Product Design and Development Practices of Undergraduate Engineering Students through an Integrated Design Project

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ABSTRACT

This study explores the application of product design and development practices among undergraduate engineering students through an Integrated Design Project (IDP) centered on the development of a pico-hydroelectric generator for harvesting energy from open-drain water flow. The project aimed to convert the kinetic energy of low-head water sources into electrical power through an efficient, cost-effective, and sustainable system suitable for urban, rural, and educational environments. Throughout the project, students applied key product design and development practices, including project planning, concept generation, design evaluation, decision-making, risk assessment, and multidisciplinary collaboration. Systematic engineering approaches such as concept selection, morphological analysis, and structural evaluation were employed to identify the most viable design solution. In addition, Design for Manufacture and Assembly (DFMA) and Failure Mode and Effects Analysis (FMEA) were integrated into the design process to enhance manufacturability, reliability, durability, and economic feasibility. The final design selected was a mini water-wheel turbine, which demonstrated superior performance under low-flow and low-head operating conditions. The project provided students with valuable experience in managing the complete engineering design cycle while addressing real-world sustainability challenges. Furthermore, the initiative contributes to the achievement of Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), by promoting renewable energy utilization and reducing dependence on fossil fuel resources. The findings demonstrate that Integrated Design Projects serve as an effective platform for developing product design and development competencies among engineering students while simultaneously producing practical and sustainable engineering solutions.

Keywords: Product design and development, Integrated Design Project, Engineering Education, Renewable Energy, Sustainable Development Goals.

INTRODUCTION

Product design and development is a multidisciplinary approach that integrates design, engineering, business, and project management principles to ensure that design activities are effectively planned, coordinated, and controlled throughout a project lifecycle. It focuses on aligning design processes with project objectives, stakeholder requirements, resource constraints, and organizational strategies to achieve successful project outcomes. In engineering and product development contexts, product design and development play a vital role in facilitating collaboration among multidisciplinary teams, improving decision-making processes, managing risks, and ensuring that design solutions meet technical, economic, and sustainability requirements.

Within engineering projects, product design and development encompasses a range of activities including

project planning, design coordination, communication management, quality control, risk assessment, resource allocation, and performance evaluation (Andreasen & Hein, 2000; Baxter, 1995). Effective product design and development enables project teams to systematically transform conceptual ideas into practical solutions while balancing functionality, manufacturability, cost, and environmental considerations. Furthermore, the adoption of structured product design and development practices supports innovation, reduces design errors, minimizes project delays, and enhances overall project performance. In engineering education, product design and development has gained increasing importance as universities seek to equip students with both technical expertise and professional competencies required by industry. Integrated Design Projects (IDPs) provide an ideal platform for applying product design and development principles by engaging students in real-world engineering challenges that require teamwork, leadership, problem-solving, and project coordination. Through participation in IDPs, students experience the complete engineering design cycle, from problem identification and concept generation to design evaluation, prototype development, and performance assessment. This experiential learning approach enhances students' ability to manage complex projects, collaborate effectively with multidisciplinary stakeholders, and develop sustainable engineering solutions (Brown, 2009; Bstieler & Noble, 2023).

An Integrated Design Project (IDP) is a collaborative and multidisciplinary approach to engineering education that combines knowledge, skills, and methodologies from various engineering disciplines to address real-world problems through a unified design process. Unlike conventional learning approaches that emphasize individual subjects, IDPs encourage students to integrate theoretical knowledge with practical applications by working on complex projects that require technical, managerial, economic, environmental, and social considerations. This approach enables students to develop holistic problem-solving capabilities while gaining hands-on experience in designing and implementing engineering solutions (Calantone et al., 2011; Cooper, 1990; Cooper, 2019). The concept of Integrated Design Projects is widely adopted in engineering education to bridge the gap between academic learning and industry practice. Through IDPs, students engage in the complete engineering design cycle, including problem identification, requirement analysis, conceptual design, detailed design, prototyping, testing, evaluation, and final implementation. The multidisciplinary nature of these projects promotes teamwork, communication, leadership, and decision-making skills, all of which are essential competencies for professional engineers (Crawford & Di Benedetto, 2021; Cross, 2008). Furthermore, IDPs provide opportunities for students to apply engineering tools and techniques while considering constraints related to cost, manufacturability, sustainability, safety, and project feasibility.

A key characteristic of Integrated Design Projects is the incorporation of product design and development principles throughout the project lifecycle (Design Council, 2019). Students are required not only to develop technical solutions but also to manage project schedules, coordinate team activities, assess risks, allocate resources, and evaluate design alternatives systematically. This integration of technical and managerial aspects helps students understand the complexities of engineering practice and prepares them to operate effectively in multidisciplinary environments. In recent years, Integrated Design Projects have increasingly focused on sustainability-driven challenges that align with global development goals (Göhlich et al., 2021; Golder & Mitra, 2018). Renewable energy, energy efficiency, environmental conservation, and community development have become common themes for engineering design projects, allowing students to contribute to meaningful societal issues while developing professional competencies. Such projects foster innovation and creativity by challenging students to develop practical solutions that address real-world needs using available resources and appropriate technologies.

In the context of this study, the Integrated Design Project focuses on the development of a pico-hydroelectric generator capable of utilizing low-flow open-drain water sources for electricity generation. The project provides undergraduate engineering students with an opportunity to apply engineering knowledge, product design and development practices, and sustainable design principles in the development of a functional renewable energy system (Heskett, 2005). Through activities such as concept generation, morphological analysis, design selection, structural evaluation, Design for Manufacture and Assembly (DFMA), and Failure Mode and Effects Analysis (FMEA), students gain valuable experience in managing and executing a complete engineering project. The project not only enhances technical competencies but also promotes

awareness of sustainable energy solutions and supports the broader goals of engineering education in preparing graduates for industry and societal challenges.

The increasing global demand for electricity, coupled with growing concerns over climate change and the environmental consequences of fossil fuel dependence, has intensified the search for sustainable and renewable energy solutions (Iqbal & Suzianti, 2021). Among the various renewable energy technologies, hydropower remains one of the most reliable and mature sources of clean energy due to its high conversion efficiency, operational stability, and minimal greenhouse gas emissions. Nevertheless, conventional large-scale hydropower plants require substantial capital investment, extensive infrastructure, and favourable geographical conditions, limiting their applicability in remote, rural, and decentralized settings. To address these challenges, pico-hydropower systems have emerged as a promising alternative for localized electricity generation (Jiao et al. 2007). Typically producing power outputs below 5 kW, pico-hydropower systems harness the kinetic and potential energy of small water sources, including streams, irrigation canals, and open-drain water flows. Their compact size, low installation cost, environmental compatibility, and ease of maintenance make them particularly attractive for off-grid communities, educational institutions, and small-scale applications. Furthermore, pico-hydropower technology offers significant potential for supporting sustainable energy development while promoting energy accessibility in underserved regions.

Malaysia's tropical climate and abundant rainfall provide a vast network of rivers, canals, and drainage systems that could be utilized for small-scale hydropower generation. Despite this natural advantage, the adoption of pico-hydropower technology remains relatively limited. As a result, many rural and isolated communities continue to experience constrained or unreliable access to electricity, while alternative energy solutions are often associated with high costs, environmental impacts, or complex maintenance requirements. Therefore, there is a pressing need to develop innovative and economically viable pico-hydroelectric systems capable of efficiently exploiting low-head and low-flow water resources that are readily available but largely untapped (Kelley & Kelley, 2013). This study was undertaken as an Integrated Design Project (IDP), providing undergraduate engineering students with an opportunity to apply product design and development practices throughout the engineering design process (Krishnan & Ulrich, 2001; Lidwell et al., 2010; Norman, 2013). The project focuses on the design, development, and evaluation of a pico-hydroelectric generator that converts the kinetic energy of open-drain water flow into usable electrical energy. Through systematic engineering methodologies, including concept generation and selection, morphological analysis, structural evaluation, Design for Manufacture and Assembly (DFMA), and Failure Mode and Effects Analysis (FMEA), students were able to integrate technical design, project planning, decision-making, risk management, and sustainability considerations into a comprehensive engineering solution (Otto & Wood, 2001; Pahl et al., 2007).

The final design adopted a mini water-wheel turbine configuration, selected for its suitability and efficiency under low-flow operating conditions. In addition to demonstrating the technical feasibility of pico-hydropower technology, the project contributes to the advancement of sustainable energy practices and aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). The objectives of this project are to design and develop a pico-hydroelectric generator system capable of utilizing low-flow open-drain water sources and to evaluate its performance under varying water flow conditions. The study also aims to analyze the efficiency, power generation capability, and electrical output of the developed system to determine its effectiveness as a renewable energy solution. Furthermore, the project seeks to assess the technical and economic feasibility of pico-hydropower technology for small-scale and decentralized energy generation applications. In addition to the technical aspects, the project serves as a platform for demonstrating the application of product design and development practices within an Integrated Design Project (IDP) environment, enabling undergraduate engineering students to develop essential competencies in project planning, design decision-making, risk assessment, teamwork, and sustainable engineering practice.

The primary scope of this project encompasses the design, fabrication, and empirical testing of a prototype pico-hydroelectric generator. Specifically, the study is delimited to the technical design of the turbine, the integration of the electrical generator, and subsequent performance evaluations conducted under strictly regulated water flow parameters. The operational capacity of the proposed system is intentionally restricted to

low-power applications, such as powering LED fixtures and charging mobile devices. Consequently, extended longitudinal field deployments and large-scale commercial implementations fall beyond the designated purview of this research.

METHODOLOGY

Concept Design

Pico-hydropower systems present an innovative, decentralized alternative, generating electricity from low-volume water flows such as small streams or open drains (Figure 1). Characterized by their compact footprint, cost-effectiveness, and ecological viability, these systems are optimally suited for localized, small-scale energy generation. Despite the abundance of accessible water resources in tropical regions such as Malaysia, small-scale hydropower remains significantly underutilized. Consequently, numerous rural and off-grid communities continue to experience limited or erratic access to electricity. Existing energy alternatives often prove financially prohibitive, environmentally detrimental, or logistically difficult to maintain. Therefore, there is a critical imperative to develop a cost-effective, sustainable, and highly efficient pico-hydroelectric generator capable of fully exploiting low-flow water sources. Current literature underscores the substantial potential of pico-hydropower (PHP) as a renewable energy solution, particularly for rural and remote electrification. Wan Simpson et al. (2006) identify PHP as an efficient, reliable, and economically viable alternative to conventional large-scale hydroelectric systems, noting that its reduced operational scale inherently minimizes environmental degradation. Within the Malaysian context, research indicates that despite the nation's significant hydroelectric potential, PHP technology remains in its nascent stages. Broader implementation is primarily hindered by a lack of public awareness, insufficient technical expertise, and existing infrastructural deficits. The pragmatic application of PHP is further substantiated by Ulrich et al. (2020), who investigated its viability as a supplementary energy source for building infrastructure. Their research emphasizes that PHP systems can generate electricity without necessitating massive dam construction or inducing severe ecological disruption. By utilizing fundamental mechanical components such as pipelines, turbines, and generators the investigated systems successfully produced up to 198W of electrical power. These findings validate PHP's efficacy as a robust supplemental or auxiliary power source for domestic and structural applications.



Figure 1: Benchmark

During the conceptual generation phase, a morphological chart was employed to systematically derive an

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array of design iterations for the pico-hydropower generator (Figure 2). This methodology involves decomposing the product into its primary functional modules, specifically the turbine configuration, shaft arrangement, support frame, and electrical generator assembly. By cataloguing various viable solutions for each module, multiple design concepts were synthesized. This approach facilitates a rigorous, structured evaluation of potential design alternatives, thereby ensuring the selection of an optimal configuration based on empirical analysis.

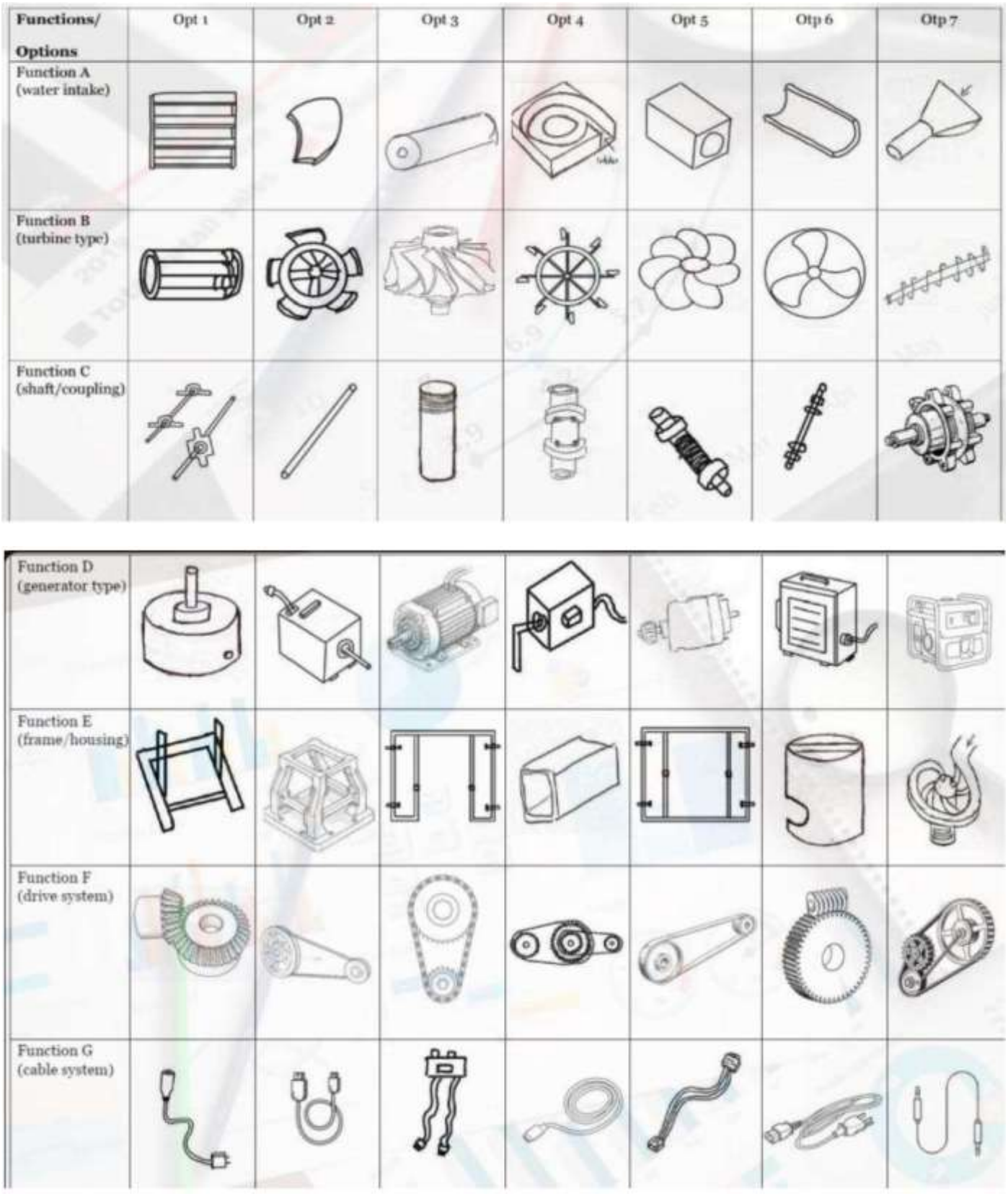


Figure 2 Morphological chart

The first concept (Concept 1) utilizes a mini waterwheel turbine coupled with a hydroelectric generator. This design prioritizes structural simplicity, rendering it particularly suitable for open-drain environments characterized by low-velocity water flow. By employing a direct-drive mechanism, this configuration emerges as a highly practical solution for small-scale power generation. Furthermore, its streamlined architectural design facilitates efficient fabrication, reduces overall capital expenditure, and simplifies long-term maintenance requirements when contrasted with more intricate turbine systems.

Concept 2 explores the implementation of a cylindrical turbine as an alternative geometry. In contrast to the mini waterwheel turbine, the cylindrical design maximizes the surface area available to induce rotational motion. This concept was developed to investigate whether a more compact turbine profile could enhance kinetic energy capture while maintaining suitability for the restricted spatial constraints of narrow open drains. Nevertheless, this geometry presents increased complexity regarding both its structural fabrication and the analysis of its hydrodynamic flow characteristics.

The third design (Concept 3) iteration explores the integration of a spiral turbine with a hydroelectric generator. The selection of a spiral geometry is predicated on its capacity to channel water flow more fluidly across the blade surfaces, potentially enhancing rotational consistency despite fluctuations in hydraulic conditions. This concept was developed to investigate the feasibility of achieving superior flow utilization and more uniform energy conversion. However, the inherent geometry of the spiral configuration necessitates significantly more advanced design and manufacturing processes when compared to conventional, less complex turbine architectures.

Concept 4 presents an alternative iteration of the spiral-based turbine, utilizing a distinct combination of functional elements derived from the morphological chart. While this design preserves the fundamental operating principle of the previous spiral concept, it features a revised arrangement of critical components specifically the shaft, support structure, and transmission assembly. This iteration was engineered to determine whether reconfiguring these elements could optimize installation flexibility, enhance conversion efficiency, or improve overall maintenance accessibility.

Design for Manufacture and Assembly (DFMA) principles were systematically applied to enhance production efficiency, streamline assembly processes, and simplify maintenance. The design utilizes simplified geometries and standardized components to minimize manufacturing lead times and reduce total production costs. For instance, the use of identical turbine blades facilitates efficient batch production, while the selection of lightweight materials, such as PVC, optimizes handling and assembly ergonomics. Furthermore, the architecture employs modular, bolt-on components, enabling rapid installation, removal, and replacement without the requirement for complex mechanical procedures. Additionally, the inherent symmetry of the design mitigates the risk of assembly errors and ensures precise component alignment. Consequently, the application of DFMA renders the mini waterwheel turbine significantly more cost-effective to produce, intuitive to assemble, and practical for real-world deployment.

Failure Mode and Effects Analysis (FMEA) serve as a systematic methodology for identifying prospective system failures and evaluating their subsequent impact on overall operational performance. For a pico-hydroelectric system, FMEA is critical to ensuring high levels of reliability, durability, and consistent energy output. This analytical framework investigates potential failure mechanisms across both the design and operational phases, facilitating the development of a more robust system resilient against breakdowns and stochastic performance degradation.

Engineering Analysis

The pico-hydroelectric generator for open drain applications is engineered to extract electrical power from the consistent kinetic energy present in open-drainage networks. This device utilizes a compact turbine-generator assembly to convert hydraulic flow into usable electricity. While open drains are prevalent in urban and semi-urban landscapes, their capacity for decentralized energy production remains largely untapped. This innovation presents a sustainable, cost-effective strategy for localized energy generation,

providing a viable utility for domestic, commercial, and educational environments. However, realizing this potential requires overcoming significant engineering constraints to ensure optimal operational performance. The system's efficiency is susceptible to fluctuations in water depth and irregular flow dynamics inherent in drainage channels. Moreover, the efficacy of energy capture is heavily dependent on turbine blade geometry; suboptimal designs fail to effectively harness low-flow conditions. Additionally, material selection is critical, as continuous exposure to aqueous pollutants and environmental debris accelerates corrosion and increases maintenance requirements. Consequently, the primary engineering challenge involves designing an optimized system that achieves a functional equilibrium between high energy conversion efficiency, structural durability, economic feasibility, and ease of maintenance in real-world conditions.

The primary external load acting on the system is the kinetic force generated by the flowing water as it strikes the turbine blades (Figure 3). As water enters through the intake channel, it exerts pressure and impact forces that initiate and sustain the rotational motion of the turbine, with the resulting force depending on the water's velocity and volumetric flow rate. In addition to these hydraulic forces, gravitational loads act on the turbine, generator, and supporting frame, influencing the overall structural stability of the system. The system is also subjected to internal loads, including coupling tension, bearing friction, and the torque transmitted through the turbine shaft. Effective management and reduction of these loads are crucial for minimizing mechanical losses, maintaining structural integrity, and enhancing the overall efficiency of energy conversion. The energy transformation process begins when the kinetic energy of the incoming water flow is converted into rotational mechanical energy as it strikes the turbine blades. The resulting torque is then transmitted through the main shaft to the drive system, which regulates and amplifies the rotational speed before transferring it to the generator. Within the generator, electromagnetic induction converts the mechanical energy into electrical energy for power generation. At the same time, the rotating components exert structural loads on the support frame, which distributes these forces safely to the foundation. Through appropriate material selection, secure mounting mechanisms, and precise component alignment, the system can effectively withstand and manage these loads, preventing structural deformation or failure while maintaining operational stability and reliability during continuous operation.

The hydrodynamic force produced by the incoming water as it strikes the turbine blades initiates rotational motion and generates torque along the turbine shaft. To ensure stable operation, maintain shaft alignment, and minimize frictional losses, the shaft is supported both radially and axially by bearings securely mounted to the structural frame. The mechanical power generated by the turbine is transmitted through a multi-stage drivetrain system, beginning with a 55 mm sprocket mounted on the turbine shaft that drives Chain 1. This rotational motion is then transferred to an intermediate gear-bearing assembly, after which Chain 2 conveys the power to a 65 mm sprocket and finally to a 73 mm sprocket connected to the generator input shaft. The progressive increase in sprocket diameter enables effective impedance matching between the turbine's high-torque, low-speed output and the generator's rotational speed requirements, thereby enhancing power transmission efficiency and ensuring optimal electrical energy generation.

The integration of virtual testing environments significantly reduces the costs and time associated with repeated physical prototyping and fabrication. By allowing engineers to predict performance characteristics, identify potential design flaws, and optimize configurations within a digital environment, ANSYS enhances product reliability, safety, and overall design efficiency. In this project, ANSYS was utilized to conduct structural analysis of the generator system, evaluating its response to applied loads through the assessment of stress distribution, strain behaviour, and deformation characteristics. The results of this analysis provide critical insights into the structural integrity and stability of the design under normal operating conditions, ensuring that all components can safely withstand expected mechanical loads (Table 1). Consequently, the application of ANSYS plays a vital role in modern engineering design and optimization by enabling computational validation of the system before fabrication, thereby ensuring that the final product is robust, reliable, and suitable for real-world implementation.

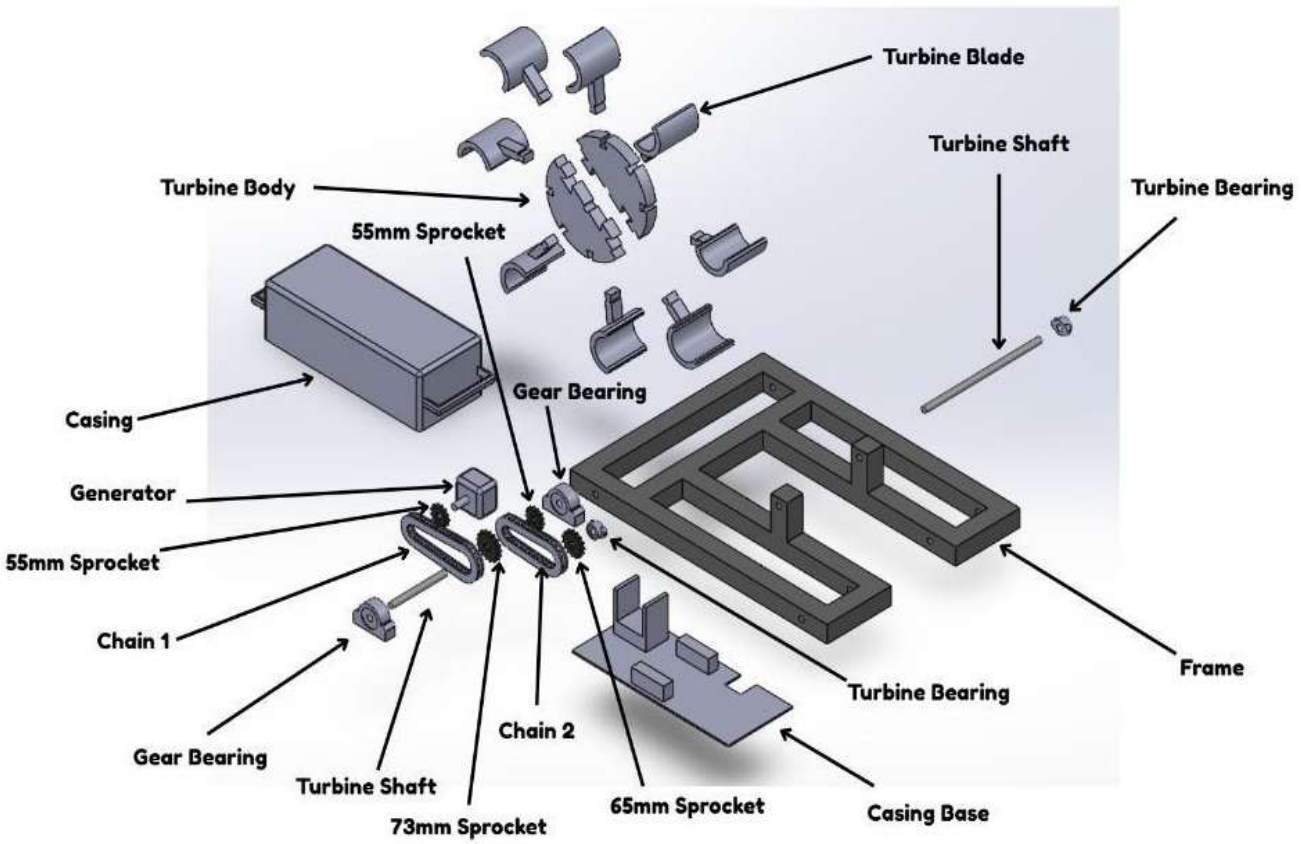


Figure 3. Mini waterwheel turbine free body diagram

Table 1. Components and materials

Material	Component	Density	Young's	Yield	Key Use Purpose
Mild Steel	Base, Shaft	7850	200	250	Main structural support, torque
Carbon Steel	Sprocket,	7850	210	310	High-strength wear components under
Stainless Steel	Bearing,	8000	193	215	Corrosion-resistant rotating and
Acrylic (PMMA)	Generator	1180	3.2	~70	Enclosure/cover, lightweight protective
PETG	Turbine	1270	2	~50	Lightweight rotating
					component, moderate stress application

Prototype Development

The physical prototype was developed by translating the selected three-dimensional Computer-Aided Design (CAD) model into a functional small-scale engineering system. The primary structural support frame was fabricated from standard 2" × 2" × 1.6 mm mild steel hollow sections, which were carefully measured, marked, and cut to the required dimensions using an angle grinder (Table 2). Following the cutting process, all edges were filed and deburred to remove sharp surfaces and improve assembly safety. The prepared steel members were then accurately aligned on a flat welding table, securely clamped to minimize thermal distortion, and tack-welded at each joint to establish a rigid and geometrically accurate frame structure. The mini waterwheel turbine and blade assembly were designed using SolidWorks software, after which the digital model was exported as an STL file for fabrication through Fused Deposition Modeling (FDM) 3D printing using PETG material. The turbine components were printed in modular sections and assembled using a rubber mallet to achieve tight mechanical interference fits. Once completed, the turbine assembly was mounted onto the shaft and installed within the frame structure. The power transmission system was subsequently integrated by measuring and cutting the drive chains to the required link lengths, ensuring

precise engagement across the multi-stage sprocket arrangement consisting of 55 mm, 65 mm, and 73 mm sprockets. To enhance durability and protect the mild steel frame from water-induced oxidation, rust formation, and long-term operational corrosion, the entire frame assembly was thoroughly coated with black anti-corrosion spray paint. This fabrication process resulted in a robust and functional prototype capable of demonstrating the intended mechanical and energy conversion performance.

The chains were installed over the sprockets to complete the power transmission system, enabling mechanical power generated by the turbine to be efficiently transferred to the generator. To protect sensitive electrical components from water exposure, a specialized water-resistant protective casing was fabricated from acrylic or polymer sheet material and mounted directly around the generator. This enclosure serves as a barrier against water splashes and moisture intrusion commonly encountered in open-drain operating environments, thereby safeguarding the generator's copper windings and enhancing operational reliability. Furthermore, all material selections and manufacturing processes were carefully determined based on the expected operational and structural demands of the system, including the estimated 70 N hydrodynamic force obtained from the ANSYS structural analysis. By aligning the design, material properties, and fabrication methods with the predicted loading conditions, the prototype achieves the necessary strength, durability, and safety requirements for stable and efficient operation.

Testing and Commissioning

To check device capabilities and evaluate the relationship between flow kinetics and generated electromotive force (EMF) via electromagnetic induction, the prototype was tested under active fluid flow settings:

$Q = V/t$

Q = Volumetric Flow Rate

V = Volume (m^3 or liters)

t = Time Elapsed (seconds or minutes)

v = Voltage Output (volt)

The experimental results from the three test runs demonstrate a clear and positive linear relationship between the water's volumetric flow rate (Q) and the electrical voltage generated by the system. In Test Run 1, a baseline voltage of 2.00 v was produced at a flow rate of 3.6 L/s. When the flow rate increased to 4.2 L/s in Test Run 2, the generated voltage rose to 2.33 v. The highest performance was observed in Test Run 3, where a peak flow rate of 4.8 L/s resulted in a maximum voltage output of 2.67 v. From an engineering standpoint, increasing the volumetric flow rate supplies greater kinetic energy to the 3D-printed turbine blades, causing the turbine and primary shaft to rotate at higher speeds. This rotational motion is subsequently amplified through the chain-and-sprocket transmission system, increasing the rotational speed of the DC motor's internal magnets. Based on Faraday's Law of Electromagnetic Induction, a faster rate of change in magnetic flux produces a correspondingly higher induced voltage. The consistent and proportional increase in voltage across all test runs indicates that mechanical losses, including friction within the KFL/KP pillow block bearings and transmission components, remain low and stable throughout operation. The peak output voltage of 2.67 v demonstrates the feasibility of the proposed prototype as a practical, low-maintenance energy harvesting system, with the potential to power low-energy devices, monitoring equipment, and environmental sensors deployed within urban drainage networks.

Table 2. Manufacturing process

Components	**Assigned Material**	**Manufacturing Process**	**Engineering Justification**
Support	Mild Steel	Cutting	Provides a high factor of safety, distributes

Frame and Base	Hollow Section (2" × 2" × 1.6 mm)	(Grinding) & Metal Arc Welding	rigid mechanical loads, and ensures structural stability under constant fluid dynamics.
Turbine Blades and Body	Polyethylene Terephthalate Glycol (PETG)	FDM 3D Printing (Additive Manufacturing)	High impact strength, lightweight for low inertia, excellent water resistance, and enables identical part reproducibility.
Protective Casing	Clear Polymer	Manual Cutting & Mechanical Fastening	Excellent optical clarity for viewing internal drive operation while providing a watertight barrier against open-drain spray.
Transmission Shafts	Standard Carbon Steel	Machining / Turning (Standardized Part Selection)	High torsional rigidity to transmit rotational torque from the turbine to the speed-increasing sprocket loops without warping.
Sprockets and Chains	Hardened Carbon Steel	Assembly / Alignment Fitting	Provides the rigid mechanical durability required to withstand multi-stage speed amplification (55 mm to 73 mm steps) under constant loads.

Finance and Costing

The direct capital expenditure required to procure raw materials and functional subassemblies for the operational prototype is itemized in Table 3.

Table 3. Bill of materials

No	Material	Quantity	Price
1	Stainless Steel Round Capillary Seamless Straight Tube 4x2mm	1	24.35
2	Hex Bolts M18 x 100	4	14.4
3	Hex Nuts M18 x 2.5 x 27	4	3.6
4	Mild Steel Square Hollow 2'' x 2'' x 1.6 mm, 1000mm-length	7	111.99
5	Pillow Block Bearing KFL	2	16.8
6	Pillow Block Bearing KP	2	13.8
7	Stainless Steel Round Capillary Seamless Straight Tube 17mm x	1	34.09
8	3D Printing Turbine Wheel	2	138.6
9	3D Printing Turbine Blade	8	314.4
10	Chain	1	20
11	Iron Cutter	1	1.7
12	3 Ton Epoxy	1	5.7
13	Epoxy Glue	4	11
14	Pony Storage Box (8.5L)	1	10.5
15	Hiro Zinc Hinge	1	2.6
16	Hiro Furniture	1	2.6
17	Spray Paint Black 400ml/400g	2	11.8
18	Micro DC 12V Fan Motor	1	20.79
Total Cost in Malaysian Ringgit (RM)			758.72

Engineering Drawing

Figure 4 show the components and complete assembly model. Figures 5-8 shows the components' drawings.

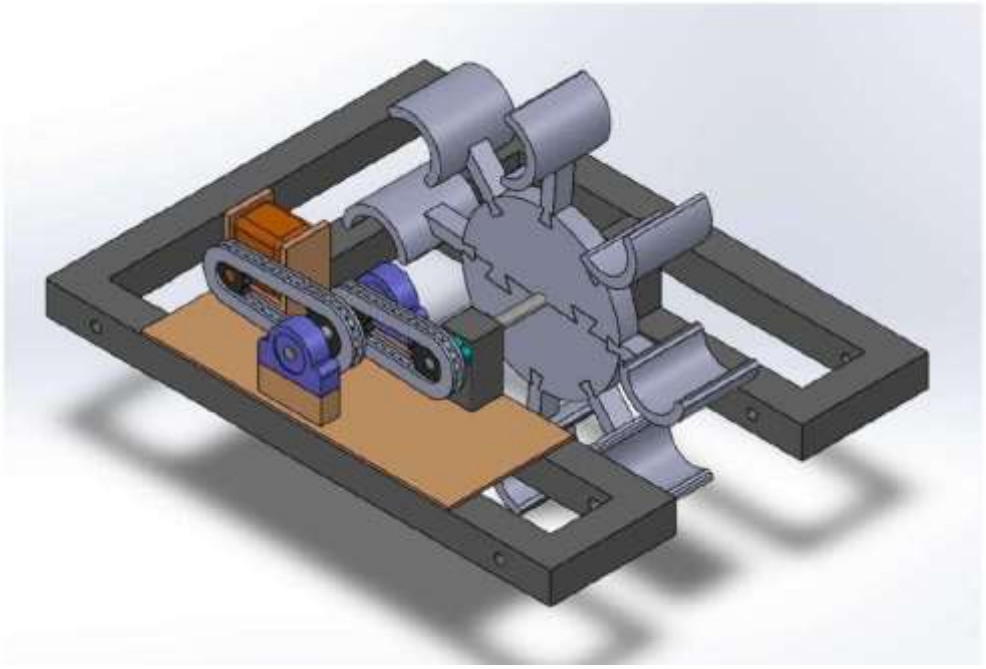


Figure 4. Complete assembly model of the Pico-hydro

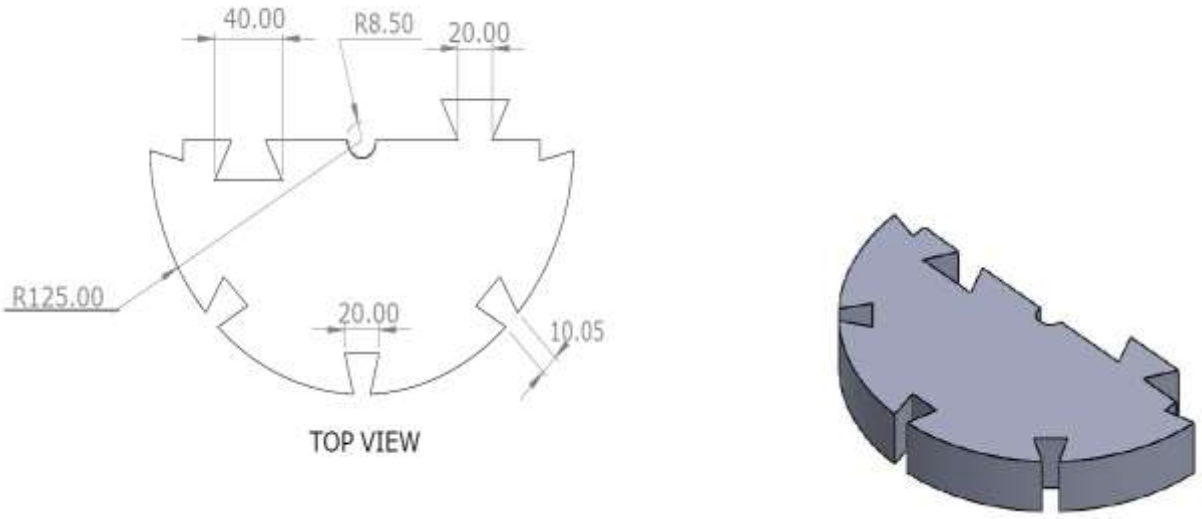


Figure 5. Water scoop holder

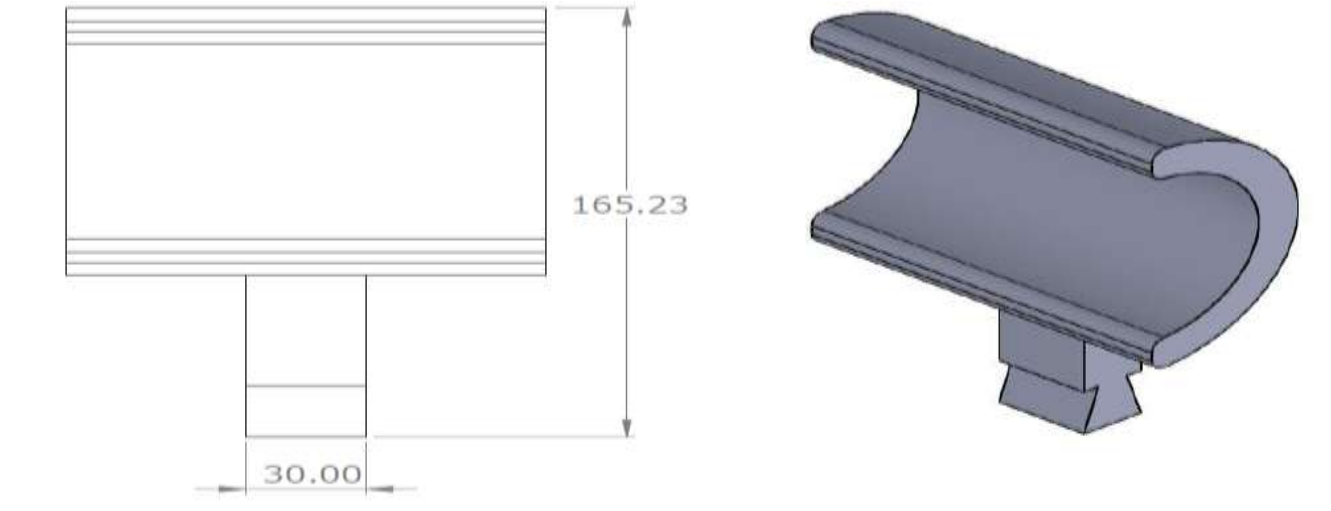


Figure 6. Water scoop

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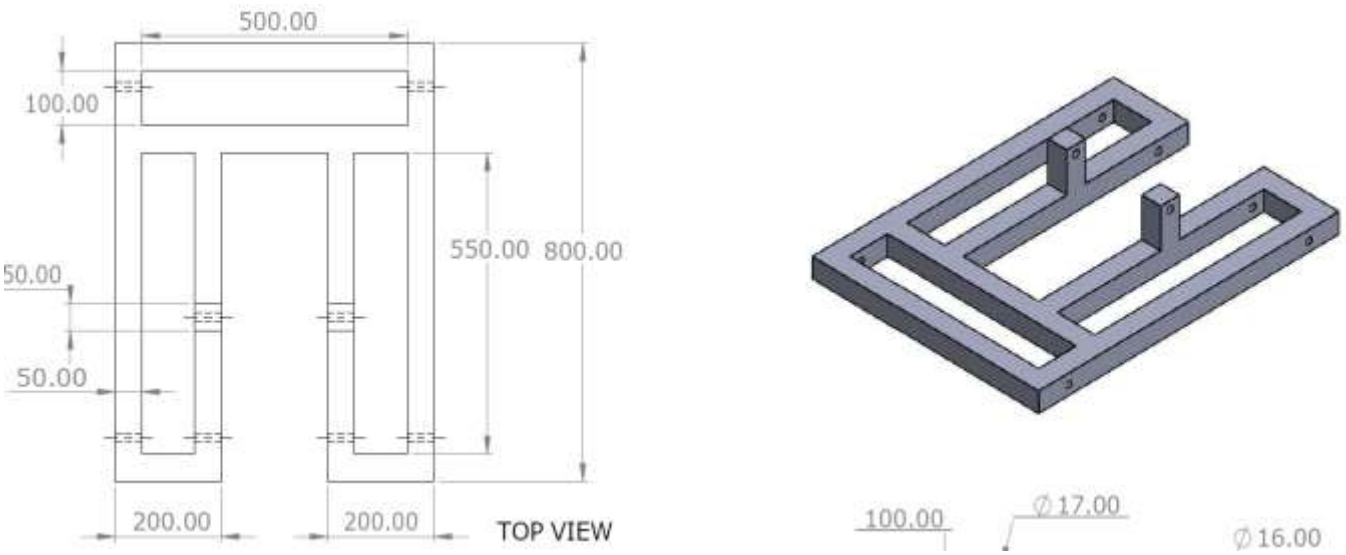


Figure 7. Structure frame

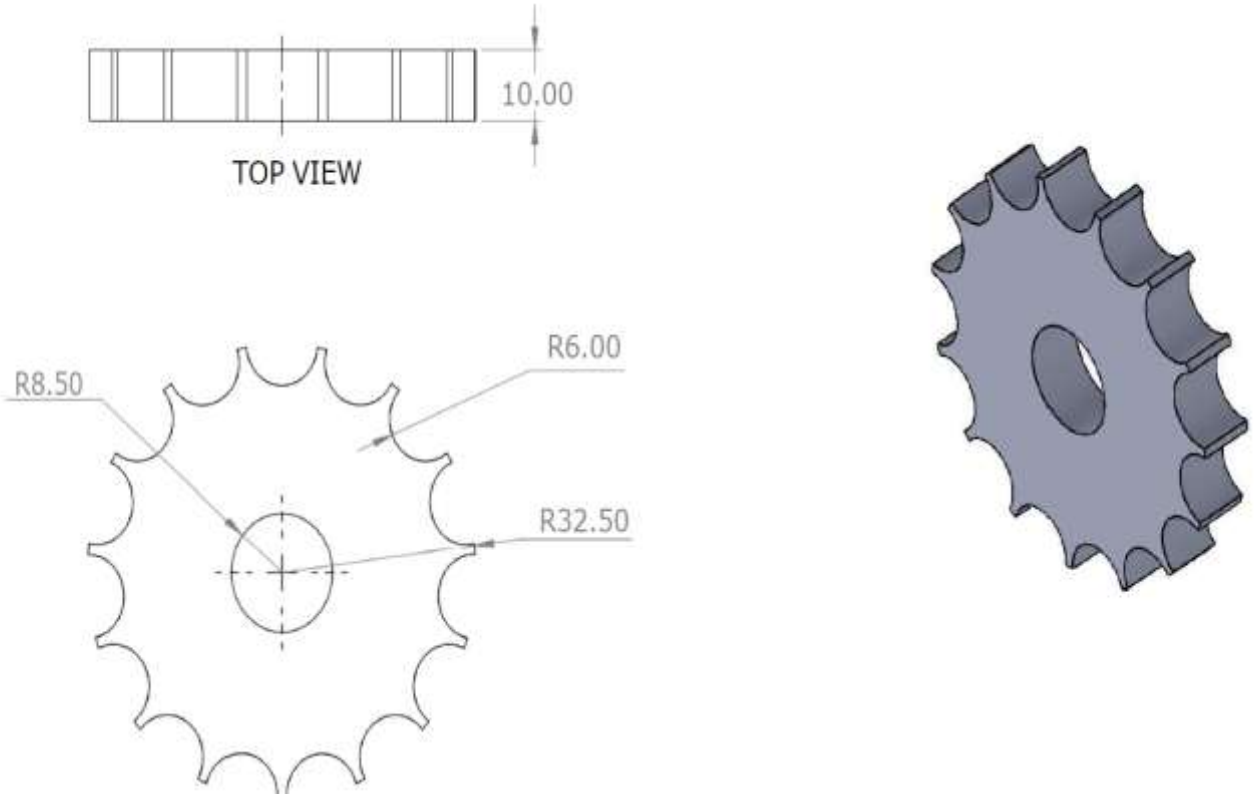


Figure 8. Gear to rotate generator

RESULTS AND DISCUSSION

To ensure a rigorous and objective selection process, a weighted decision matrix (Figure9) was utilized to evaluate the proposed design concepts. Each concept was assessed against critical performance metrics, including operational efficiency, maintenance requirements, economic viability, structural complexity, and suitability for low-flow hydrodynamic conditions. To reflect their varying degrees of importance to the project objectives, each criterion was assigned a specific weighting factor. These weights were applied to the raw scores to derive a total weighted score for each design. The analysis indicated that the mini waterwheel turbine achieved the highest cumulative score, demonstrating an optimal equilibrium between performance, cost-efficiency, and practical implementation. Consequently, this design was selected as the definitive configuration for the project.

The Factor of Safety (FoS) analysis indicates strong structural integrity and resilience, with safety factor values ranging from a minimum of 2.9122 to a maximum of 15. Since all FoS values remain well above the commonly accepted minimum threshold of 2.0, the structure operates safely within the elastic limits of its materials, eliminating the likelihood of plastic deformation or catastrophic failure under normal operating conditions. In addition to its structural robustness, the system demonstrates reliable power generation performance. Based on an influent flow rate of 0.285 L/s and a hydraulic head of 6 m, the theoretical hydraulic power input (P_{in}) was calculated to be 16.817 W. Assuming a conservative overall system efficiency (η) of 50%, the estimated electrical power output (P_{out}) is 8.408 W. These results confirm that the proposed design satisfies its technical and operational requirements by providing both structural reliability and sustainable energy production. Consequently, the system represents a practical, cost-effective, and environmentally sustainable solution for decentralized small-scale power generation applications (Figure 9).

Table 4. Weighted decision matrix

No.	Design / Criteria	Archimedes Screw Turbine	Mini Water Wheel Turbine	Cylindrical Turbine	Spiral Turbine
1	Efficiency	Baseline	−	S	+
2	Cost	Baseline	+	+	S
3	Complexity	Baseline	+	S	S
4	Maintenance	Baseline	+	S	S
5	Environmental	Baseline	+	S	+
6	Low Head Water	Baseline	+	S	+
7	Scalability	Baseline	−	+	−
	Total (+)		5	1	3
	Total (−)		2	0	1
	Total Score		3	1	2
	Rank		1	3	2

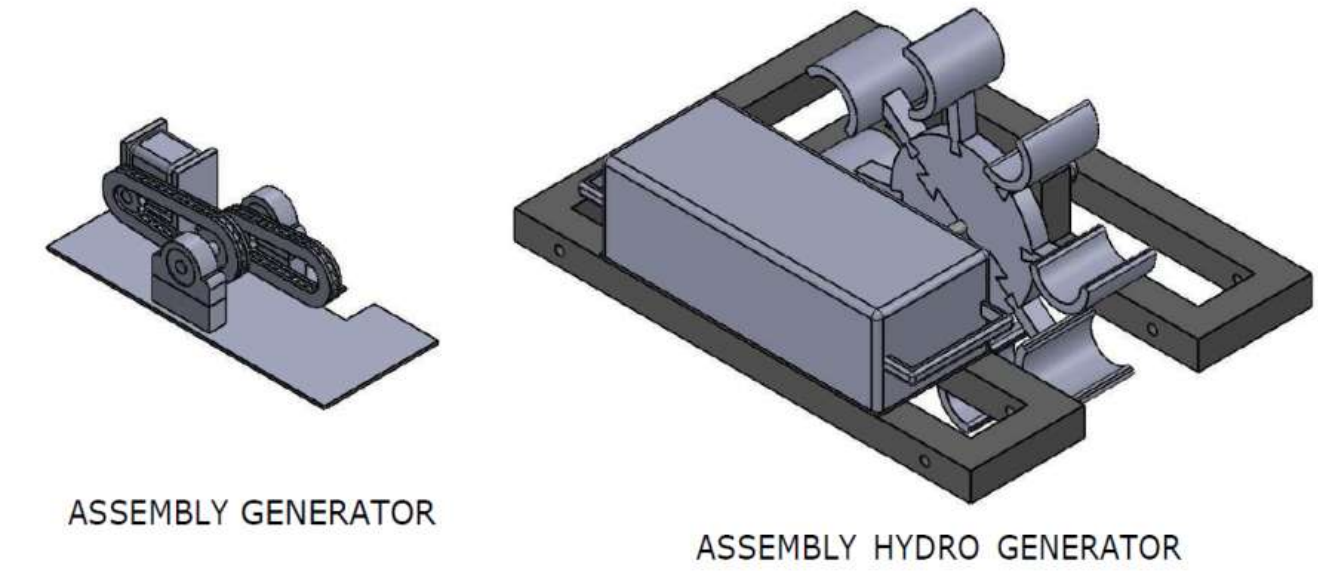


Figure 9. Complete model with gear cover

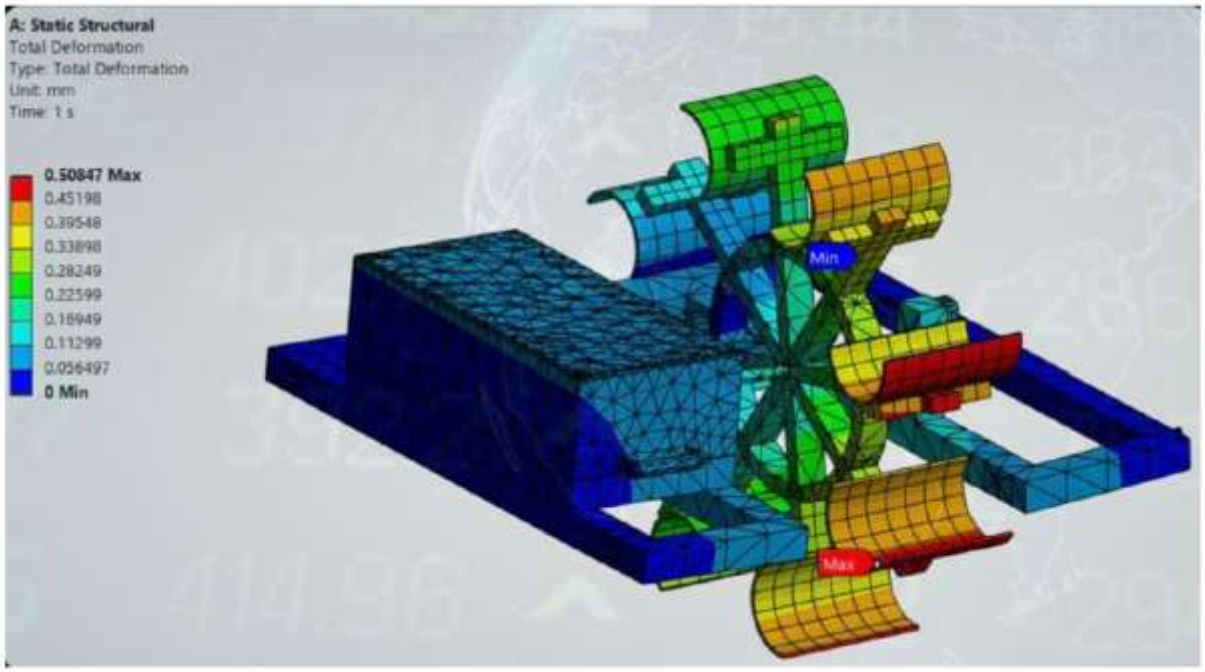


Figure 10. FEA

The proposed prototype (Figure 11 and 12) contributes directly to the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), by harnessing renewable energy from the otherwise wasted kinetic energy present in urban and semi-urban drainage systems. Unlike conventional hydropower technologies that often require significant infrastructure such as dams and may disrupt natural ecosystems, the system generates electricity with minimal environmental impact while preserving the existing water flow. The use of 3D-printed PETG components and acrylic materials further enhances sustainability by reducing material consumption and manufacturing waste. Additionally, the prototype incorporates reusable and replaceable components that support circular economy principles, extending the system's operational lifespan and minimizing resource depletion. Its modular design enables individual parts, such as turbine blades, bearings, or transmission components, to be replaced independently when damaged, eliminating the need to discard the entire assembly. As a result, the prototype offers an environmentally responsible, cost-effective, and sustainable solution for decentralized renewable energy generation while supporting long-term climate action and resource efficiency objectives.



Figure 11. Actual working prototype

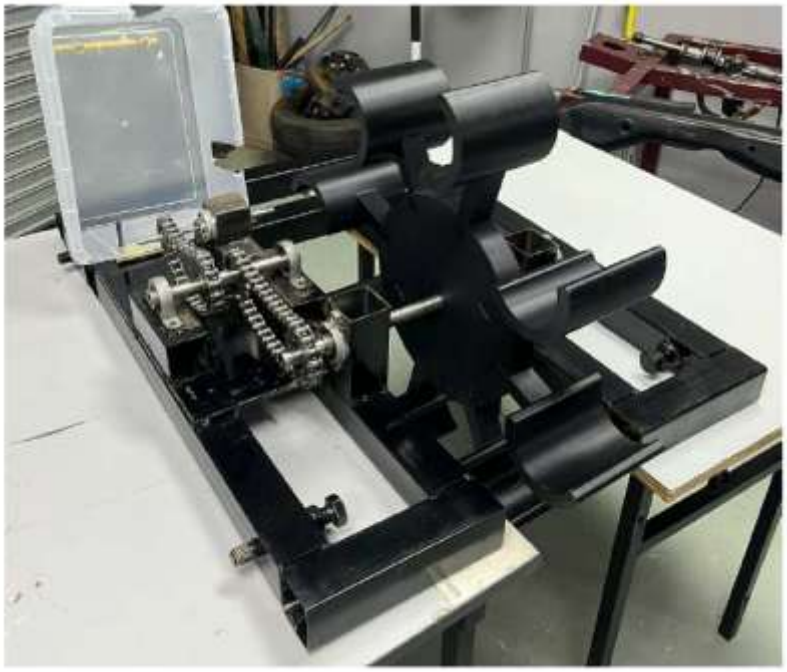


Figure 12. Chain and sprockets

The total cost of developing the prototype was RM 758.72, with the largest expenditure attributed to the 3D-printed turbine wheels and blades, which accounted for RM 453.00, representing approximately 59.7% of the total project budget. While additive manufacturing proved highly effective for rapid prototyping, design validation, and performance testing, it remains relatively costly for small-scale production. To improve economic viability for future commercialization, the turbine components could be manufactured using injection molding with durable engineering plastics, significantly reducing production costs while maintaining performance and reliability. Through this manufacturing optimization, the estimated unit cost could be reduced to below RM 300.00, enhancing the affordability, scalability, and market competitiveness of the open-drain pico-hydro system. Consequently, the proposed design demonstrates strong potential for large-scale deployment as a cost-effective and sustainable renewable energy solution for decentralized power generation applications.

CONCLUSION

The aim of this project was to investigate the potential of low-head water flow in open drainage systems as an alternative source of small-scale renewable energy. To achieve this objective, a pico-hydro electric generator was designed, analyzed, and physically fabricated to harness the kinetic energy of moving water within open drains and convert it into electrical energy suitable for low-power applications in urban and semi-urban environments. The design process began with concept generation and selection using morphological charts and a weighted Pugh evaluation method, through which the mini waterwheel turbine configuration emerged as the preferred design, achieving the highest weighted score of 4.10 based on efficiency, cost, complexity, maintenance requirements, and suitability for low-head conditions. Design for Manufacturing and Assembly (DFMA) principles were incorporated to ensure ease of fabrication and maintenance, while Failure Mode and Effects Analysis (FMEA) was conducted to identify and mitigate potential failures in critical components such as bearings, chains, sprockets, and turbine blades. Structural validation was performed using ANSYS static structural analysis, which showed a maximum total deformation of only 0.508 mm under the calculated hydrodynamic load of 70 N. The minimum factor of safety obtained was 2.912, exceeding accepted engineering requirements and confirming that the mild steel frame and overall assembly would remain structurally stable during continuous operation. Furthermore, the theoretical bending stress was calculated at 42.2 MPa, significantly lower than the 250 MPa yield strength of mild steel, indicating no risk of permanent deformation under normal operating conditions. Experimental testing of the fabricated prototype was conducted under three controlled flow conditions, with results demonstrating a positive linear relationship between volumetric flow rate and output voltage. The highest

voltage generated was 2.67 V at a flow rate of 4.8 L/s, confirming the system's capability to convert hydraulic energy into useful electrical power. The total prototype cost was RM 758.72, and the project successfully aligned with Sustainable Development Goal (SDG) 7, Affordable and Clean Energy, as well as SDG 13, Climate Action, by promoting renewable energy generation through the utilization of otherwise wasted water resources. Overall, the developed open-drain pico-hydro electric generator has been demonstrated to be a structurally robust, technically feasible, and economically promising renewable energy solution for decentralized small-scale power generation, particularly in resource-limited communities and urban drainage environments.

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