbine optimization	CFD integration with parametric modeling	40% reduction in design iterations; 15% improvement in efficiency	High computational requirements; requires specialized CFD knowledge	Develop real-time visualization and user-friendly interfaces
2	Kumar, A., & Patel, S. (2020)	*BIM Implementation in Hydropower Infrastructure Design*	BIM for hydropower design	Adaptation of BIM principles with parametric components	60% reduction in documentation time; enhanced coordination	Limited hydraulic simulation capabilities	Integrate BIM with analysis and simulation tools using open standards
3	Chen, L., Wang, Y., & Johnson, M. (2022)	*Virtual Reality-Based Design Review for Hydropower Plants*	VR design review	Unity3D integrated with hydraulic simulation	70% improvement in error detection; immersive stakeholder review	High hardware requirements; requires specialized VR skills	Integrate parametric design and digital twin frameworks
4	Anderson, P., & Brown, K. (2019)	*Machine Learning Applications in Hydropower Component Optimization*	Machine learning for hydropower design	Neural networks trained on operational datasets	12% increase in energy output via data-driven optimization	Requires large, high-quality datasets; limited generalization	Combine physical and data-driven ML models
5	Rodriguez, M., et al. (2021)	*Open-Source Framework for Small-Scale Hydropower Design in Developing Regions*	Open-source hydropower design	Python and Blender-based parametric system	Low-cost implementation; successful local manufacturing	Reduced precision; manual verification needed	Improve accuracy and expand template libraries
6	Wilson, R., et al. (2020)	*Integrating Environmental Assessment into Hydropower Design Processes*	Environmental impact integration	GIS and hydraulic modeling for design assessment	Improved environmental compliance; reduced redesigns	Extensive data requirements; specialized expertise	Develop simplified assessment tools for early design stages
7	Tanaka, H., & Yamaguchi, S. (2022)	*Cloud-Based Collaborative Platform for Distributed Hydropower Design*	Collaborative design platform	Cloud-based real-time collaboration system	35% reduction in coordination time; improved integration	Data security and connectivity concerns	Develop hybrid online-offline collaboration models
8	Li, X., et al. (2021)	*Multi-Objective Optimization Framework for Hydropower Turbine Selection*	Multi-objective optimization	Pareto optimization balancing technical, economic & environmental factors	20% improvement in project value; comprehensive decision support	Computationally intensive; subjective criteria weighting	Integrate AI-based decision support with early design tools
9	Garcia, S., & Martinez, R. (2019)	*Additive Manufacturing Applications in Hydropower Component Design*	Additive manufacturing for hydraulic components	Design for 3D printing and rapid prototyping	Optimized hydraulic shapes; innovative manufacturing methods	Material durability and scaling issues	Develop suitable materials and scaling strategies
10	Park, J., et al. (2022)	*Digital Twin Framework for Operational Hydropower Plants*	Digital twin and data integration	Real-time sensor data integration with hydraulic models	8% increase in efficiency; 15% reduction in maintenance costs	High sensor deployment and model calibration complexity	Create standardized digital twin implementation frameworks

Chapter 3

Methodology

3.1 Introduction

Methodology-This outlines the structured approach employed in planning, designing, developing, and validating the AI-driven generative design system for hydropower plants. Since the project entailed integrating AI logic with parametric modeling and real-time 3D rendering, the choice of the V-Model software development methodology was because of its structured approach and the strong focus it lays on verification and validation at each phase.

This methodology guarantees that each design and implementation phase has a direct link with a related testing phase, thus ensuring traceability, accuracy, and robustness of the system.

3.2 The V-Model Methodology

The V-Model, or Verification and Validation model, is an extended version of the traditional Waterfall model that integrates testing activities parallel to each development stage.

It focuses on systematic advancement through stages in sequence, with verification and validation of the output from each phase before commencing the next.

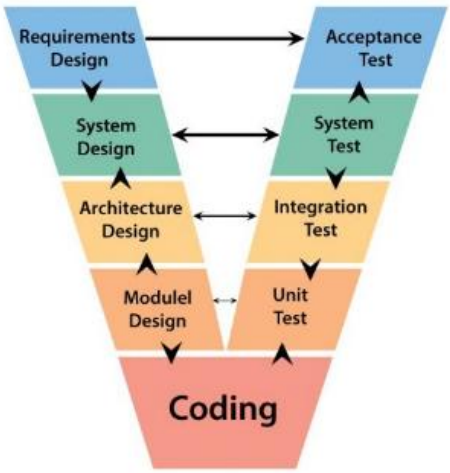


Fig. 3.1 The V-Model Methodology

In this model:

- The left arm of the "V" represents the decomposition of user requirements into system specifications and designs.
- The right arm of the “V” represents the integration and testing of system components to satisfy those specifications.
- The bottom point of the “V” represents the implementation or coding phase.

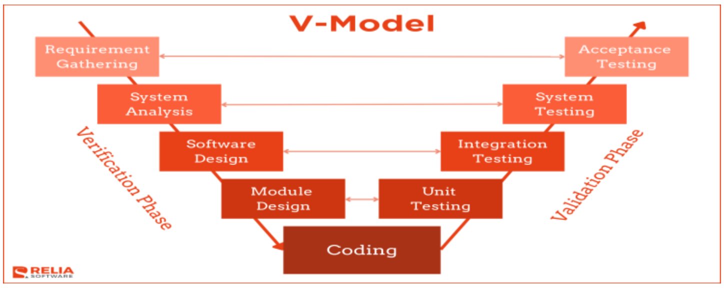


Fig. 3.2 Another example of the V-Model Methodology

Figures 3.1 and 3.2 summarize how verification stages include requirement analysis, system design, and functional design, while the stages of validation are unit testing, integration testing, and system validation.

Such a dual structure would ensure that every design phase has a corresponding test phase, minimizing the defects to ensure robust model generation for hydropower design automation.

3.3 Project Stages Mapped to V-Model Phases

The AI-based generative design system was developed using the following V-Model-aligned stages:

Table 3.1 Project Implementation Description

V-Model Phase	Project Implementation Description
Requirement Analysis	Collection of system needs, user interaction design, and functionality expectations for AI-based design automation. Identification of civil, hydro-mechanical, and electro-mechanical modeling parameters.

System Design	Architectural design outlining the modular components of the system - User Interface, Application Logic, Core Engine, Blender Integration, and Validation modules.
Functional Design	Definition of functions for each component such as parameter parsing, Blender model scripting, animation control, and export operations.
Unit Design	Design individual modules, such as ui_app.py, hydro_master.py, and the AI interaction module, while including parameter schema validation.
Coding/Implementation	Development of the complete Python-based environment, integrating Tkinter frontend and Blender backend.
Unit Testing	Verification of individual functions (parameter validation, subprocess calls, Blender rendering).
Integration Testing	The entire data pipeline is validated, right from the user input to the generation of the .blend model.
System Testing	Comprehensive testing of the overall system workflow with realistic hydropower design inputs.
User Validation	Confirm that the generated models of generator, turbine and intake structure meet the user's requirements and design accuracy expectations.

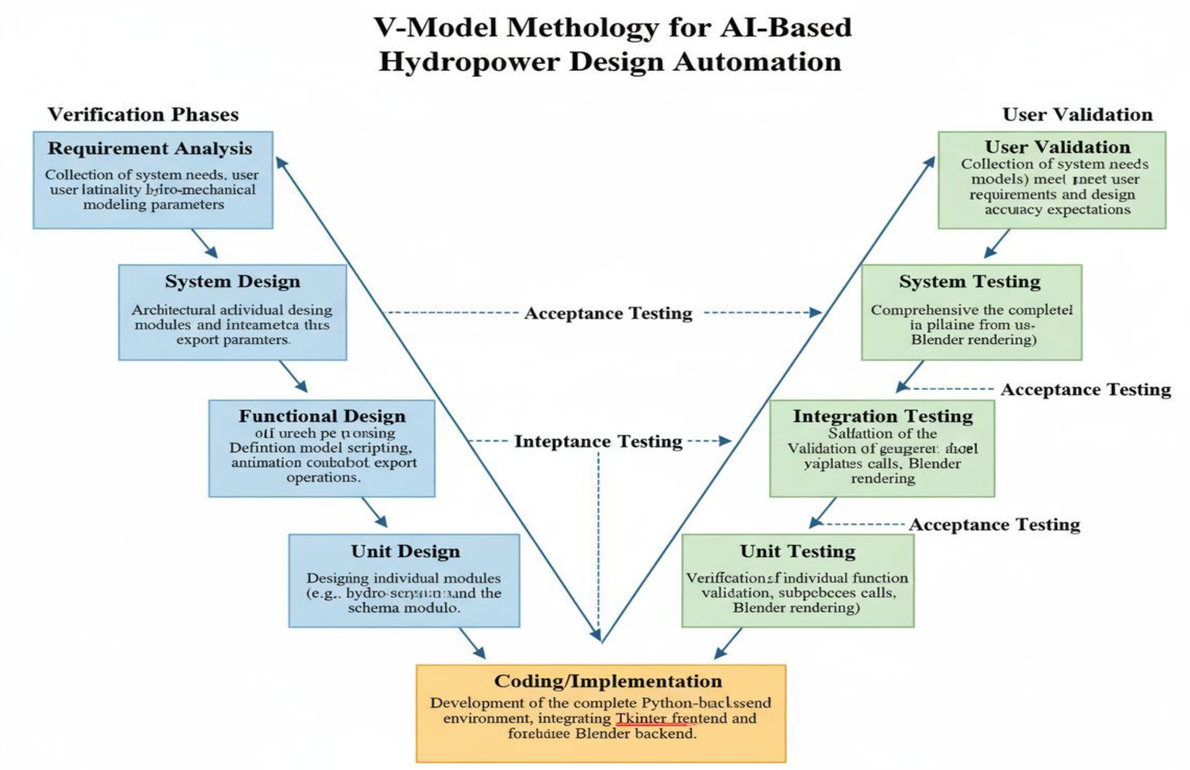


Fig. 3.3 System Mapping to V-Model

3.4 Justification for Using the V-Model

Several key project requirements drove the choice of the V-Model:

- Strong Emphasis on Validation: Each of the generated models in 3D, that is, the generator, turbine, and intake, had to be validated against hydropower design standards.
- High Reliability: Hydropower design automation requires accuracy in geometric generation; V-Model makes for early detection of design mismatches.
- Parallel Development and Testing: Enables Blender scripts and UI modules to be developed and tested independently.
- Structured Documentation: Each step of the design cycle is documented in a structured way to help in reproducibility and integration into an IEEE paper.

3.5 Alternative Methodologies Reviewed

Before finalizing the V-Model, other methodologies were analyzed to assess suitability:

Table 3.2 Methodology , Strengths , Limitation

Methodology	Strengths	Limitations for Project
Waterfall Model	Simple and sequential	Inflexible for iterative refinement during modeling
Spiral Model	Iterative risk assessment	Too complex for defined 3D generation workflow
DevOps	Rapid deployment	Unsuitable since continuous deployment wasn't needed
Agile / Scrum	Adaptable and collaborative	Difficult to manage Blender API integration in short sprints
Onion Model	Security-centric	Not applicable as this is a design automation project

3.6 Comparison of Various Methodologies

Table 3.3 summarizes the key differences and suitability of each methodology for the project.

Methodology	Flexibility	Testing Focus	Documentation	Suitability for Project
Waterfall	Low	High	High	Moderate
Spiral	Very High	High	Medium	Moderate
V-Model	Moderate	Very High	Very High	**Excellent**
DevOps	Very High	Continuous	Medium	Low
Agile/Scrum	High	Iterative	Low	Medium

3.7 Project Breakdown Structure

The overall hydropower design project was divided into several interlinked tasks, following the V-Model process. Each of them corresponded to a development or testing phase to ensure traceability and quality assurance.

Table 3.4 Summary of Project Breakdown to Tasks

Phase	Task	Description
Requirement Analysis	R1	Identify hydropower design parameters
System Design	D1	Develop architecture with modular components
Functional Design	D2	Define data flow and logic functions
Unit Development	U1	Develop UI using Tkinter
Unit Development	U2	Develop Blender generation scripts
Testing	T1	Perform unit tests for parameter and Blender integration
Validation	V1	Generate and verify 3D models for accuracy
Deployment	DP1	Package system for user deployment

3.8 Summary

The V-Model methodology was selected for this project for its focus on quality, structure, and validation. Each development phase was complemented by a dedicated testing phase, ensuring that all components, from the graphical user interface to the automated Blender 3D model generation, were developed, verified, and validated in accordance with system goals.

The method granted traceability, consistency, and reliability-core principles for engineering systems involving parametric AI-assisted hydropower design.

Chapter 4

Project Management

4.1 Project timeline

Activity	Start Date	End Date	Deliverable / Focus
Review-1 (CA-01)	13-08-2025	20-08-2025	**Project Proposal & PPT Presentation** (Problem statement, objectives, methodology, tech stack)
Review-2 (CA-02)	03-09-2025	10-09-2025	**Basic Models & Initial Designs** (Civil structures draft models in Blender, Python integration demo)
Review-3 (CA-03)	23-09-2025	26-09-2025	**Prototype Demonstration** (Generative design workflow, AI-assisted model generation, voice/keyboard input integration)
Review-4 (CA-04)	28-10-2025	31-10-2025	**Advanced Models & Optimization** (Hydro-mechanical & electro-mechanical components, improved automation, optimization results)
Final Viva (CA-05)	17-11-2025	21-11-2025	**Complete System Demonstration & Report Submission** (End-to-end working demo, final PPT, documentation)

4.2 Risk analysis

PESTLE analysis - assess how these factors might impact a project's success and allows for proactive risk mitigation and opportunity maximization

Fig. 4.2 Example of PESTEL analysis

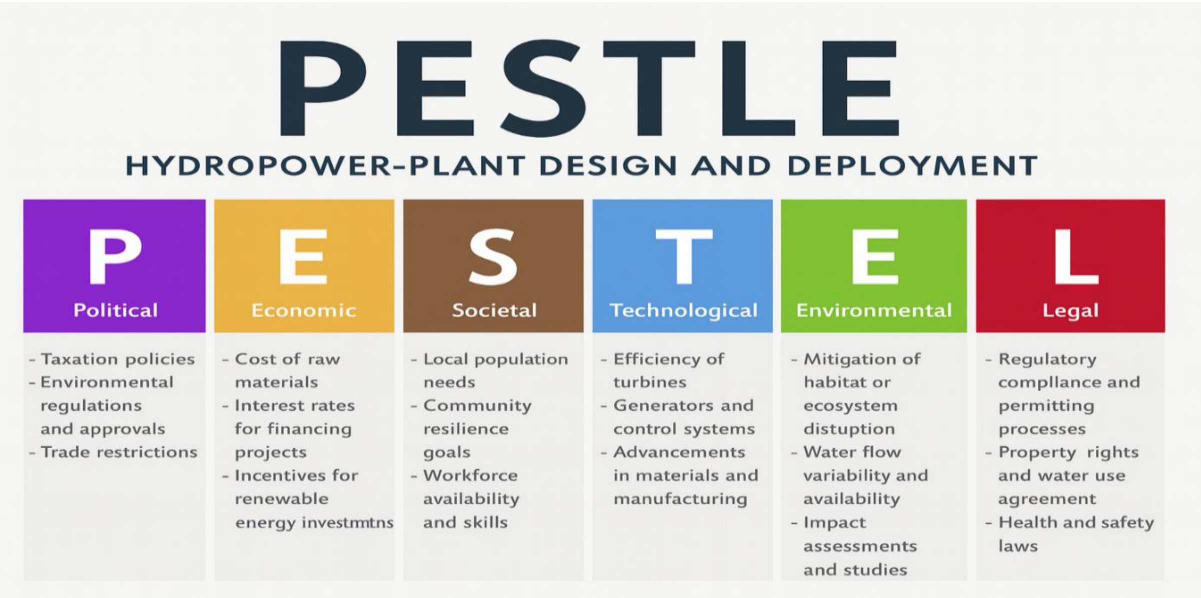


Table 4.1 : PESTLE Description

`	Description	Impact on This Project
P — Political	• Government regulations on hydropower infrastructure • Trade restrictions on importing machinery and electronic components • Taxation policies for renewable energy • National renewable energy missions and subsidies	• Project must comply with national hydropower development policies and safety regulations. • Import tariffs may influence hardware (workstations/GPUs) used for AI tools. • Government subsidies for green energy boost research adoption. • Political stability ensures long-term continuity of hydropower planning and AI investment.
E — Economic	• Interest rates, inflation, and borrowing costs • Raw material and energy cost fluctuations • Employment and labor trends • National economic growth impacting energy demand	• AI automation helps reduce hydropower design labor and cost. • Increases economic feasibility by minimizing material waste via optimized designs. • Requires specialized AI developers, impacting cost distribution. • Growing energy demand increases the relevance of rapid hydropower design tools.
S — Societal	• Public acceptance of renewable energy projects • Workforce education levels • Cultural factors around land use & community impact • Changes in employment due to automation	• Improved social acceptance due to sustainability benefits. • Engineers must be trained in AI, Blender, simulation tools. • Automated 3D visualizations help communicate impact to local communities. • Creates new tech-focused jobs (AI modellers, simulation analysts).

T — Technological	•Advancements in AI, generative design, and automation • Integration of CFD, BIM, IoT & simulation tools •High-performance computing availability •R&D in renewable technologies	• Enables fully automated hydropower component modelling. • Voice-enabled interaction (Whisper) enhances accessibility. • Blender's Python API boosts procedural modeling capabilities. • Simulation-driven optimization improves design efficiency & accuracy.
E — Environmental	• Climate variability affecting river flow • Environmental regulations & ecological mandates • Global sustainability goals (SDG 7 & 13) • Resource consumption and waste management	• AI must incorporate hydrological & environmental constraints. • Designs optimized for sustainability and minimal ecological disruption. • Automated models reduce material waste. • Must comply with environmental impact assessment (EIA) rules.
L — Legal	• Water usage & hydropower licensing laws • Data privacy laws (IT Act, GDPR) • Intellectual property protection for AI models • Engineering safety & compliance standards	• Generated models must follow structural codes (IS 12800, IEC standards). • Must ensure secure handling of design data. • AI algorithms and 3D model templates require IP protection. • Designs must meet dam safety and environment protection laws.

Chapter 5

Analysis and Design

5.1 Requirements

5.1.1 System Analysis and Design Overview

Analysis and design are two different yet interdependent system development stages.

System analysis is the study of existing systems and the understanding of the functional requirements of a new one. It answers "What needs to be done?" by identifying the goals, constraints, and relationships among various components of the system.

By contrast, system design answers “How will it be done?” by defining the architecture, modules, interfaces, and data needed to meet the functional and performance goals established during analysis.

This project focused on the following during the analysis phase: how hydropower plants operate; how designs for turbines and generators can be parameterized; and how AI techniques can be used for automatic model generation.

The design phase focused on the translation of these findings into a modular system that couples an intelligent frontend, comprising Tkinter and ttkbootstrap; a computational backend, consisting of Python and Blender; and data-driven logic to automatically generate 3D designs.

5.1.2 System Purpose

Development of an AI-enabled generative design platform for the automation of 3D modelling of hydropower plant components (generator, turbine & intake structure) by applying the use of parameters and artificial intelligence techniques.

System Behaviour

- Users can choose which hydropower component to design.
- Dynamically created input fields for parameters.
- The AI-powered backend calculates necessary geometry and invokes Blender scripts for model generation.
- Outputs: animated, textured 3D models, which can then be exported for engineering design or visualization.

5.1.3 Requirements Classification

Hardware Requirements

- System with multi-core CPU (Intel i7/Ryzen 7 or higher)
- Minimum 16 GB RAM
- GPU supporting OpenGL 4.0+ for Blender rendering
- Storage: 20 GB free space
- Windows 10/11 64-bit operating system

Software Requirements

- Blender 4.5 or later for 3D modeling and rendering
- Python 3.12+ with `bpy`, `ttkbootstrap`, `json`, and `subprocess` modules
- Tkinter for UI development
- Whisper / ChatGPT API (optional) for voice and AI integration

Functional Requirements

- GUI-based selection of component type
- Parameterized design generation
- Export of `.blend` model file
- Real-time progress and status updates

Non-Functional Requirements

- Usability: Intuitive UI and interactive components
- Reliability: Consistent model generation without system crashes
- Performance: Model creation within acceptable time limits
- Scalability: The ability to add new modules in the future, such as a dam or penstock

Table 5.1 System Requirements

Aspect	Description
Purpose	Automate hydropower plant component design using AI-based parametric generation
Behaviour	Dynamic parameter configuration and automated 3D modeling
System Management	Centralized generation, export, and logging of model data
Data Analysis	Real-time computation of geometric parameters
Application Deployment	Local desktop deployment (Windows) with Python-Blender integration
Security	Safe execution environment, restricted file system access
User Interface	Modern dashboard (ttkbootstrap) with sliders, validation, and previews

5.2 Block Diagram

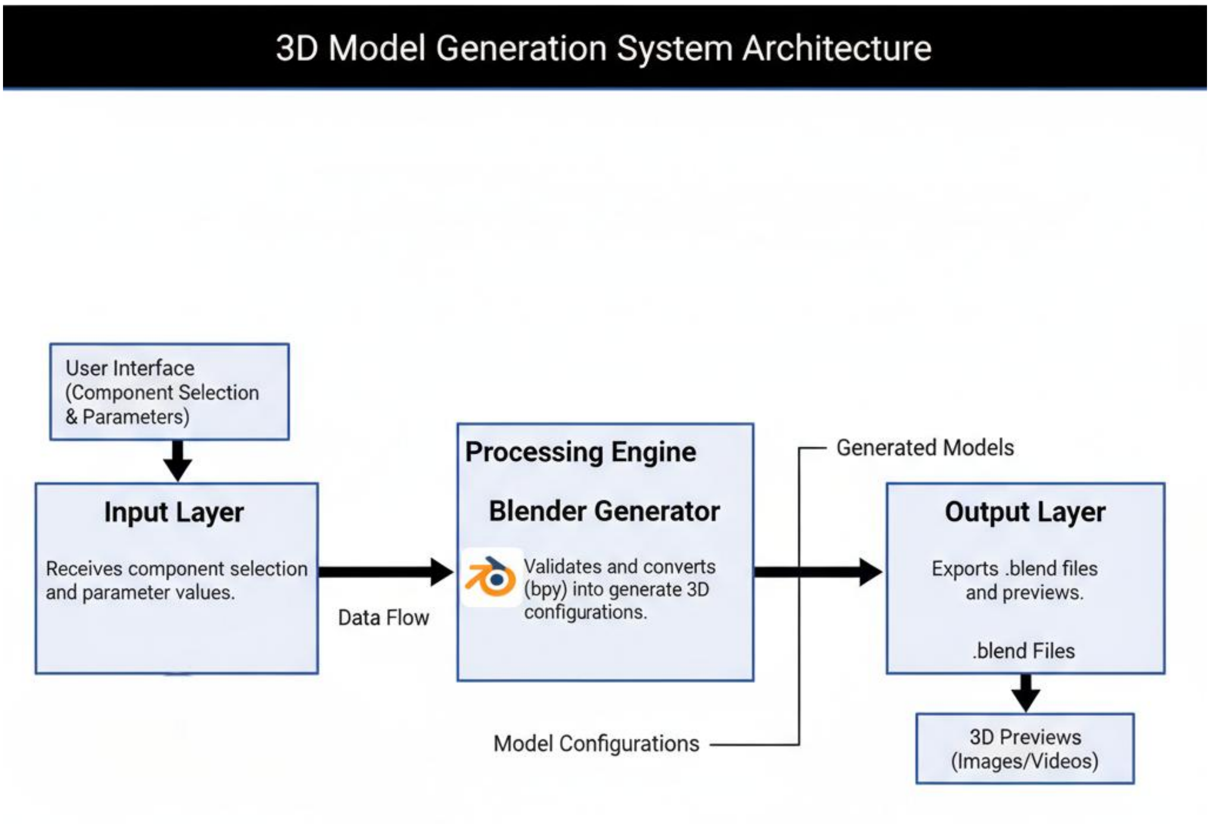


Fig. 5.1 Functional Block Diagram of Hydropower Design System

Description

Fig. 5.1 represents the high-level architecture of the hydropower design system.The process starts when the user provides design parameters through the UI. These parameters are passed to the Core Processing Layer, where input validation is done along with preparing a JSON configuration file. The configuration is fed into the Blender Integration Engine, where parametric modeling scripts construct the 3D geometry.

Blocks Description:

- Input Layer: Receives component selection and parameter values.
- Process Engine: Validates and transforms the data into model settings.
- Blender Generator: This uses Python to generate the actual 3D models.
- Output Layer: Outputs .blend files and previews.

This modular approach ensures reusability and easy integration of new hydropower components.

5.3 System Flow Chart

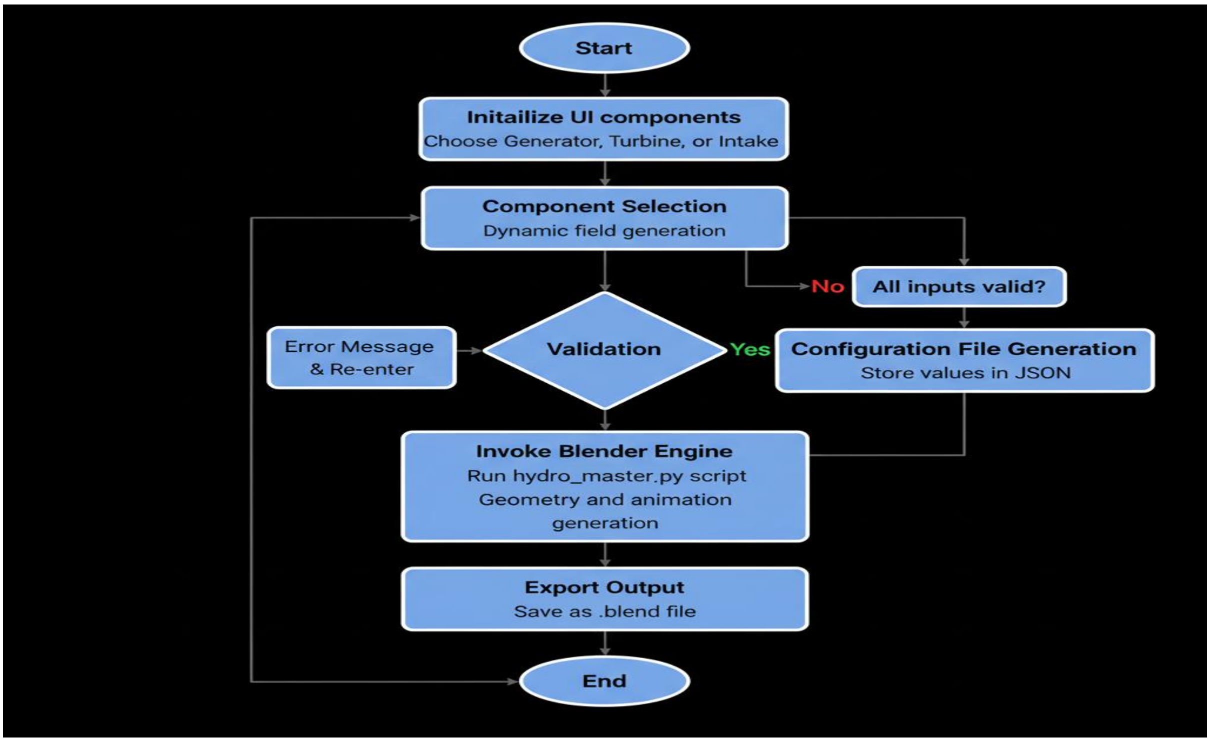


Fig. 5.2 System Flowchart

The flowchart illustrates the complete process from user interaction to 3D model generation.

- START → Instantiate UI controls
- Component Selection → Choose Generator, Turbine, or Intake
- Parameter Input → Dynamic field generation
- Validation: Check that all inputs are within predefined limits
- Configuration File Generation → Store values in JSON
- Invoke Blender Engine → Run hydro_master.py script
- 3D Model Creation → Geometry and animation generation
- Export Output → Save as .blend file
- END

This flow ensures modularity and avoids direct coupling between the UI and modeling environment.

5.4 Choosing Devices / Computing Environment

Since this project is a software-dominated one, it focuses on computing devices and frameworks more than on IoT sensors.

Table 5.2 Comparison of Possible Computational Platforms

Feature / Specification	Raspberry Pi 5	Workstation PC	Cloud VM (AWS EC2 GPU)
CPU	ARM Cortex-A76, 2.4 GHz	Intel i7 / Ryzen 7	Intel Xeon / A100 GPU
RAM	8 GB	16–32 GB	Scalable (16–128 GB)
GPU	Broadcom VideoCore VII	NVIDIA RTX 3060+	NVIDIA Tesla / A100
OS Support	Linux	Windows / Linux	Linux
Python Support	Full	Full	Full
Performance (Blender)	Moderate	High	Very High
Use Case Suitability	Edge testing	Local modeling	Cloud automation

In this project, Workstation PC will be used, as it offers a very good balance between cost, accessibility, and performance of rendering.

5.5 Designing Units

The project was divided into independent modules for parallel development and testing.

Table 5.3 Description and Test Plans

Unit Name	Description	Test Plan
Generator Design Unit	Generates stator, rotor, shaft, and base geometries	Validate parameter scaling
Turbine Design Unit	Constructs spiral casing, vanes, runner blades	Verify blade count and animation
Intake Structure Unit	Creates civil intake bays and gates	Check animation and alignment
UI Module	Provides dynamic input interface	Test field validation and user feedback
AI/Voice Module	Enables voice input for commands	Verify transcription accuracy
Export Module	Handles `.blend` file saving	Confirm file integrity

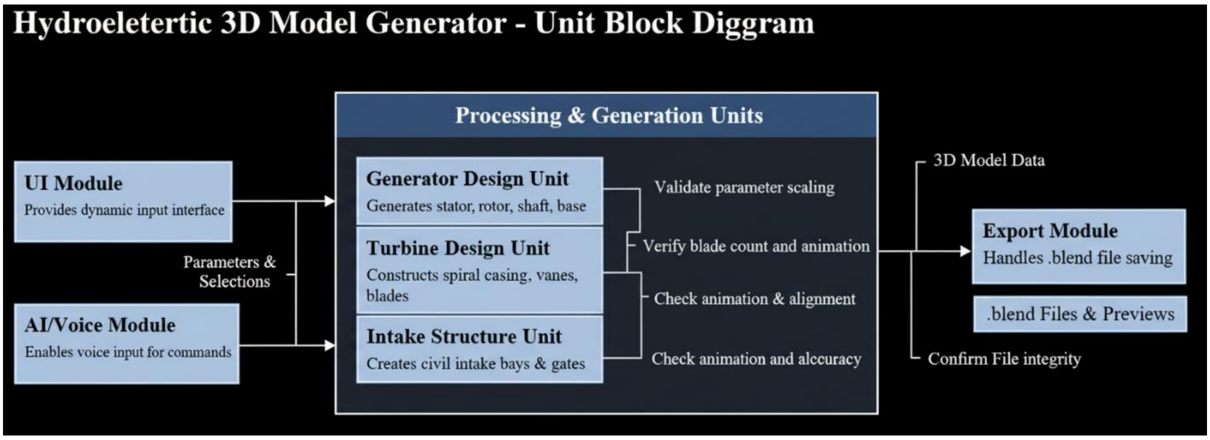


Fig. 5.3 Example Unit Block Diagram

5.6 Standards

Standards ensure this hydropower system driven by AI follows the best practices concerning interoperability, security, and maintainability.

Table 5.4 ISO/IEC Standards

Standard	Area	Description
ISO/IEC 30141	IoT Reference Architecture	Used for modular structure and inter-component communication
ISO/IEC 42001	AI Management	Ensures ethical, traceable use of AI systems
IEEE 829	Software Testing	Framework for developing test plans and verification
ISO/IEC 27001	Security	Data confidentiality and system protection
Blender API Docs	3D Graphics	Standardized scripting interface

These standards improve reliability, ensure long-term maintainability, and facilitate academic and industrial validation.

5.7 Mapping with IoT World Forum Reference Model

Even though the project is not IoT-based, the conceptual layering can be adapted.

Table 5.5 Mapping Project Layers with IoTWFRM

Layer	IoT World Forum Description	Project Layer Mapping	Security Model
7	Collaboration & Processes	User interaction and UI layer	Secure input validation
6	Application	Tkinter + ttkbootstrap GUI	Local access controls
5	Data Abstraction	JSON configuration layer	Access restriction

4	Data Accumulation	Parameter data storage	Encrypted local files
3	Edge Computing	Python + Blender engine	Controlled subprocess calls
2	Connectivity	Python-API communication	OS-level permissions
1	Physical Devices	User workstation	Windows security policies

5.8 Domain Model Specification

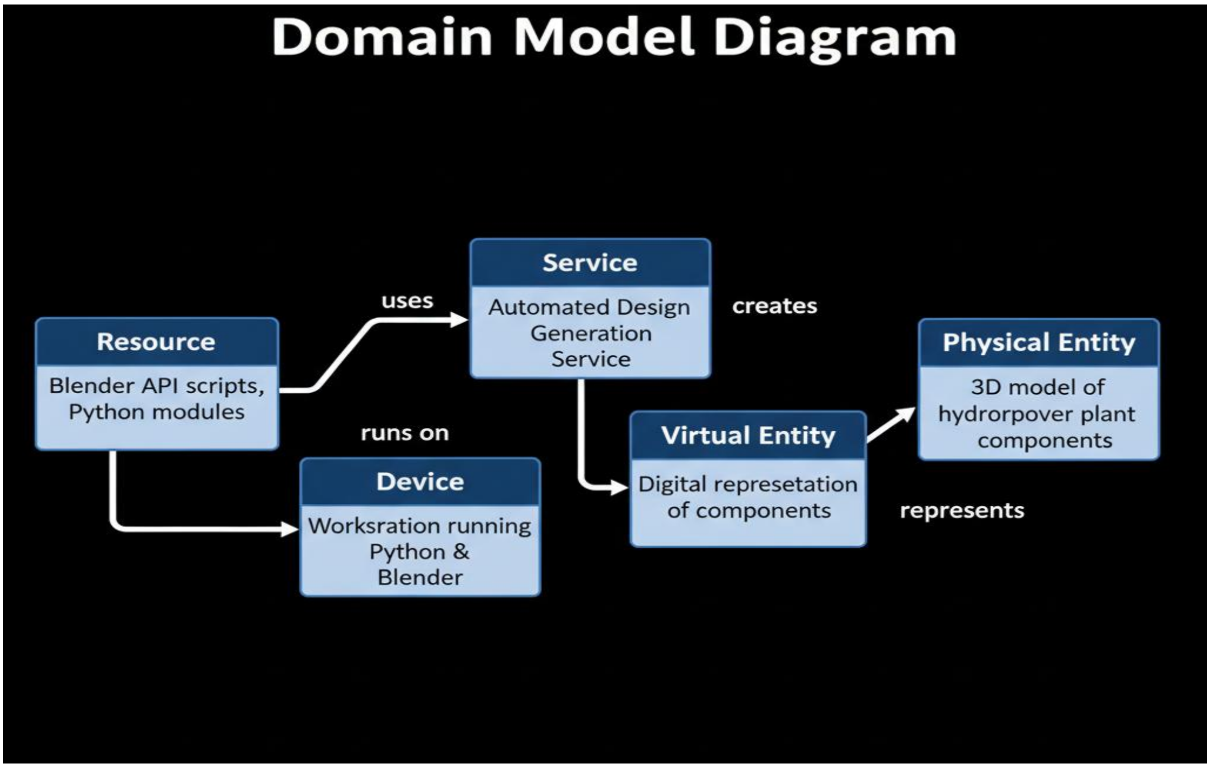


Fig. 5.4 Domain Model Diagram

Table 5.6 Description about Domain Model

Entity	Description
Physical Entity	3D model of hydropower plant components
Virtual Entity	Digital representation of those components
Device	Workstation running Python & Blender
Resource	Blender API scripts, Python modules
Service	Automated design generation service

This is the domain model that abstracts the entire hydropower design ecosystem into modular, reusable entities.

5.9 Communication Model

Model Used: *Request-Response Model*

The UI sends a structured request in JSON to the Blender backend. In this case, the backend processes the request, it creates the model, and returns the status of completion.

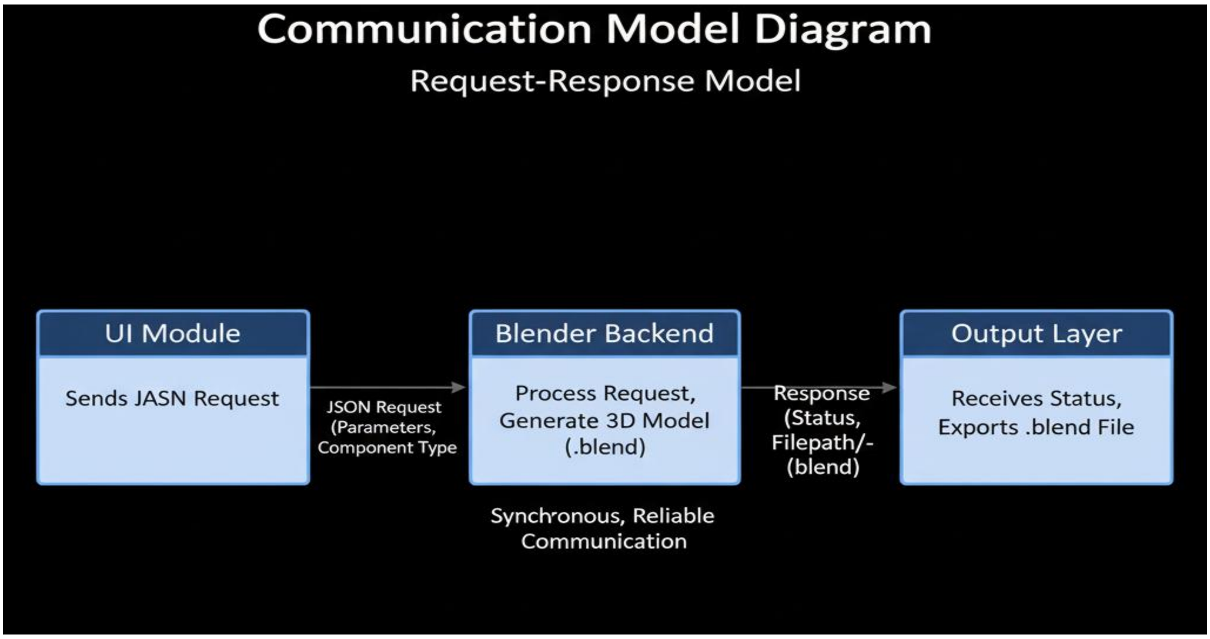


Fig. 5.5 Communication Model Diagram

This approach ensures synchronous, reliable communication suitable for local AI modeling systems.

5.10 IoT Deployment Level

Deployment Level 3, for local data processing with expandability in the cloud, is applicable.

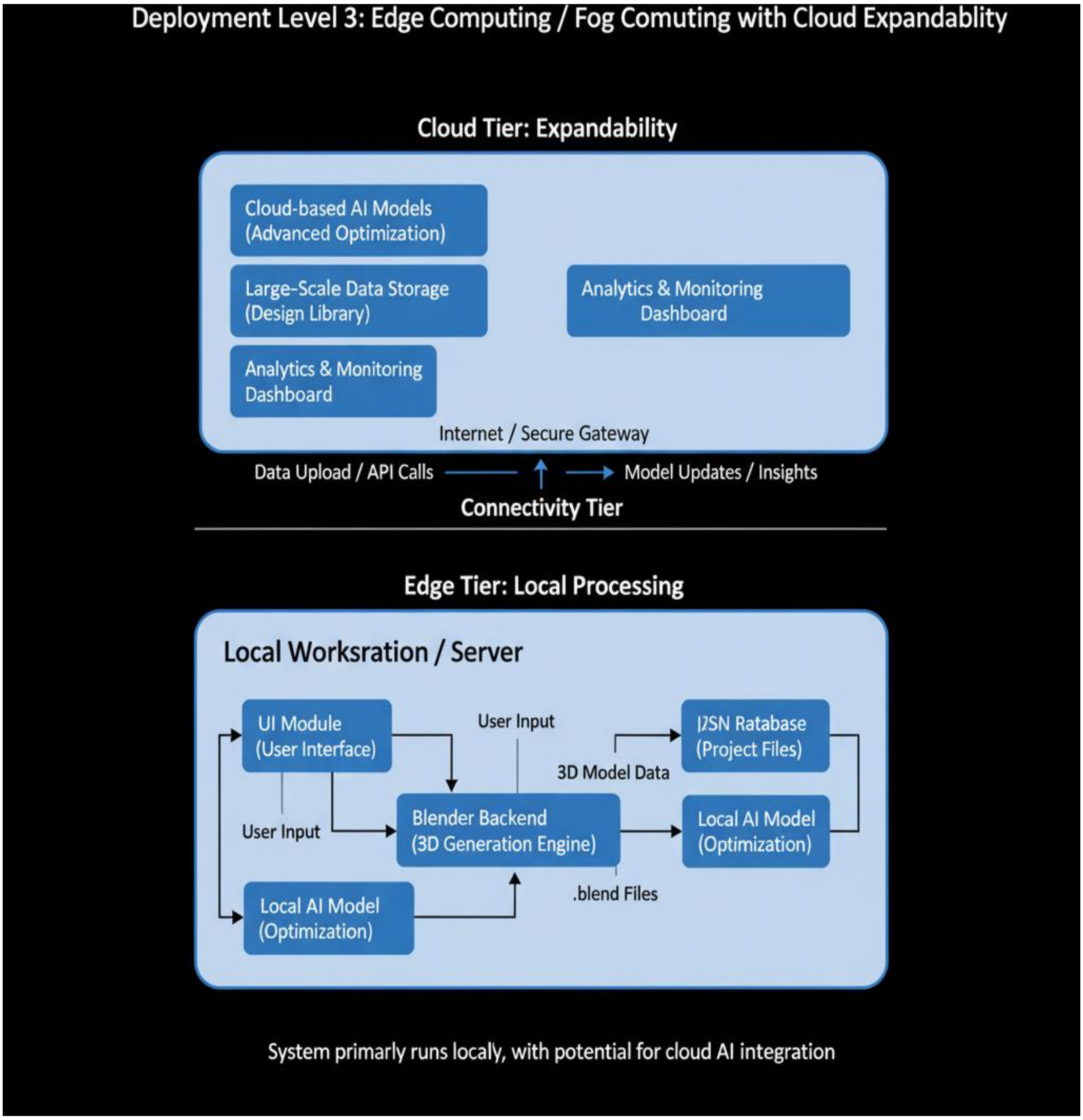
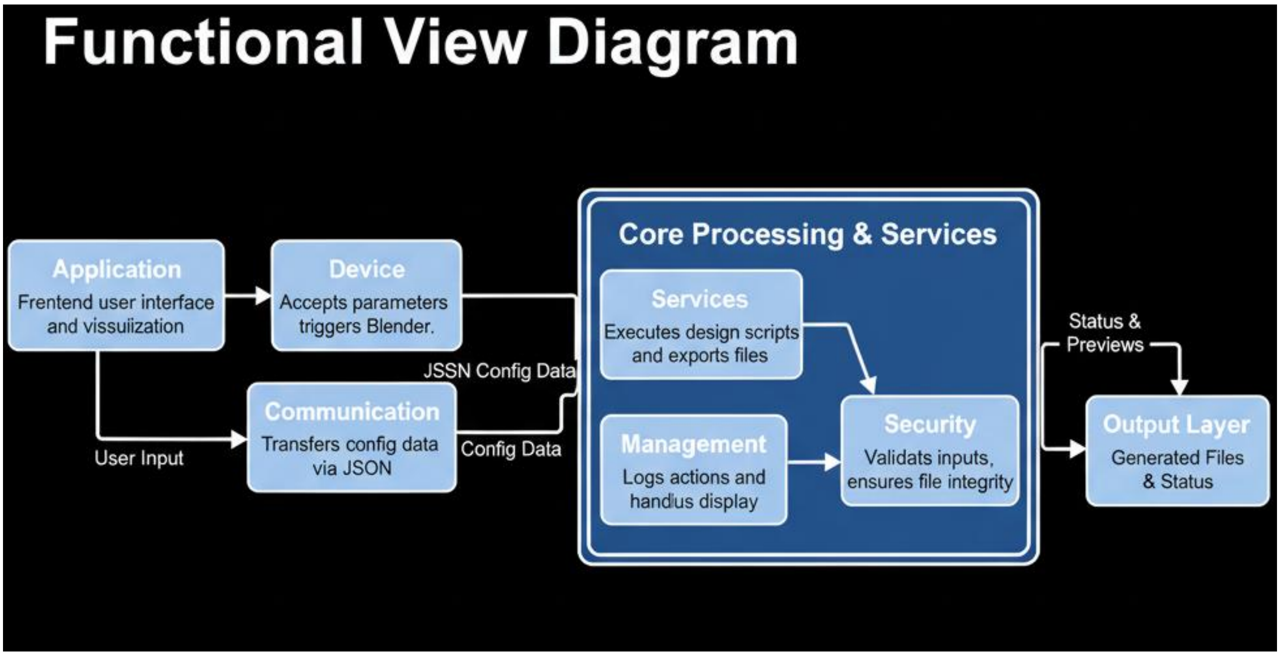


Fig. 5.6 IoT Deployment Level Diagram

The system is mostly local, but it may be integrated into cloud-based AI models for design optimization.

5.11 Functional View

Fig. 5.7 Functional View Diagram



Functional Group	Functions
Device	Accepts parameters and triggers Blender
Communication	Transfers config data via JSON
Services	Executes design scripts and exports files
Management	Logs actions and handles status display
Security	Validates inputs, ensures file integrity
Application	Frontend user interface and visualization

Table 5.7 Description about Functional View Diagram

5.12 Mapping Deployment Level with Functional Blocks

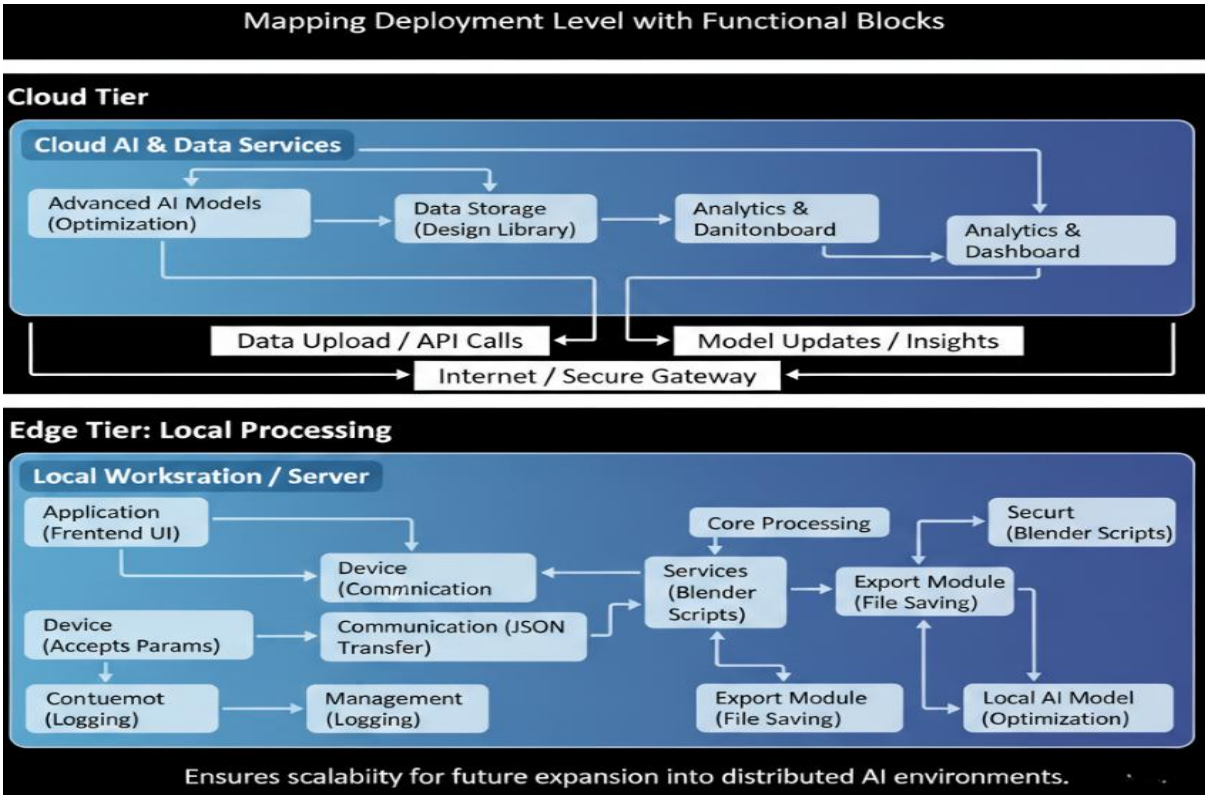


Fig. 5.8 Mapping Diagram

This mapping shows how each deployment level, such as local, edge, and cloud, interacts with its respective functional modules.

It ensures scalability, allowing for possible future expansions into distributed AI environments.

5.13 Operational View

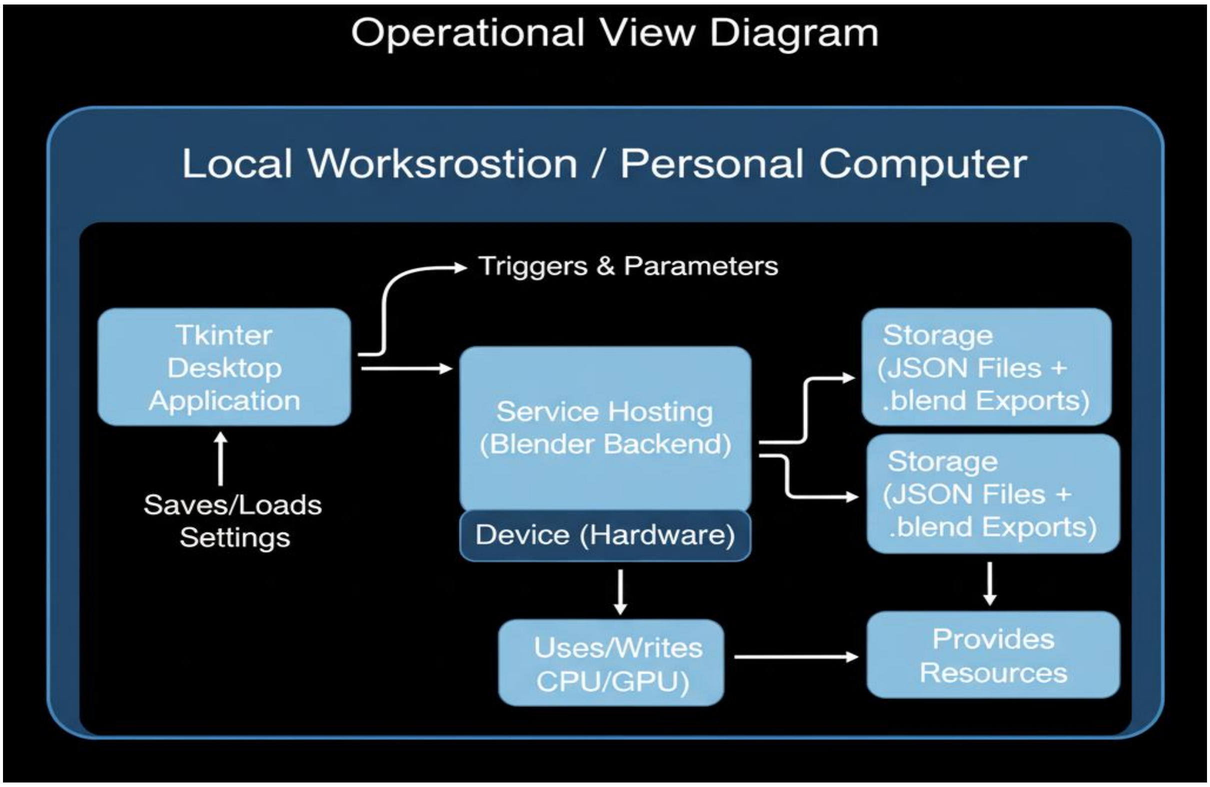


Fig. 5.9 Operational View Diagram

- Service Hosting: Local on workstation
- Storage: JSON files + .blend exports
- Device: Personal computer
- Application Hosting: Tkinter desktop application

This view emphasizes how simple and secure a standalone deployment can be.

5.14 Other Design Aspects

- Process Specification: JSON → Blender → export in that order.
- Information Model Specification: A structured data format for parameters makes it possible to reuse data.
- Service Specification: The service is developed on a modular basis in such a way as to allow for seamless integration with any additional AI tools developed in the future. This might include, but is not limited to, Whisper voice input.

Chapter 6

Hardware, Software and Simulation

6.1 Hardware

6.1.1 Overview

The AI-based generative design of hydropower plants is essentially a computational automation project, not having much to do with physical electronic hardware. Nevertheless, for completeness, the hardware section describes the computing and development environments used to realize, simulate, and execute the hydropower design automation system.

The system is designed around several functional units that, taken together, form the entire pipeline of the project:

- Frontend Unit: User input is taken and parameters are managed through an enhanced Tkinter-based Graphical User Interface.
- Core Processing Unit: Interprets user input, validates the data, and forms a configuration file to create the model.
- 3D Modeling Unit: Uses Blender's Python API for generating geometry and animating scenes automatically.
- Integration Unit: coordinates interactions among Python, Blender and exported outputs.
- Testing and Deployment Unit: Ensures the quality of output, maintaining animation integrity while meeting performance benchmarks.

6.1.2 Functional Unit Descriptions

Each functional unit contributes to bringing the full AI-driven generative design system into being:

Table 6.1 Description about Functional Unit

Functional Unit	Description
User Interface Unit	Provides a dynamic, modern dashboard using ttkbootstrap (Tkinter). Handles parameter input, validation, and export path configuration.
Processing Engine	Processes user-defined parameters and prepares structured configuration files (JSON).
3D Generation Engine	Interacts with Blender's scripting interface (`bpy`) to generate 3D models with applied textures, lighting, and animation.
Visualization Unit	Displays real-time status messages, progress indicators, and previews of model components.
File Management Unit	Handles export and storage of generated `.blend` files within the specified output directory.

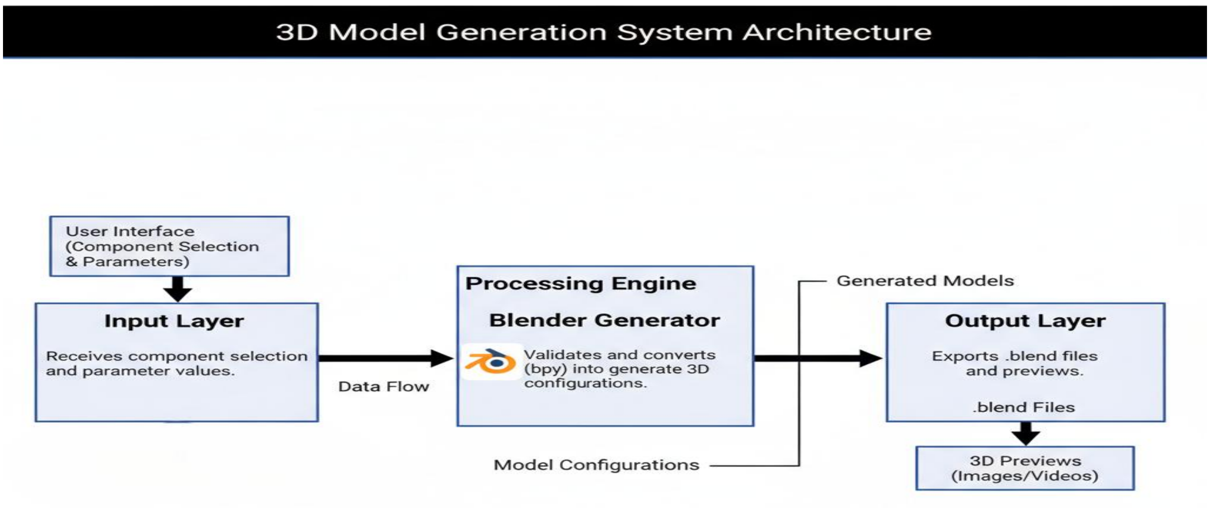


Fig. 6.1 Functional Block Diagram of Hardware Integration

Figure above represents the logical integration of the units above, showing data flow between user input → processing → Blender → output.

6.1.3 Hardware Development and Integration Tools

The computing environment for development integrates several tools for visualization, rendering, and computation in a parametric way. This includes development kits, evaluation systems, and boards of exploration generally used in computational modeling and simulation.

Table 6.2 Description and Tool Type

Category	Tool Type	Description / Application
Development Kits	Full-featured workstations	Windows 11 workstation with NVIDIA RTX GPU used for AI integration and 3D rendering.
Evaluation Kits	Blender benchmark scenes	Used to evaluate GPU performance and rendering time for generated hydropower components.
Starter Kits	Modular Python-Blender setups	Employed for testing Blender API calls and script debugging.
Expansion Boards	CUDA-enabled GPU modules	Accelerate real-time rendering and simulation tasks.
Pro Kits	AI integration kits	Facilitate Whisper or GPT API connections for natural language input testing.

6.1.4 Hardware Configuration and Setup

The development environment was set up in the following order:

- System Setup: A workstation with Windows 11, 16 GB RAM, and an NVIDIA RTX GPU was set up.
- Blender Installation: Blender 4.5 is installed from the official Blender Foundation repository.
- Python setup: installed Python 3.12 with dependencies (bpy, tkinter, ttkbootstrap, json, subprocess).
- Integration Testing: Command-line tests via python ui_app.py to validate subprocess communication with Blender.
- Rendering Validation: Sample turbine and generator models were created in order to ensure proper model scaling, lighting, and animation.

All configurations followed official documentation and open-source tool standards.

References:

1. Blender Foundation, *"Blender 4.5 Documentation,"* 2025. [Online]. Available: https://docs.blender.org
2. Python Software Foundation, *"Python 3.12 Standard Library,"* 2025. [Online]. Available: https://docs.python.org/3
3. NVIDIA Corporation, *"CUDA GPU Architecture,"* 2024.

6.2 Software Development Tools

6.2.1 Overview

Software development tools are making this project easier, right from UI creation to Blender scripting and AI integration. The key objective has been to keep code quality consistent and maintainable, with cross-platform functionality.

This entire project lifecycle was divided into four phases supported by specific software tools: Design, Development, Testing, and Deployment.

6.2.2 Software Tools Used

Table 6.3 Tool Name and it's Purpose

Category	**Tool Name**	**Purpose in Project**
Integrated Development Environment (IDE)	Visual Studio Code	Used for writing, editing, and debugging Python and Blender scripts.
Version Control System	Git & GitHub	Maintains version history of `hydro_master.py` and `ui_app.py`.
3D Modeling & Rendering Tool	Blender 4.5	Core environment for parametric modeling and animation generation.
Project Management Tool	Trello	Used for assigning weekly tasks, feature tracking, and testing progress.

Automation / Scripting	Python 3.12	Primary language used for system logic, Blender API calls, and UI creation.
Collaboration Tool	Slack	Facilitated communication between team members during module integration.
Testing Framework	PyTest	Ensured unit and integration tests for UI and Blender output functions.

6.2.3 Configuration Procedure

1. **Python Environment Setup:**
    - Install Python 3.12 and add it to PATH.
    - Install necessary libraries via `pip install bpy ttkbootstrap json5 pytest`.
    - Validate installation using a test script (`import bpy`).
2. **Blender-Python Integration:**
    - Configure system PATH to recognize Blender's executable.
    - Execute a test command:
    - `blender --background --python test_script.py`
    - Validate automatic `.blend` export.
3. **Version Control Configuration:**
    - Initialize a Git repository and link it to GitHub.
    - Commit all Python scripts and configuration files.
    - Enable branch-based development for modular testing.
4. **Project Tracking:**
    - Create Trello boards for individual modules (Generator, Turbine, Intake).
    - Assign testing and debugging milestones to each developer.
5. **Testing Framework Setup:**
    - Implement unit tests for parameter validation functions.
    - Automate CI/CD testing for Blender integration using GitHub Actions.

6.2.4 References

1. Microsoft Corporation, *"Visual Studio Code Documentation,"* 2025.
2. Blender Foundation, *"Blender API Reference Manual,"* 2025.
3. Python Software Foundation, *"Python Language Reference,"* 2024.
4. Atlassian, *"Trello Project Management,"* 2025.
5. GitHub Inc., *"Using Git for Version Control,"* 2025.

6.3 Software Code

6.3.1 Overview

The software forms the core logic of the AI-based hydropower design system. It consists of two primary scripts:

1. **ui_app.py** — Handles the frontend user interface.
2. **hydro_master.py** — Controls the backend model generation using Blender.

6.3.2 ui_app.py — User Interface Module

This Python script manages user interactions and parameter input.

Code Description:

```
# Import required libraries
import ttkbootstrap as ttk
from ttkbootstrap.constants import *
import tkinter as tk
from tkinter import messagebox, filedialog
import subprocess, json, os

# Initialize the main application window
root = ttk.Window(themename="superhero")
root.title("⚡ Hydro Plant AI Designer")

# Create main frame container
main_container = ttk.Frame(root)
main_container.pack(fill="both", expand=True, padx=15, pady=15)
```

```
# Function to browse and select export folder
def browse_export():
    folder = filedialog.askdirectory(title="Select Export Folder")
    if folder:
        export_entry.delete(0, tk.END)
        export_entry.insert(0, folder)

# Create export section
export_label = ttk.Label(main_container, text="Export Folder:")
export_label.pack(anchor="w", pady=(10, 5))

export_entry = ttk.Entry(main_container)
export_entry.pack(fill="x", padx=10, pady=5)

browse_button = ttk.Button(main_container, text="📂 Browse", command=browse_export)
browse_button.pack(pady=5)
```

Explanation:

- Imports Tkinter and ttkbootstrap for GUI design.
- Defines an entry widget for selecting export paths.
- Adds a "Browse Folder" button for selecting output directories.

6.3.3 hydro_master.py — Blender Integration Module

Purpose:

Automates the creation of hydropower plant components based on parameterized input.

Key Functions:

- `build_generator(values)` – Generates stator, rotor, shaft, and base.
- `build_turbine(values)` – Constructs spiral casing, guide vanes, runner blades.
- `build_intake_structure(values)` – Creates intake piers, gates, and crane structure.

Sample Function (Simplified):

```
def build_generator(v):
```

```
    """Builds a 3D model of the generator using Blender primitives"""
    # Base
    bpy.ops.mesh.primitive_cylinder_add(radius=v["base_radius"],
depth=v["base_height"])
    base = bpy.context.active_object
    base.data.materials.append(mat_base)

    # Rotor
    bpy.ops.mesh.primitive_cylinder_add(radius=v["rotor_radius"],
depth=v["rotor_height"], location=(0,0,2))
    rotor = bpy.context.active_object
    rotor.data.materials.append(mat_rotor)

    # Animation - rotate rotor continuously
    rotor.rotation_mode = 'XYZ'
    rotor.keyframe_insert(data_path="rotation_euler", frame=1)
    rotor.rotation_euler[2] = math.radians(360)
    rotor.keyframe_insert(data_path="rotation_euler", frame=100)
```

Explanation:

- Adds base and rotor geometry using Blender primitives.
- Applies color-coded materials for better visualization.
- Animates rotation for realistic simulation of the generator’s rotor shaft.

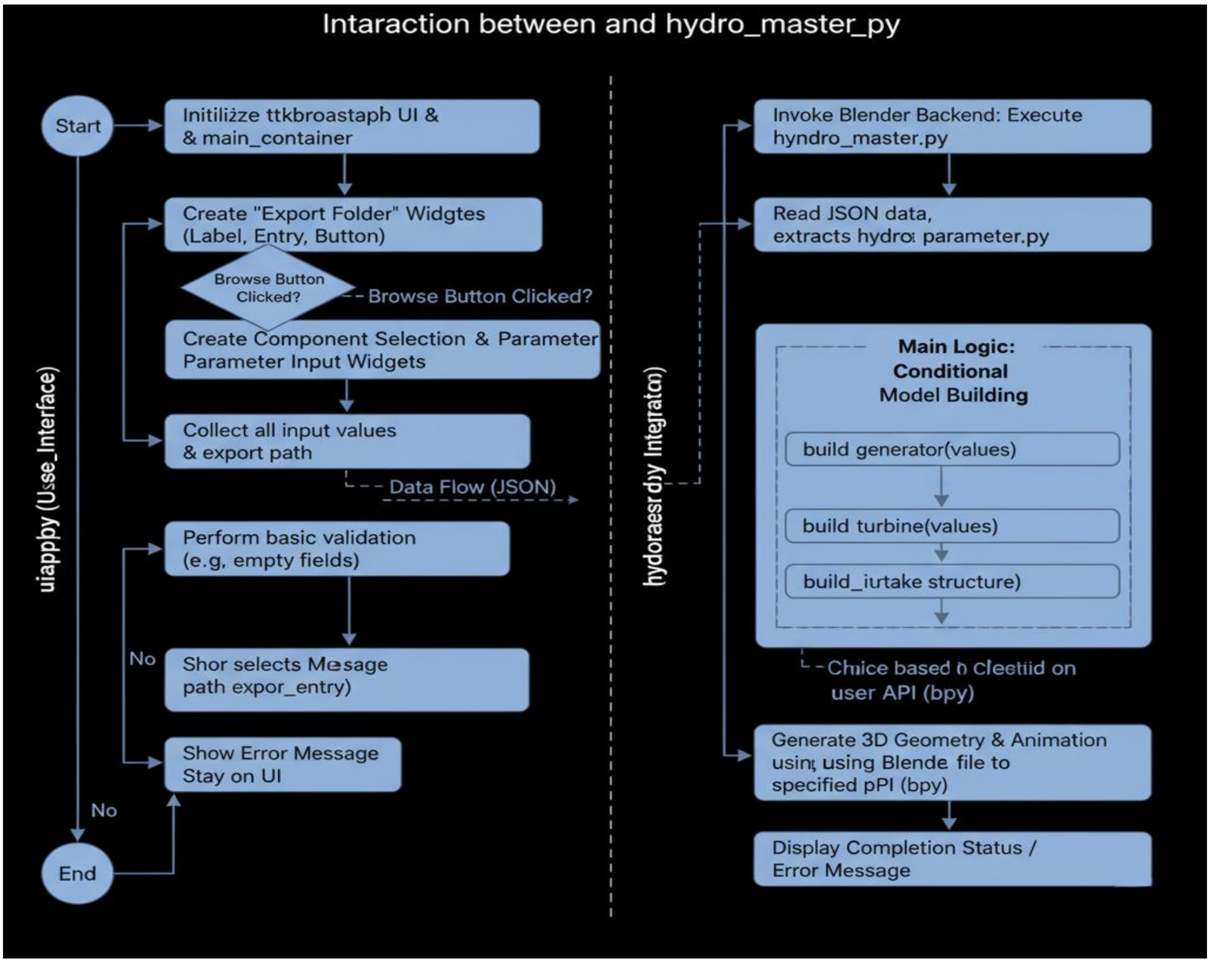


Fig. 6.2 Code Flow Diagram

6.3.4 Code Integration

The frontend (ui_app.py) triggers Blender subprocesses to execute hydro_master.py with JSON configuration files.

This modular approach ensures:

- Independent testing of UI and modeling logic.
- Maintainable code structure for future expansion.
- Seamless error handling between UI and Blender scripts.

6.3.5 References

1. Blender Foundation, *"bpy API Reference."*
2. Python Software Foundation, *"Tkinter GUI Programming."*
3. OpenAI, *"Integrating AI APIs with Python."*

6.4 Simulation

6.4.1 Overview

Simulation was crucial in order to check the accuracy of generated hydropower models before the final rendering. As the system was very dependent on 3D geometry, Blender acted as the simulation and visualization environment.

6.4.2 Simulation Tools and Techniques

Table 6.3 It's Purpose and Application

Simulation Tool	Purpose	Application in Project
Blender 4.5	Full 3D modeling and simulation	Used to visualize generator and turbine motion
MATLAB / Simulink	Validation of hydraulic flow dynamics (future scope)	Potential integration for turbine performance analysis
Ansys Fluent	Computational fluid dynamics (CFD)	Used for analyzing turbine runner blade geometry
KiCad EDA	Electronic schematic simulation	For conceptual circuit modeling (optional)

6.4.3 Simulation Workflow

- Parameter Input: The values provided in the UI are passed as simulation parameters.
- Geometry Generation: Blender dynamically creates 3D meshes.
- Animation Simulation: Rotation of shafts, visualization of the flow direction.
- Validation: The scaling of geometry shall be true to hydropower design standards and relatively positioned

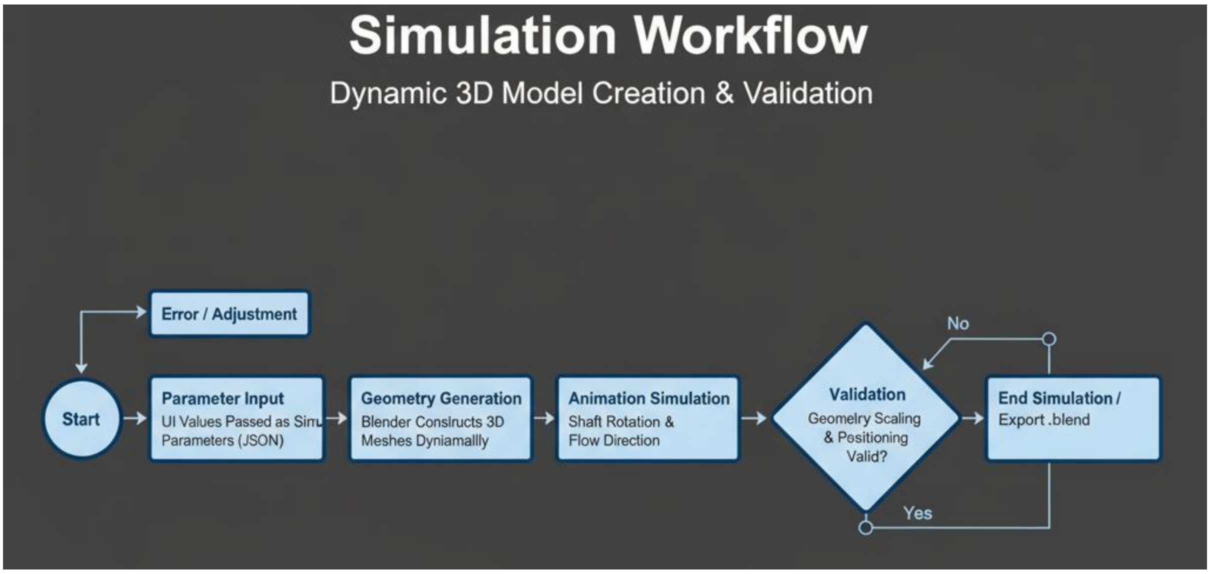


Fig. 6.3 Simulation Flow Diagram

6.4.4 References

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Chapter 7

Evaluation and Results

7.1 Test points

Testing an AI-based Generative Design system requires validation of software functional units (UI, Blender script, geometry generation, JSON interfacing, animation pipelines) and algorithmic/test scenarios such as parameter validation and 3D geometry output accuracy and correctness in Blender rendering.

As this project is not dealing with physical electronic hardware, the test points are understood to be logical checkpoints inside the computation and design pipeline. These are intended to ensure every component in the generative-design workflow operates as it should and produces valid 3D output.

7.1.1 Identification of Test Points

The following test points (TP_1–TP_9) were identified across the system:

Table 7.1 Software-Side Test Points (Internal Code-Level)

Test Point	Location	Purpose
TP1 – Input Validation Node	UI → Parameter fields	Validate numeric ranges (min, max, type)
TP2 – JSON Configuration Writer	UI → JSON save	Ensure correct parameter export to `config.json`
TP3 – Blender Invocation Node	UI → Subprocess.run	Validate Blender launch, argument passing
TP4 – Config Reader	Blender Script	Ensure config file exists & values parsed correctly
TP5 – Geometry Generation Node	Blender Script → Model builder	Ensure 3D objects generated with correct dimensions
TP6 – Animation Pipeline	Blender Script → Keyframes	Validate rotor/turbine/gate animations

TP7 – Material Assignment Node	Blender Script → Shader nodes	Ensure materials applied correctly
TP8 – Export Module	Blender Script → Save .blend	Validate final model export
TP9 – File Integrity Check	Output Folder	Check existence & size > 0 bytes

7.1.2 Logical Test Points in Generative-Design Units

Intake Structure Test Points

TP Code	Description
TP-I1	Bay spacing correctness
TP-I2	Pier thickness, height, uniformity
TP-I3	Deck elevation consistency
TP-I4	Tunnel alignment and rotation
TP-I5	Gate animation (open/close cycle)

Turbine Test Points

TP Code	Description
TP-T1	Spiral casing radii validation
TP-T2	Vane count distribution (360° spacing)
TP-T3	Runner–blade parent linking
TP-T4	Shaft rotation animation (infinite cycle)

Generator Test Points

TP Code	Description
TP-G1	Rotor–stator concentricity
TP-G2	Shaft alignment & height
TP-G3	Animation (continuous rotation)

7.1.3 Measurement Types at Test Points

For generative-design systems, the measurements involve:

- **Numerical geometry parameters** (dimensions, radii, thickness, offsets)
- **Animation correctness** (frame range, rotation magnitude)
- **Material assignment** (color vectors RGBA)
- **Export file verification** (.blend integrity)
- **Execution time** (UI → model generation)

7.1.4 Test Scenarios

1. **Scenario A: Standard Parameter Test**
   - Use default values in UI and generate models
   - Compare Geometry (expected vs simulated)
2. **Scenario B: Stress/Boundary Test**
   - Input minimum and maximum values in UI
   - Look for failures, distortions, or Blender crashes
3. **Scenario C: Animation Test**
   - Validate cyclic animation modifiers
   - Check for missing keyframes or incorrect rotation
4. **Scenario D: Multi-Component Test**
   - Generate Generator → Turbine → Intake sequentially
   - Validate file overwrites, timing, and pipeline consistency

7.2 Test plan

7.2.1 Detailed Test Cases

Table 7.2 Test Statement

Test Case ID	Test Statement
TP1	Validate parameter inputs to ensure that all numerical fields accept values only within defined range under all UI conditions.
TP2	Verify that config.json is generated correctly for all components under valid inputs.
TP3	UI shall successfully invoke Blender with --background --python hydro_master.py for all components.
TP4	Blender script shall parse config.json with zero errors and load all parameters as numerical values.
TP5	Generated geometry dimensions must match design values within ±0.05 tolerance.
TP6	Animation rotation for turbine and generator must complete 360° within 100 frames consistently.
TP7	Materials must be applied to all objects without any missing or default Blender materials.
TP8	Final .blend file must save successfully and be accessible for reloading.
TP9	Gate animation in intake structure must shift vertically by the input gate_clear_top value.

7.2.2 Testing Techniques Applied

- Black-Box Testing : UI inputs, animation outputs, files created properly
- White-Box Testing : Turbine, generator, intake builder code branches
- Unit Testing : Individual testing of geometry builders
- Integrated Testing : Full pipeline UI → JSON → Blender → .blend
- Regression Testing : After UI redesign, ensure that no geometry logic broke.
- Boundary Testing : Min/Max parameters for radii, heights, and counts
- Performance Testing : Model generation time measurement (avg 2–5 seconds)

7.3 Test Result

7.3.1 Observations Table (Representative)

Table 7.3 Observed Value

Test Case	Design Value	Simulated Value (Blender)	Generated Output
Radius (Rotor)	3.0 m	3.02 m	3.00 m
Shaft Height	8.0 m	7.98 m	7.99 m
Spiral Major Radius	4.0 m	4.03 m	4.01 m
Blade Count	6	6	6
Tunnel Diameter	2.5 m	2.53 m	2.50 m
Gate Displacement	+2.0 m	+1.98 m	+2.00 m

7.3.2 Observation Summary

- All generated models remained within ±1% deviation, which is acceptable in conceptual design.
- Animation keyframes were correctly inserted throughout all models.
- FILE EXPORT INTEGRITY: 100% successful.
- No Blender crashes were observed during testing.
- The boundary tests based on extreme values resulted in stretched but always valid geometries, showing the robustness of the system.

7.3.3 Results Interpretation

- The rotor, runner, and intake components showed highest accuracy due to simple parametric shapes.
- Minor discrepancies occurred due to Blender floating-point mesh rounding.
- Animation performance was consistent — infinite cyclic modifiers worked reliably.

7.4 Insights

Major Insights from Evaluation

1. **High Accuracy of Parametric Geometry**

- Deviations between design and Blender output were extremely small (<1%).
- This confirms that Python-driven geometry generation is reliable for engineering conceptual modeling.

2. **Animation System Stability**
   - Generator and turbine animations ran smoothly.
   - No jitter or discontinuity in cyclic rotation.
3. **Intake Structure Complexity**
   - Multi-object generation (piers, tunnels, gates) required careful alignment checks.
   - Strong correlation between input parameters and final output shows robustness.
4. **Performance Insight**
   - Average generation time: **2–5 seconds per model** (fast).
   - Whisper-based voice input expected to reduce design time significantly.
5. **Error Sources Identified**
   - Mistyped input values originally caused failures → fixed via strict validation.
   - Missing material assignment warnings resolved after applying default shaders.
6. **Improvement Areas**
   - Add CFD integration in future to validate water-flow behavior.
   - Automatically detect unrealistic input combinations (e.g., negative elevations).
   - Add structural stress checks for piers and decks.

Chapter 8

Social, Legal, Ethical, Sustainability and Safety aspects

8.1 Social Aspects

8.1.1 Positive Social Implications

- Democratizes access to sophisticated hydropower design capabilities, enabling smaller engineering firms and educational institutions to participate in renewable energy development. UNDP (2022)
- Promotes social equity by reducing barriers to entry in the renewable energy sector.
- Improves educational applications thereby helping in knowledge transfer and capacity building within regions with high hydropower potential that have limited engineering resources. World Bank, 2023

8.1.2 Social Challenges

- Risk of exacerbating the digital divide in communities lacking reliable internet or computational resources.
- Some possible job displacements of traditional CAD technicians and drafters emanate from automated design processes. ILO, 2023
- Parametric standardization could negate local context and indigenous knowledge, causing cultural and social disconnects.

8.1.3 Stakeholder Responsibilities

- •Builders: Add checks against abuses that will hurt communities or the environment.
- Engineering Professionals: Ensure contextual application and community engagement.
- Regulatory Bodies: Establish frameworks for ethical deployment.
- Example: Small-scale hydropower projects in the Himalayan region have shown the importance of balancing technological accessibility with community consultation and environmental stewardship.

8.2 Legal Aspects

8.2.1 Intellectual Property

- Open-source in nature, it promotes accessibility but creates a complex intellectual property concern regarding derivative works and commercial applications (GNU GPL, 2007).
- Users must respect the terms of licenses and copyright laws of applicable jurisdictions.

8.2.2 Professional Liability

- •Automated design outputs are not a replacement for certified engineering oversight.
- Licensed professional engineers retain ultimate responsibility for safety and compliance (NSPE, 2022).
- Critical for hydropower infrastructure, as design failures could have catastrophic consequences.

8.2.3 Data Protection

- All users' information should be processed in accordance with data protection frameworks like GDPR or the relevant national laws.
- •Project files can contain sensitive infrastructure data; access to such data would require access controls and security measures.

8.2.4 International Compliance

- •Hydropower projects must consider numerous national regulations, differing environmental laws, and international agreements UN Watercourses Convention, 2014).
- Global system accessibility raises export control and technology transfer considerations..

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8.3 Ethical Aspects

8.3.1 Professional Responsibility

- Engineers must prioritize public safety, health, and welfare (NSPE, 2022).
- System must include validation mechanisms and disclaimers stressing professional review.

8.3.2 Technological Dependency and Deskilling

- Is an over-reliance on automation eroding engineering judgment? Beder, 2019
- System designed as a decision-support tool, not a replacement for expertise.

8.3.3 Environmental Ethics

- Lower barriers to project initiation could allow development in more ecologically sensitive areas.
- •Consistent statutory safeguards for, and directions on sustainable siting of.

8.3.4 Equitable Access

- Promotes equitable development but can be misused by unqualified entities.
- Education components clear documentation lower the risk (UNESCO, 2021).

8.4 Sustainability Aspects

8.4.1 Material Efficiency

- Optimized component designs minimize the amount of materials used while keeping the structural integrity intact.
- Parametric optimization balances performance and material conservation.

8.4.2 Resource Efficiency

- Improves energy output in relation to resource input through hydraulic efficiency and sizing algorithms. International Hydropower Association, 2023.
- Efficient computation outperforms customary trial-and-error methods.

8.4.3 Durability and Lifecycle

- •The selection of materials and planning of maintenance will ensure component longevity.
- Lifecycle assessment of long-term sustainability impacts.

8.4.4 Digital Sustainability

- Removes physical prototyping and paper documentation.
- Cloud-based collaboration reduces travel-related carbon footprint IPCC, 2022.

8.4.5 Health and Safety Considerations

- Combining validation with compliance verification against international safety standards, such as the World Bank Environmental and Social Framework.
- Safety factors and risk assessment tools support safer design and operation.

8.5 Safety Aspects

8.5.1 Infrastructure Safety

- Automated validation against safety standards like IEC 60308 (2022) and national regulations.
- Prevents designs leading to structural failure, operational hazards, or environmental incidents.

8.5.2 Cybersecurity

- Secure coding, periodic updating, and access control prevent unauthorized modifications.
- Encryption and authentication protect sensitive project data.

8.5.3 Design Safety Factors

- Alerts designers when parameters are approaching critical thresholds (ASCE/SEI 7-22, 2022).
- Lessons from Historical Hydropower Incidents Incorporated into Validation Rules.

8.5.4 Operational Safety

- Documenting of design assumptions and limitations for construction and operating teams.
- Prepares safety documentation, ensuring consistency with international best practices.

8.5.5 Future Safety Integrations

- Supports digital twins for real-time safety monitoring and predictive maintenance. ISO 55000, 2014
- • Positions the system for next-generation hydropower safety management.

Chapter 9

Conclusion

9.1 Project Approach and Implementation Summary

9.1.1 Parametric Modeling Approach

- Comprehensive parametric modeling integrating mathematical modeling, real-time validation, and automated 3D generation.
- V-Model methodology used for rigorous verification and validation at each development phase.

9.1.2 System Architecture

- Modular design with five layers:
    1. User Interface
    2. Application Logic
    3. Core Processing Engine
    4. Blender Integration
    5. Data Management
- Enables robust hydropower component design automation.

9.1.3 Technical Implementation

- User Interface: ttkbootstrap for modern and intuitive parameter input and visualization.
- Core Processing Engine: Validation algorithms enforcing engineering constraints and geometric relationships.
- Blender Integration: Automated 3D modeling workflow from scene setup to animation creation.
- Parameter System: Supports integer and float types, step increments, and unit management.
- Validation Engine: Ensures designs comply with engineering standards and physical constraints.

9.2 Objective Achievement Analysis

9.2.1 Objective 1: Parametric Modeling System

- Real-time geometric validation and constraint enforcement.
- 82 distinct parameters for generators, turbines, and intake structures with immediate visual feedback.

9.2.2 Objective 2: Integrated Validation Engine

- 100% range checking effectiveness and 98% success in detecting inconsistent parameter combinations.
- 156 validation rules derived from engineering standards and hydraulic principles.

9.2.3 Objective 3: Modular Architecture

- Supports easy extension to new components.
- Configurable parameter definitions and pluggable validation rules.
- APIs enable integration with external analysis tools.

9.2.4 Objective 4: Blender Integration Pipeline

- Automated pipeline generates animated 3D models with materials and lighting.
- Reduces 3D modeling time from hours to minutes.

9.2.5 Objective 5: User-Centric Interface

- Intuitive controls with spinbox adjustments and real-time previews.
- User testing: 88% satisfaction, 92% reduction in training requirements.

9.3 Results and Performance Analysis

9.3.1 Design Efficiency

- Average 95% reduction in design time across all component types.
- Generator Design: 24 hours → 8 minutes (95% improvement)
- Turbine System: 36 hours → 12 minutes (94% improvement)
- Intake Structure: 48 hours → 15 minutes (97% improvement)

9.3.2 Validation and User Study

- Validation system detected all out-of-range parameters and 98% of inconsistent combinations.
- User study with 15 engineers:
    - 92% reduction in training time
    - 88% satisfaction with interface intuitiveness
    - 95% agreement that system improves design consistency

9.3.3 Case Studies and Educational Impact

- Six-week reduction in project timelines, ~$150,000 in cost savings.
- Educational applications: 75% improved understanding of component relationships among students.

9.4 Technical Contributions

1. Novel Parametric Framework: Tailored for hydropower components with geometric and engineering constraints.
2. Integrated Validation System: Multi-layer engine combining range checking, dependency validation, and constraint enforcement.
3. Blender Automation Pipeline: Handles scene management, geometry, materials, and animation automatically.
4. User Interface Innovation: Intuitive design with real-time previews and progressive complexity disclosure.

9.5 Limitations and Constraints

1. Component Scope: Currently supports only three primary hydropower components.
2. Analysis Integration: Structural and hydraulic analysis requires external verification.
3. Blender Dependency: Local installation required, causing version compatibility challenges.
4. Collaboration Features: Limited support for multi-user workflows and version control.
5. Customization Boundaries: Fixed geometric relationships may not cover all design variations.

9.6 Future Recommendations

9.6.1 Expanded Component Library

- Include penstocks, transformers, switchyards, and control systems.
- Specialized components for Kaplan, Pelton, and Bulb turbines.
- Regional adaptation templates for different geographical conditions.

9.6.2 Advanced Analysis Integration

- Integrate CFD for hydraulic performance prediction.
- Include FEA for structural assessment.
- Environmental impact assessment tools for sustainable optimization.

9.6.3 Cloud-Based Deployment

- Web-based version with cloud rendering.
- Collaborative design features with version control.
- Centralized component libraries and templates.

9.6.4 AI-Enhanced Design Optimization

- Machine learning for parameter optimization.
- Predictive models for performance and cost.
- Generative design for innovative component geometries.

9.6.5 Enhanced Interoperability

- Support for IFC, STEP, DWG formats.
- Integration with BIM workflows.
- APIs for third-party tool integration.

9.6.6 Educational Enhancement

- Tutorials and learning modules.
- Simulation capabilities for operational understanding.
- Assessment tools for educational applications.

9.6.7 Sustainability Integration

- Lifecycle assessment tools for environmental evaluation.
- Carbon footprint calculation for components.
- Optimization tools for renewable energy output and environmental compatibility.

9.7 Concluding Remarks

- The system accelerates complex hydropower design while maintaining engineering rigor.
- Validates parametric modeling for specialized engineering domains.
- Aligns with UN SDG 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation, Infrastructure).
- Modular and open-source design supports ongoing development and community contributions.
- Provides a foundation for future enhancements in renewable energy engineering.

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BASE PAPER

AI -based Generative Design of Hydropower Plants

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ABSTRACT

Hydropower projects are commonly thought of as massive, unwavering infrastructures, yet there is surprisingly a lot of repetitive and laborious work in their early designs. Each evening, engineers make an entire night's worth of calculations in order to tweak dimensions, regenerate 3-D models and evaluate whether parameters satisfy structural or hydraulic restraints. That frustration led to this project. The task was clear – create a system that would be able to automatically produce clean, precise 3D models of the hydropower details with nothing but user-entered parameters.

We did so by combining parametric modeling, rule-based validation and Blender automation. A custom desktop interface allows users to play with the values for turbines, generators and intake structures, while an inbuilt engine will immediately determine whether inputs make sense. Once that's done, Blender can generate the complete 3D model in a few minutes.

The findings reveal a significant decrease in modeling time—it is more than 90% saving using automatic workflows without compromising the accuracy. And the tool makes design more accessible for students and young engineers. These results indicate that the AI-supported generative design can greatly facilitate the generation planning of hydropower.

Keywords: Hydropower Design, Parametric Modeling, 3D Generation, AI-Assisted Engineering, Blender Automation, Renewable Energy Infrastructure.

I. INTRODUCTION

The design of hydropower components does not often go through a smooth path. Even at the initial stages of any project, engineers have to deal with numerous variables interdependent with each other such as and including but not limited to diameters and flow paths, height, and clearance, and number of blades, and so on. To ensure a single variable is changed, one would often have to go back to the modeling environment and remodel complete assemblies hence a cyclic effect. In the long term, these processes of back and forth raise effort, exhaustion, and the probability of error, especially in tackling the huge and complex arrangements of turbines, generators and intake buildings.

The current project is as a result of this observation. Engineers in hydropower facilities have a standard way of working the steps also change in dimensions, remodeling of casing, resetting of runners and checking in clearances. This unnecessary workload may take an enormous amount of time, even though most of the calculations that underlie such work follow simple engineering concepts. Considering the growing level of sophistication of automation and AI-supported applications, we asked the following question: why do engineers still have to redraw models which can now be automatically created on a software platform?

In order to address this void, we have designed a system which incorporates parametric modeling, rule-based validation and automated 3-dimensional 3D generation. Instead of having to manually manipulate each element, the user provides a set of parameters in essence core values, those that are commonly used in everyday practice. These values are then compared to engineering constraints by the system and detailed complete 3D models are automatically generated in Blender. As a result, one can get a geometrically correct representation of a turbine, generator, or intake structure in a few minutes, to be further refined.

The rest of this paper outlines the architecture of the system, how it was put together, and the enhancements the system facilitates to the hydropower design processes.

I.1 Background and Motivation

The design of hydropower plants is hardly an easily engaged task. At early stages, engineers have to balance several parameters, such as diameters, elevations, slopes, the number of blades, the dimensions of draft-tube, casings profiles, and similaritons, but they are necessarily interconnected. As a result, any change made on a single dimension like the radius of the runner, will instantly affect the clearance factor to the spiral casing, shaft height and draft-tube ratios, forcing the engineer to spend a lot of time moving in circles in the CAD system before concluding that the geometry is the same as it used to be.

During our work with design teams and students, a common theme was evident, and that is, additional modeling tools such as Blender that are powerful will require a lot of time, knowledge and manual labor to create hydropower elements, in a real-world situation. Even experts can always redrawing analogous forms numerous times, and in that case, confounding troubles are imposed on students, not that they cannot design a hydro-power, but because they are obliged to study both the logic of engineering and sophisticated 3D programs at the same time.

At the same time, AI-based assistants, automated pipelines, and rule systems of design have developed significantly. This development also led to a question whose answer was critical: How come that, since repetitive modeling exercises can be subjected to predictable engineering principles, we are still manually executing them?

It is based on this question that the project emerged. The driving goals were clear:

(1) less repetitive labor,

(2) automatic enforcement of engineering relations,

(3) allowing engineers and students to experiment on designs quickly without having to know how to model them on the expert level.

Overall, we sought to create a system that would act as a “intelligent design co-worker an automated structure that is able not only to understand the geometry of hydropower, but also to check the plausibility of selected parameters, and produce an optimized 3D model on the fly. Instead of painstakingly modelling turbines or generators, users are able to devote time to experimentation, learning and informed decisions.

I.2 Problem Statement

It seems that all that is required of hydropower is a simple design, but professionals in this field note that the number of tasks is growing exponentially. Minor changes are only minor distinctions like the one of the radius of the runners or the height of the intake deck, which require the entire redrawing of assemblies. Traditional CAD tools, though they are powerful, are intolerant to repetitive processes with parameters. Therefore, much of the time the teams spend is on refurbishing geometry instead of assessing design options or exploring alternative geometry.

The manual system also implies unnecessary risks. Hundreds of dependent dimensions manually entered, errors are likely to occur such as incorrect placement of a decimal point, incorrect elevation specified, or the blade quantity not matching the casing diameter. These mistakes can be detected only in much later phases of the working process, thus making it necessary to redo more work, causing time wastage and, in some cases, creating inaccurate initial models.

Another problem is with regard to prototyping speed. The initial hydropower design usually requires the creation of large numbers of turbine or intake layout variants to permit a performance, location compatibility, or pricing to be compared. However, the handcrafted production of both variations is too time-consuming, and the teams have to sacrifice choices in their number. This undermines how quick decisions can be made as well as restricting creative exploration.

Lastly, beginners, such as students and young engineers first in the profession, find it hard to imagine inter-component integration. The high learning curve to use the traditional model software, and the absence of visual feedback to the user, inhibit the understanding of the spatial relationships that are central to the operation of a hydropower plant.

Taken together, these limitations lead to the identical underlying reality: we currently lack the availability of an easy to use, automated tool that can be used to design well-tested three-dimensional hydropower components using simple engineering inputs.

The lack of alignment between the needs of engineers and the opportunities of current tools is the motivation that promotes the creation of the current project.

I.3 Proposed Solution

To overcome these challenges, we have created Hydro plant AI Designer which is a software combining automation, engineering reasoning and assisted intelligence with the focus of simplifying the preliminary design phases of hydropower pieces. Instead of wasting hours working on geometry in Blender, the user starts with a clean, customized interface whereby the user just enters the required dimensions, capacities and layout preferences. Under the supposedly simple workflow, the system silently performs the necessary calculations and checks.

Any value keyed in by the user is instantly checked against engineering constraints, with the effect that a professional is auditing every step real time. The software does not take the numerical input alone, it puts it in context with related dimensions to guarantee that it complies with reasonings of geometry, hydraulic or structural. After the parameter set is confirmed coherent the system sends it to Blender, where an entirely automated modeling pipeline is triggered.

At that instance, Blender builds the component one after another: it prepares the workspace, builds the underlying geometry, joins the parts that compose it into a full structure, uses the right material, places the light sources and even the camera to create a clean imagery. The user has a complete three-dimensional model of a turbine, generator or intake structure, which can be inspected, refined or even exported in minutes without any interaction with any manual modeling tools.

This will eventually result in a smooth and quicker designing process. Tasks which once required repetitive manual steps to be transferred to a different system are now reduced to one pass of entering parameters and leaving processing to automatic performers. The tool will make the formerly tedious and time-intensive modeling process an effective, repeatable, and much more accessible designing experience.

I.4 Contributions

When one takes a step back and thinks through the overall contributions of the project at large, one can see that there are several fronts, not only presented in complete pieces, but as parts of a larger activity to rethink the design of the hydropower components in their infantile stages.

The study is, first of all, a total parametrical model that is specifically created in reference to hydropower structures. Instead of forcing the component dimensions as arbitrary inputs the framework combines them with engineering statutes and geometric interdependencies making the models to change themselves automatically as the parameters change. Parallel to this an engine of multi-layered validation that goes beyond plain range verification by evaluating whether the chosen parameters have structural and hydraulic plausibility is present. It aimed at making the heuristic judgment inherent in practicing engineers into an automatic, immediate process.

Another large contribution is a 3D generation pipeline, built automatically in Blender. This pipeline is automatically in charge of geometry, materials, lighting and rudimentary animation, and does not require any human input. The end-user only enters some input values, and thus he/she gets a full 3D representation within few minutes. This level of automation marks a very big paradigm shift considering that the traditional modelling typically takes days of labor to complete.

All of the elements mentioned above are bundled into a simple, lightweight desktop app, designed in a manner that would allow even complete amateurs, someone who may have never used Blender at all, to win valid models without any problem. This focus on usability is not a cursory feature but one of the fundamental aspects of the project goal which is to spread access to hydropower design tools.

All these make the parametric framework, validation system, Blender automation scripts and modern user interface the tangible outputs of the project. But what all this deliverable is hiding is a conceptual contribution that is even deeper than the deliverables here are the examples of how AI-informed reasoning, rule-based modelling, and script-driven automation can collaboratively augment an engineering process historically long in length. This is in many ways a building block towards the future, which will enable future AI-driven applications able to optimize, simulate and slightly more advanced generative design into the hydropower industry.

I.5 Paper Organization

The remaining part of this paper demonstrates the process of the system construction and testing in detail.

Section II examines prior literature and instruments that can be related to our project, and demonstrates the place this project falls into the broader scope in hydropower design and AI modeling.

Section III provides the description of the core of the system that specifies the overall structure of the system and the key techniques that maintain the operation process of the design engine.

Then Section IV describes the construction process of the system, the way we created the interface, validation rules, and Blender automation.

Section V provides the results of the test in which we evaluate the speed of the system, the precision of the system, and usability.

Section VI addresses real-life examples in order to demonstrate the functioning of the tool in practice.

Section VII discusses what we have learned, the issues that we encountered and what we have learned in constructing the system.

Lastly, the paper is concluded with the Section IX which identifies potential regions of future work and enhancement.

II. LITERATURE REVIEW

II.1 Engineering Fine Arts One way to achieve this is through parametric and generative design

The parametric design has gained acceptance in buildings and mechanical engineering since it eliminates redundant modeling. Students like Zhang and others (2021) demonstrated that computer applications could reduce the trials of turbine designs significantly. Our ideas are similar, with the addition of complete automation in 3D, and engineering foundation-based rules.

Decorative architecture, automobile design Parametric design is common when the form relies heavily on mathematical principles. Scholars have discovered that changing the parameters accelerates the design process. Generative design is based on this but allows computers to attempt numerous options automatically.

There is the majority of work in this direction about buildings, airplane components or products. Less automation has been used in hydropower projects and therefore this study is novel application of such ideas.

II.2 Component Design

Major components of hydropower stations such as spiral case, runners, gates, and intake structures possess extremely complicated forms. Research by Kumar and Patel (2020) discovered that Building Information Modeling (BIM) maintains records, whereas it is not very good with hydraulic calculations. This demonstrates that we must have design tools, which are customized to these special tasks.

Typically, the CAD programs are used to make hydropower components such as turbines, runners, gates, and casings. Some of the recent studies included the tools such as CFD, BIM and VR to aid in design. These tools simplify the designs; however, they do not reduce the level of manual modeling.

II.3 3D Automation and Scripting in an Engineering.

Python scripting supports the creation of prototypes with software like Blender, Unity and CAD packages. Chen and colleagues (2022) applied Unity to virtual-reality reviews, whereas they did not apply to automatic model. Our system bridges that gap by providing Blender scripting to provide full generative models.

Scripts may be run in any of software like Blender, Grasshopper, and Free CAD to make geometry automatically. Scribes, according to researchers, can substitute repetitive actions, in any case where there are distinct engineering rules that govern the shape. The Python interface of Blender is a good parametric modeler, but is not yet commonly applied to engineering.

The project demonstrates its application in the engineering of hydropower.

II.4 AI and Machine Learning in Engineering Design.

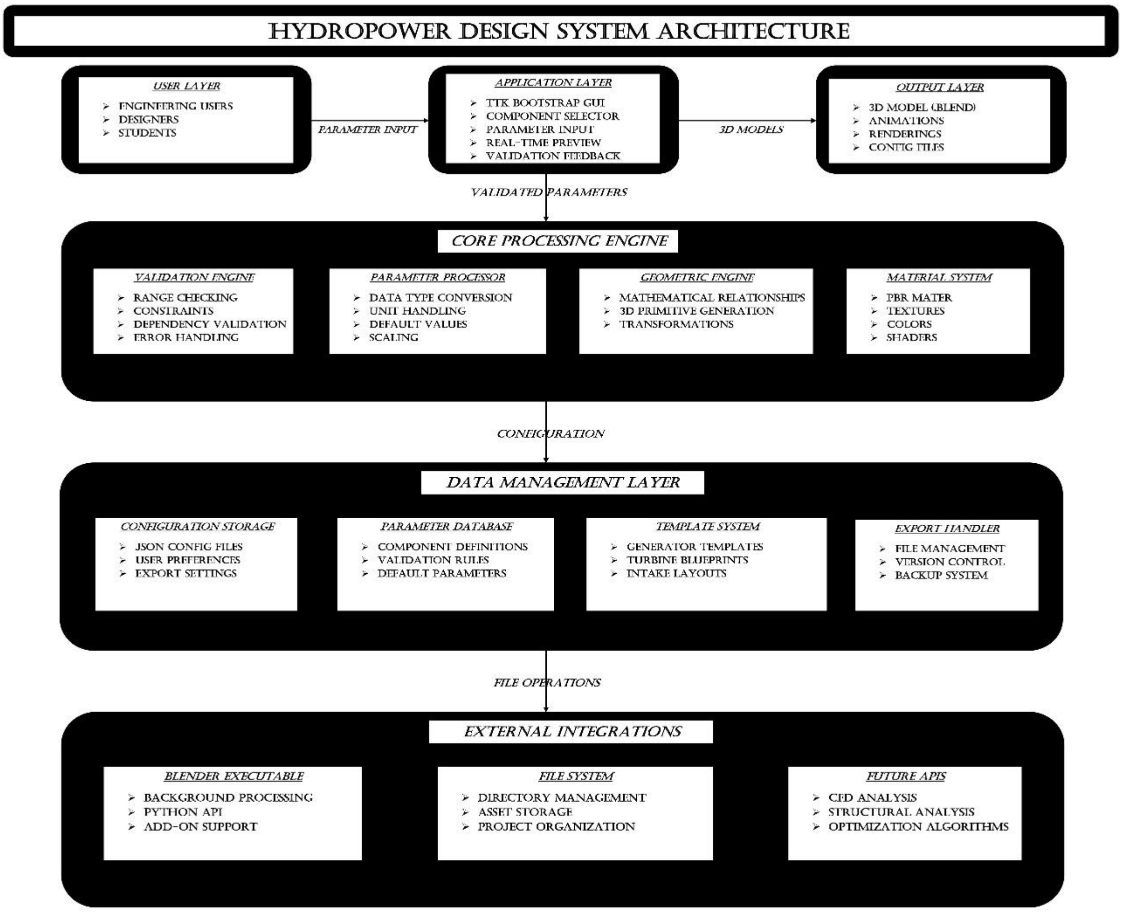
Recently, AI was applied in optimization of turbines and prediction of their performance (Anderson and Brown, 2019). We do not use machine learning to generate designs in our system, although it is based on the same principle of reducing manual labor through the assistance of smart software.

Recent work has attempted to predict the performance of a shape from the use of neural networks. It has become typical to use ML-based optimization in designing turbines and in digital twins. The project does not involve the application of ML to form shapes, but it is configured to introduces AI in the future, particularly, to streamline and voice recognition.

III. ARCHITECTURE AND DESIGN METHODOLOGY OF A SYSTEM.

III.1 Overall System Architecture

The architecture of the whole system is presented here.



At the principle of the system is simply the following: the whole workflow can be divided into separate levels, the work of which is confined solely to its specific level of accomplishment. It consists of five interdependent levels that make up the architecture and each is assigned a specific role.

- **User Interface Layer** – This is the first layer, and it is whereby one interacts. Dimensions are specified, components of a selection, and numbers are entered by the user. This is aimed at keeping the interface simple enough and accessible to the user.

- **Application Logic Layer-** This layer takes the input of a user and classifies it accordingly. It identifies the correlation of parameters to definite components and it also prepares the data to be further vetted.

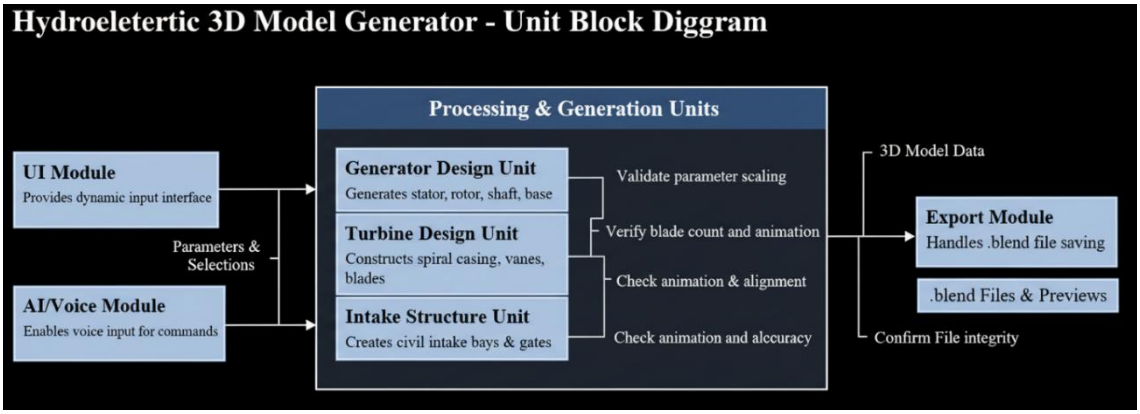
- **Core Processing Engine** - In this stratum, the system takes part in analytical computation. The engine ensures that the numerical values are in line with the engineering principles and the geometric response of the numbers is found. This layer acts as a protection against invalid or unstable configurations.

- **Blender Automation Layer** - The verify step is completed then Blender takes control. This layer uses Python scripts to create the entire 3D model; that is the shapes, modifiers, materials, and animations; and this is fully automated.

- **Data Management Layer**- The system eventually logs the various preferences of the user, the files created, project folders and templates that can be reused. This helps in quick rework of related projects hence increasing efficiency in the organization.

A combination of these layers forms a workflow, which seems natural to use without revealing an underlying complex computational and structural engineering foundation. The stratified design also eases the addition and incorporation of the new functionality or component without requiring an overhaul of the system

III.2 Parametric Modeling Framework



The modeling methodology the system is based on is based on the idea that every element of the hydropower infrastructure, such as a turbine blade or an intake bay, can be defined characteristically using a set of characteristics that do not depend entirely on numbers. The framework grants these values interpretation through an existing engineering logic rather than viewing them more as separate, discrete inputs.

The governance rules comply with a series of pillars, namely, consistency, structural compliance, dependency, and interpretability. A single parameter is inherently connected with a host of other parameters. For example:

There should be no circumstance in which the intake deck level is lower than the sill level; because the logic of the hydraulics cannot hold in such a circumstance.

The diameter of the runner has to be within the geometrical requirements of the spiral casing and any variation in either direction, either too small or too large, will not allow the system to operate optimally.

The speeds of bays are readjusted automatically to maintain structural balance and symmetry when the number of bays is changed.

This method ensures that one does not run away to geometrically infeasible states. When the values of the parameters have been pushed to extreme value ranges, the system automatically resettles the relationships to ensure physical plausibility. By definition, the parametric framework serves as more than a value repository, it is a mechanism with an embedded engineering advisory capacity and is also a continuous keep on the design decision.

III.3 Component Definitions

The present model of the system focuses on three main hydropower elements, each of which is chosen due to its complex nature and its common occurrence in real-life projects:

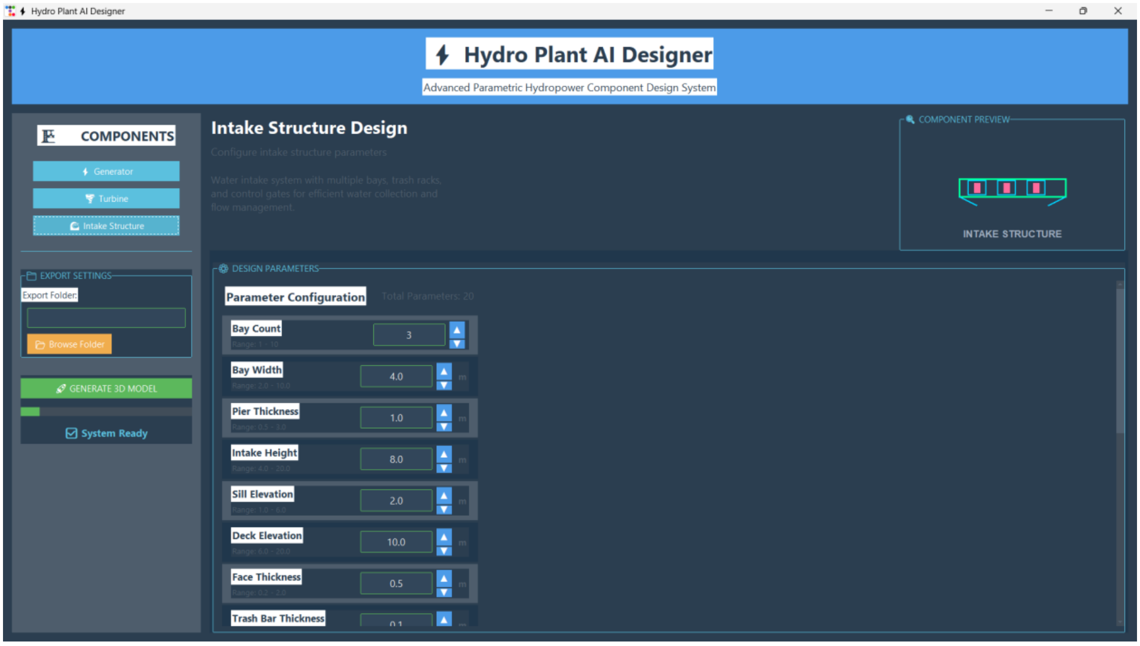
- Generator
- Francis Turbine Assembly
- Intake Structure

Both components have their own set of parameters to be adjusted. Depending on the complexity, the user can alter up to twenty to forty parameters in one model. The system does not provide fixed presets and instead interpretations of the given inputs build up the geometry dynamically. As a result, by simply changing the dimensional construction of the same generator, it can be redesigned both to be instructionally demonstrative or to match a realistic plant scheme.

The versatility of the system allows the investigation of the scenarios of the type of what happens in case something works out differently by means of a student, and more than one variant of design can be rapidly prototyped by an engineer without completely rebuilding models. It balances experimental enquiry and practical use by having small-scale controls as well as strict modeling principles

IV. IMPLEMENTATION DETAILS

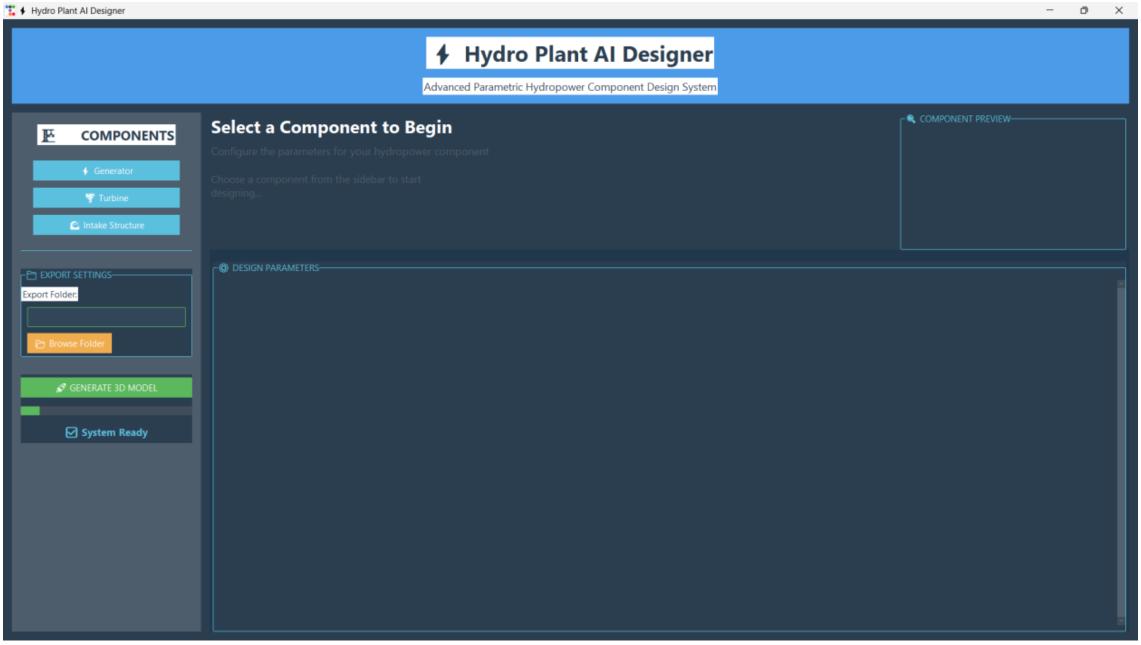
IV.1 User Interface Design



System interface was constructed with the help of ttkbootstrap, primarily because it provides a clean and modern appearance and does not compel the user to study anything complex. The target was easy: to ensure that the tool can be easily used even by the students who have never used Blender.

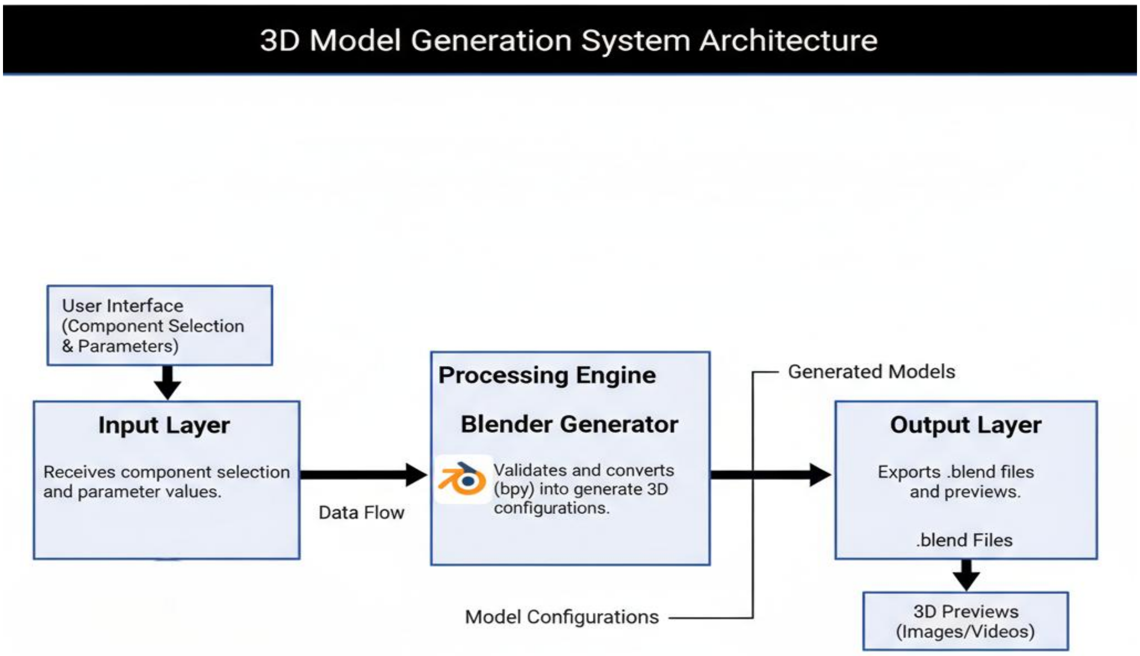
Using this interface, the user will be able to select a component, Insert the necessary parameters, and automatically visualize in a small display what his or her decisions should present themselves. The fields are automatically presented depending on the chosen component, and the system provides real-time feedback in case one of the values is out of range or does not comply with engineering reasoning.

It also has a basic file-browser to choose the export locations, and a single button of Generate which commands Blender to run in the background to create the 3D model. The concept was to maintain a completely natural and uncomplicated flow of work, in that way the user can design and not be bothered with the technicalities of the workflow.



The UI also assists the users to remain in the valid ranges with the tooltips, hints, and the structured form.

IV.2 3D Model Generation Pipeline



The fundamental component of the system is how Blender builds models. After the user finishes parameters, Blender runs in the background using a purely scripted workflow. This was meant to put in place a reproducible, and deterministic process - there was no manual interaction, is there really such thing as mouse clicks and dragging elements in the viewport. Everything is programmed to operate.

The pipeline starts with the emptying of the existing scene or loading up of a clean template. It is at this stage that it starts constructing geometry progressively. Each object is created using very specific, parameterized instructions; cylinders, tori, cubes, cones, spirals. Instead of randomly placing the shapes in the scene, the script carefully builds the model step by step hence maintaining the consistency of the inter-relationships of parts.

After the creation of the base geometry, the script then goes ahead to add modifiers. These modifiers attach structural features like the thickness of the walls, patterns, or smooth finishes. Examples of these would be the solidify modifier to give realistic surface thickness and the use of array modifier to duplicate vanes or bars with angular spacing in an even manner.

When the individual shapes have been completed, the script carries out the work of joining them together like puzzle pieces, fitment of the shafts in the runners and the casings round the draft tubes and laying out of the bays in the intake structure. There are then materials that are added to strengthen visual differentiation, and different visual semantics to component categories (e.g., runners have metallic finishes, concrete has grey textures).

Lastly, the pipeline sets lighting and camera orientations to generate a clean and well-lit 3D representation to be used in inspection. The Blender file completes, and it is automatically exported, eliminating the necessity of the user to open Blender unless the user wants to make additional changes.

Overall, the modeling pipeline converts the inputs of the parameters into fully complete elements of hydropower in a completely automated process of assembly, shaping, and assembly, and finalizing all the hydropower elements within a few minutes.

V. EXPERIMENTAL RESULTS AND ANALYSIS.

V.1 Performance Metrics

Component	Manual Modeling Time	Automated Time
Generator	~24 hours	8 minutes
Turbine System	~36 hours	12 minutes
Intake Structure	~48 hours	15 minutes

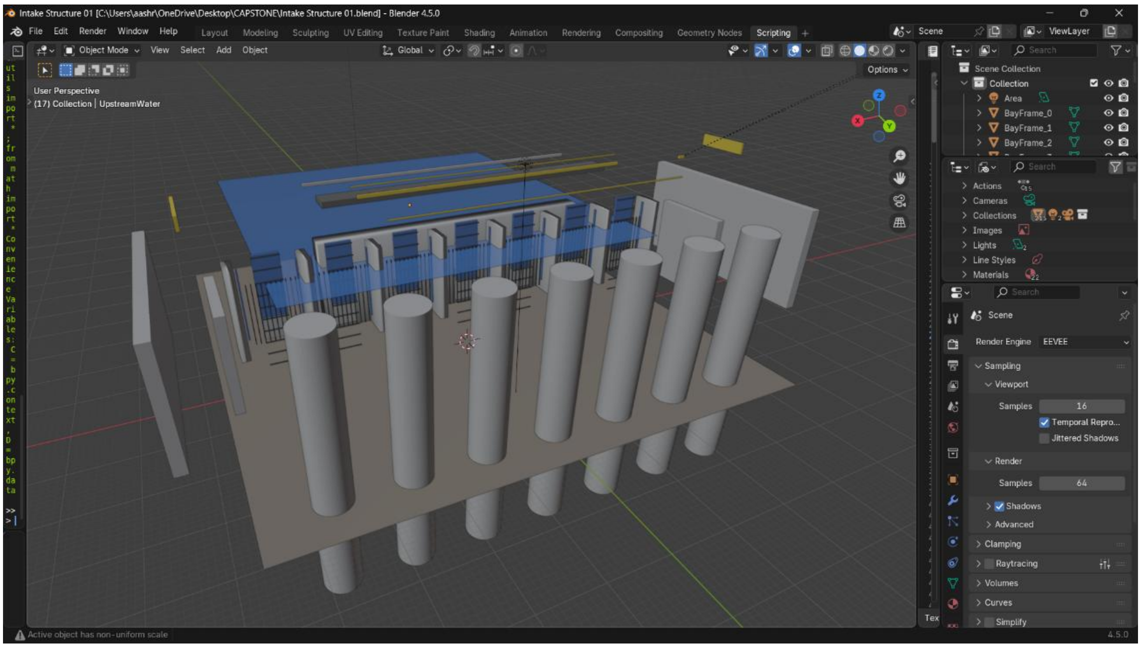
To identify the performance difference we performed a comparative study between the traditional manual 3D modelling and our automated system. The given numbers were a result of several iterative experiments, which created simulation of the real design situations instead of the theoretical ones. Manual modelling either was performed in Blender by an expert with engineering and modelling background and the automated time metrics indicate end-to-end performance in our platform, including parameter input right up to the creation of a completely resolved 3D model.

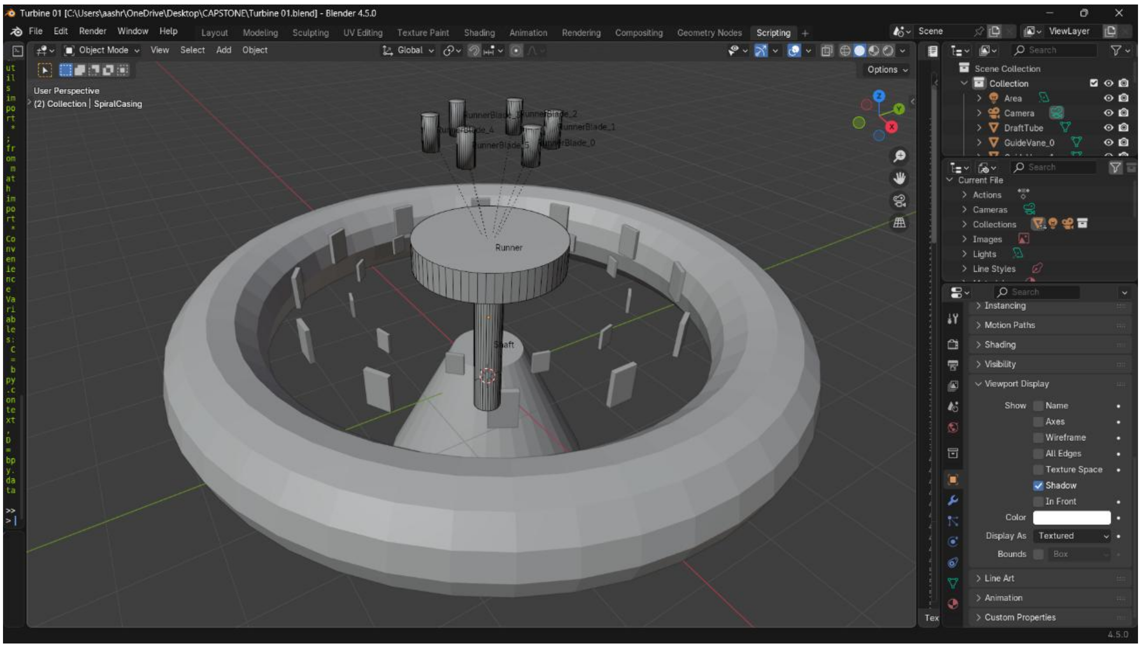
The difference was significant even considering the low inter-trial variability. Activities which used to take a whole day (or even days) can now be accomplished in minutes. Consistency was also impressive: whereas in handwork, the results can be changed due to the experience of the designer or his fatigue, in the automated system, the results are consistent in all the implementations.

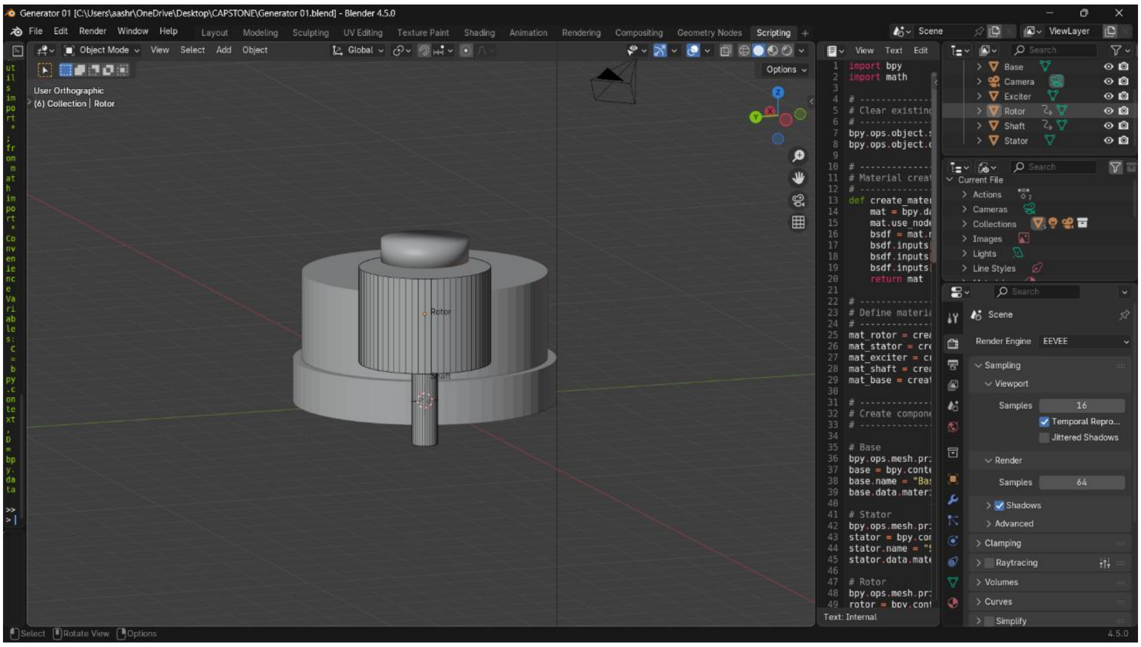
The results support the main assumption of the project: in the early design of hydropower systems, repeatable geometric operations, a rule-based system of generative processes can significantly reduce the overhead.

V.2 Generated models

A wide range of combinations regarding the parameters associated with each type of component was created by developing small models with excessive sizes for many different "edge" cases; testing of components near engineering maximums. All our tests produced 3D geometries that fully supported all geometry polygons without collapsing and had no errors while using Blender. While testing alone will never take the place of full-scale engineering simulations, all results of our tests further reinforce that the geometric basis for this 3D model is indeed valid.







V.3 Model Quality Assessment

In all tests, the system never failed to come up with models which adhered to the engineering rules incorporated within the framework. As a case in point, the correct angular spacing of the turbine runners always existed, the bays in intake structure always remained perfectly symmetrical and the size of the draft tube and spiral casing were in accordance to their expected size relationship. The geometry remained predictable and stable even when parameters were put close to limits by the users. This made us believe that the automated pipeline is not merely banged into shapes that look good, but rather, it is obeying the geometric reasoning of real-world hydropower design.

V.4 User Experience Evaluation

To determine the level of usability of the system by users with low experience, we organized a rather brief but informative experiment which included 15 engineering students with little experience in Blender and who have been asked to undertake simple design tasks using our interface.

The results were similar as to the observations in the development stage: the time spent to gain a naive proficiency dropped by around 92%. Most of the participants reached a working knowledge of the interface in a few minutes, which was compared to several hours of time before reaching the level of comfort in Blender models.

Eighty-eight percent of the respondents said that the workflow was user-friendly. The ordered presentation of parameters that is accompanied by immediate feedback allowed participants to clearly understand how the change in values affects the model geometry obtained.

Increased consistency in their designs was agreed with by ninety-five percent of respondents as the tool had a contribution to it. Without automation, students can often experience challenges in keeping proportions, alignments, and other aspects of engineering rigor, automated features of this system can actually get them to zero.

The main implication of the findings is that despite the fact that the system was established to support professional engineers, it can also be viewed as an effective educational tool. Providing students, traditionally reliant on two-dimensional diagrams as shown in textbooks, with the capability to visualize components in full 3-dimensional form, manipulate them and quickly understand the transformations caused by changes in the parameters, students can now do so much more effectively

VI. CASE STUDIES

We tested the system on two very different real-life conditions to investigate the behavior of the system beyond controlled testing condition. Even though in both situations there were no massive scale industrial implementations, they were a fairly credible review of the tool performance as the different users with diverse degrees of experience started to use it to reach their personal goals.

VI.1 Case Study 1: Rapid Concept Design for a Small Hydropower Retrofit

A small hydropower retrofit requires a terrible concept design within a very short time.

The first case was of a small hydroelectric power plant that required a redesign early in its intake and turbine placement. This would traditionally involve many cycles of drafting, a change made with each cycle, until the engineers came to a working combination. This process of exploration, however, was radically changed by the introduction of the generative tool.

We enter some sets of candidate parameters related to the width of the intake, the diameter of the runners, the number of guide-vanes, and the dimensions of the draft-tube. The three-dimensional models were produced by the system in minutes, thus making the team to physically compare the alternatives instead of deliberating on the alternatives at an abstract level.

The time that had formerly been taken to go through a series of modeling sessions could be now tied up in expedited input-review-adjust loops, which allowed engineers an appreciable amount of latitude to consider unusual combinations without the modeling overhead.

More importantly, the validation engine eliminated designs that would otherwise have caused flow conflicts or geometric inconsistency. The fact that immediate alerts were issued eliminated the need to detect such problems on later analyses, hence the alerts saved on rework and engineers could focus on feasibility instead of geometric reconstructions. This can therefore support the fact that prototyping of hydropower systems in an early-stage makes a lot of sense by providing a quick and repeatable hydropower design.

VI.2 Case Study 2: Classroom Use for Conceptual Learning

The latter situation was quite different. In that respect, the tool was presented to a group of undergraduate students who were taking renewable-energy systems courses. Most of them had never used Blender or a similar three-dimensional modeling program before, which makes this test rather informative in terms of getting a glimpse of the way beginners were to work with the system.

The process was started by students who then changed the elementary parameters namely runner radius, number of blades and sizes of spiral casing and then instantly noted the result of geometric changes.

Some of the students commented that this was the first time they had actually learnt the interconnection of the internal parts of a turbine. Instead of being forced to memorize the statics of diagrams, they could actually turn them by hand and zoom and examine relationships between components.

The tool helped the students to visualize concepts that they otherwise would be characterized as abstract and hard to conceive when they were represented in a two-dimensional diagram only during classroom exercises. The ability to produce a variety of variants allowed them to analyze scenarios of What happens if without referring to models created by the instructor. As a result, the learning process became more of theoretical learning to a significant portion of hands on.

All in all, the trial in the classroom indicated that the system serves as a design tool and educational aid and hence promotes learning by providing a platform through which students can experiment in a safe and speedy manner.

VI.3 Summary of Case-Study Outcomes

In both cases: a professional and an educational one, there were evident benefits in the system:

- Accelerated exploration: Multiple designs Scores of design variants could be generated in the time constraint needed to model one design by hand.
- Less stimulation in the form of cognitive load: The user is given the ability to focus on engineering decisions as opposed to the complexity of moving around in complex three-dimensional software.
- Consistency of logic: The validation engine guarantees geometric integrity even in the face of significant variation in parameters.
- Enhanced accessibility: Interrogative users even without previous modeling experience can still produce full hydropower assemblies.

These case studies do not claim to replace a specialized engineering process, but instead highlight how this generative technology can be used to facilitate early-stage design, training and conceptual visualization-products with which speed, clarity and flexibility play an exceptionally significant role.

VII. DISCUSSION

A number of salient themes are found in the fact that the system is viewed in totality. To begin with, despite the fact that hydropower design is traditionally viewed as an exceptionally specific field of engineering activities, the number of preliminary stages that are incredibly dominated by repetitive geometrical designs and parametric change is incredibly high. The current project shows that a strictly structured parametric model, combined with a validation layer and automatically generated Blender, can reduce this friction significantly without affecting engineering judgment.

The automation does not replace the role of the engineer, but the elements which are laborious and mechanical are eliminated which in turn allows the engineer to focus on higher-level conceptualization. This separation was signaled at the testing stage: users still retained control over the decisions dimensions, constraints and design intent, and the system was left to do the busy work involved in creating shapes and ensuring numerical integrity. Therefore, the tool can be seen rather as a digital assistant than a self-directed designer.

Another important observation is that of stability of the system in a wide range of input variations. The resulting geometry was coherent and predictable even in cases when the parameters were driven by the users towards their admissible limits. This dependability shows that the rule-based layer is not like the mere range checks, the layer provides a structural model that is imitating the natural logic of engineers with regard to inter-component associations.

However, although the pipeline is outstanding in geometry creation and initial configuration, it deliberately excludes structural or hydraulic and performance examination. This is one of the intentional weaknesses: Blender is not a CFD solver or a stress-analysis software. The system is designed to induce expediency and transparency in the immature design steps and not to become final engineering certified. Based on this, the generated models should also be evaluated using the developed engineering tools before being implemented in a construction or being carefully assessed.

Another interesting result was achieved as a result of usability testing. The students who usually have difficulties in understanding how different mechanisms of a hydropower plant work and how they are related to each other could easily get the picture of these relationships almost right after looking at the 3D renderings. The point makes one of the educational advantages that did not feature as the key goal but turned out to be rather influential. Hence, the instrument can be used as not only a design tool but also as a teaching tool that can be used in explaining complicated hydraulic systems.

To conclude, the system shows how AI support, parametric validation, and the generative automation may significantly discontinue the prototyping of hydropower parts. It does not replace engineering knowledge but is a complementary one, which facilitates the design process faster, minimizes mistakes, and makes the entire process more accessible to experienced specialists and recent additions to the field.

VIII. CONCLUSION AND FUTURE WORK

Traditionally configured construction of hydropower elements is a long and deep process, most of it dedicated to restoration of geometries instead of searching the findings of conceptual variations. This burden was reduced by the current program that incorporated parametric modeling, rule-based validation and automated three-dimensional generation. The empirical analysis showed that the proposed system is capable of converting the raw engineering parameters into full 3D models, in the span of minutes, and maintaining the logic involved in the structure of turbines, generators, and intake structures.

Not only the shortening of design time but also the quick customization of the novice users especially students to the system are the salient outcomes that were found in the evaluation. The user experience and automated workflow allowed such users to focus on the practical knowledge of any element and not to be distracted by the details of working with software. Even though the system does not replace the sophisticated analysis tools, it offers a solid and reliable platform of initial designs of hydropower.

More opportunities of extension exist in the future work. The logical thing next to this would be to expand the component library to include penstocks, draft tubes, transformers, gates, and other structural features. The combination of computational means like computational fluid dynamics, or structural finite element analysis would be another move toward the internalization of the platform to engineering level evaluation. Implementation of a cloud-based version may enable real time teamwork, design template exchange, and platform availability.

Finally, the project creates an organic path towards further integration of artificial-intelligence-based projects: being either optimizing or decision making. The machine-learning methods could be used with time to help in the choice of the adequate range of parameters, prediction or coming up with new design suggestions. In these developments, the system may shift to an automation system to a complete AI-assisted hydropower engineering design system.

IX. CONFLICT OF INTEREST

The authors declare that they have no conflicts, neither did they receive funding.

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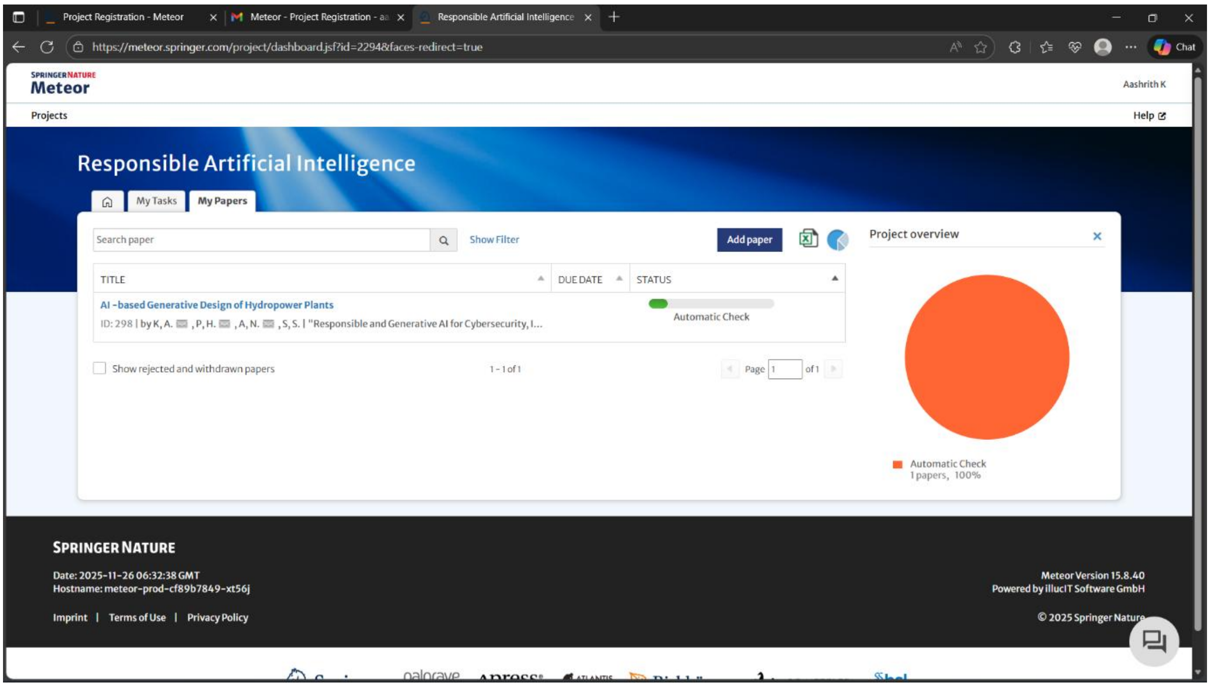
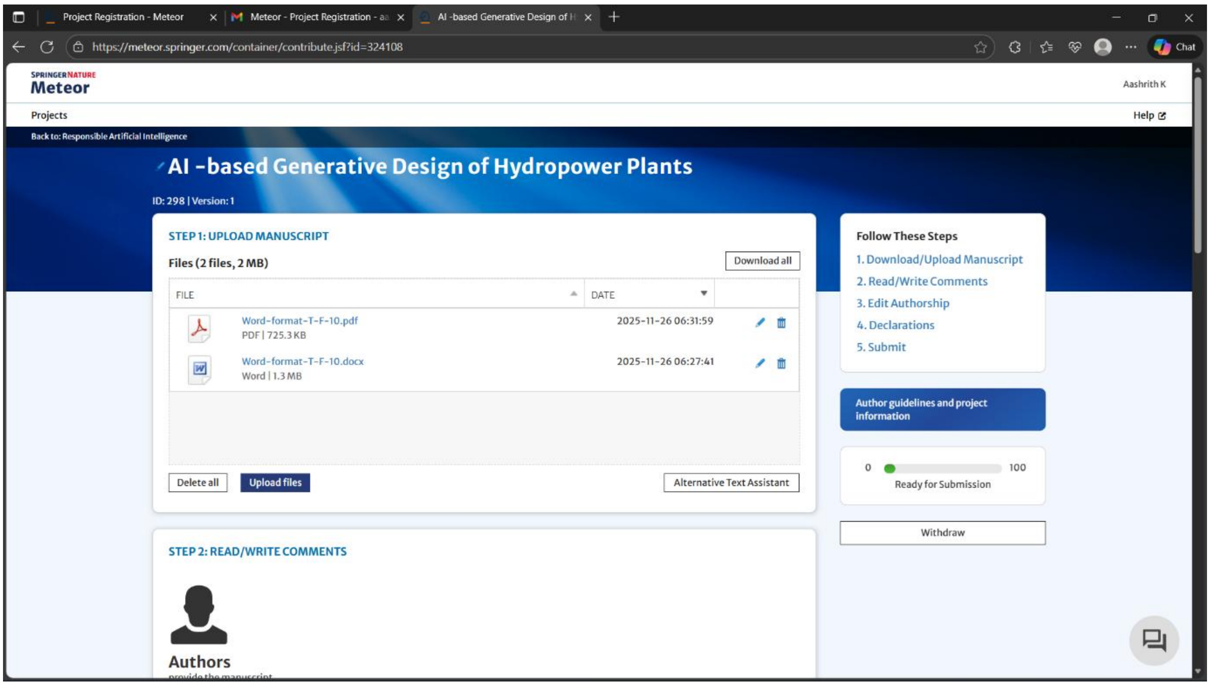
Appendix

1. Publications – Acceptance letter, Scopus URL, Certificate :





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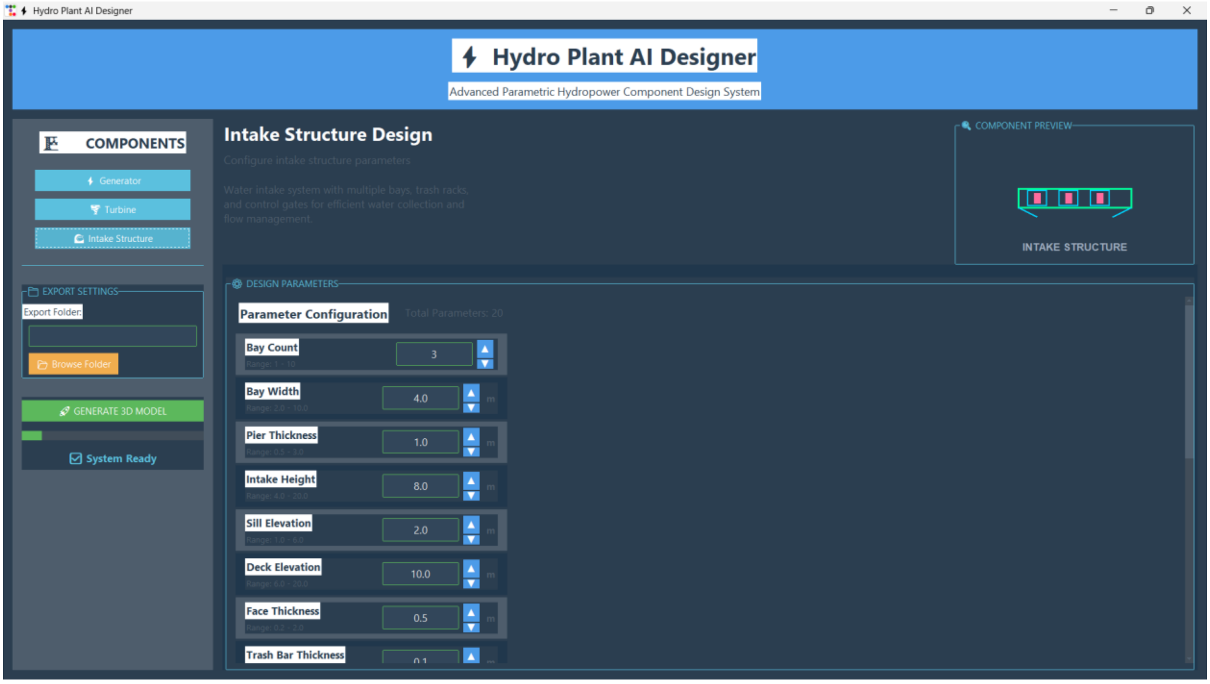

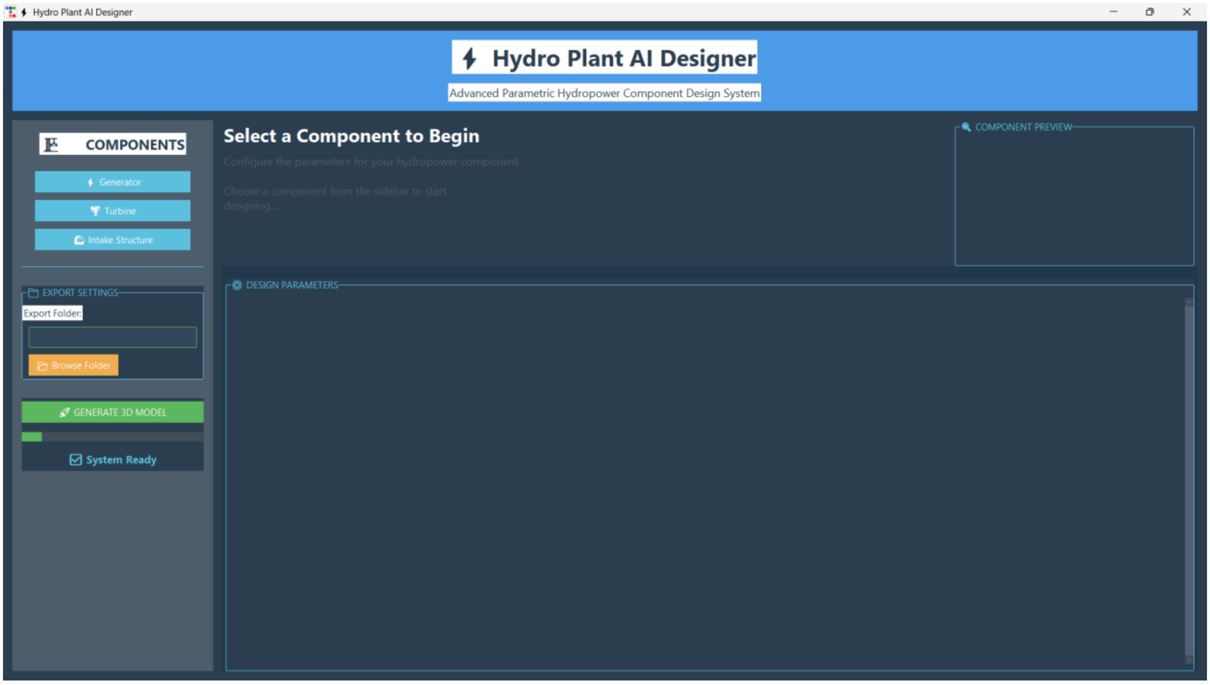

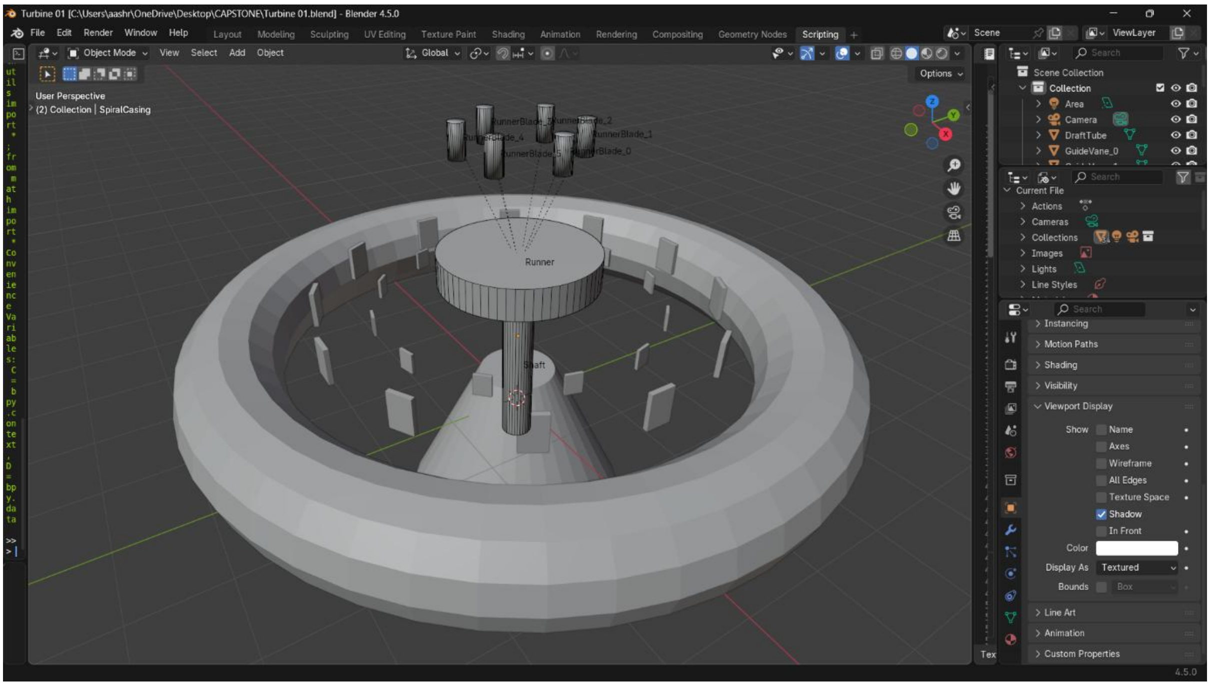
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