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From Proof of Concept to Industrial Deployment: Application of Multi-Level FBS, TRIZ and Lean Six Sigma to Wave Energy Conversion

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Abstract

This study presents a structured, integrated methodology that combines Lean Six Sigma and TRIZ to support the transition of a wave energy converter from a laboratory proof-of-concept to an industrializable system. It addresses key techno-economic challenges, including high cost, limited efficiency, maintenance constraints, and scalability limitations, by systematically resolving underlying technical contradictions through the DMAIC framework. In the Define phase, industrial requirements were established, focusing on robustness, maintainability, and performance under irregular wave conditions. A laboratory-scale prototype based on a point absorber coupled to a linear generator was developed to validate the wave-to-wire conversion concept. The Measure phase quantified system performance, recording peak voltages up to 3.7 mV and demonstrating a correlation ($R^2 = 0.75$) between experimental and theoretical results. The analyze phase integrated performance data with Function-Behaviour-Structure analysis to identify root causes and key contradictions in system scaling. In the Improve phase, TRIZ tools were used to generate optimised design solutions, including coil redesign, hydrodynamic improvements, and a segmented generator architecture. Finally, the Control phase outlines a roadmap for a Generation 2 prototype under real sea conditions. Overall, the study contributes a systematic, need-driven framework that bridges the gap between conceptual validation and industrial deployment, while proposed design solutions require further experimental validation.

1. Introduction

The global energy crisis, combined with the climate emergency, demands a rapid transition to renewable, sustainable, and low-carbon energy sources. In this context, the scientific community is increasingly focusing on marine energy, particularly wave energy, due to its high energy potential and relative predictability. However, its exploitation at an industrial scale remains limited, largely due to persistent technical challenges (efficiency, reliability in marine environments), economic factors (high maintenance costs), and methodological gaps (lack of integrated approaches for scaling up).

Globally, oceans cover approximately 71% of the Earth's surface and offer an average energy density of 2 kW per meter of wave front [1]. Thanks to its geographical location in the Indian Ocean, Madagascar has a coastline of about 5,000 km directly exposed to waves. This largely untapped energy resource represents a major opportunity for local energy development and reducing dependence on fossil fuels. However, existing wave energy solutions are often complex, costly, and poorly adapted to the irregular wave regimes characteristic of Madagascar's coastal areas and do not fully meet local constraints on simplicity, robustness, and affordable maintenance.

To ensure that the proposed design is not only technically sound but also operationally viable in the target environment, this study begins by translating the specific contextual constraints of Madagascar into quantifiable engineering requirements. The logistical challenges of accessing remote coastal sites, characterised by limited supply chains and a need for basic tools, impose strict maintenance design criteria, targeting a mean time to repair (MTTR) of less than 48 hours with locally available resources. Similarly, the economic ceiling for the levelized cost of energy (LCOE) is set to be competitive with existing diesel-based solutions in isolated villages, which are typically high, thereby defining a strict capital expenditure (CAPEX) and operational expenditure (OPEX) budget for the system. Finally, the highly irregular wave climate along Madagascar's coastline, characterised by significant wave height variability exceeding 40% during a single season, is used as the primary boundary condition for generator sizing and control logic. By anchoring the entire design process to these quantified targets (maintainability, cost, and wave irregularity tolerance), the subsequent TRIZ analysis and Lean optimisation are grounded in a specific, measurable set of industrial requirements, ensuring that the final concept is genuinely adapted to its intended context of use.

In this context, the central issue of this study is the following question: how can we design a wave energy system that is simple, reliable, and efficient, adapted to Madagascar's environmental, technical, and economic conditions, and capable of evolving toward industrial deployment? To address this issue, this work is based on several hypotheses and adopts an innovative methodological approach. It is first assumed that the oscillatory motions induced by waves can be efficiently converted into electrical energy using a linear generator, enabling direct conversion with reduced mechanical losses. The choice of a point absorber-type wave energy device is considered particularly suitable for moderate and irregular wave regimes. Furthermore, the electrical performance of the system is assumed to be highly dependent on wave parameters, notably amplitude and frequency.

Faced with the limitations of conventional design approaches, this study proposes integrating TRIZ (Theory of Inventive Problem Solving) and Lean methodologies. This combination aims to resolve the technical contradictions inherent in scaling up, such as performance vs cost or reliability vs simplicity, via

TRIZ, and to optimise the entire value chain, from design to deployment, by eliminating waste and improving efficiency via Lean. The goal is to transform an experimental proof of concept into an industrializable system that is robust, economically viable, specifically adapted to the Malagasy context, and capable of significantly contributing to the energy autonomy of isolated coastal areas. From this perspective, this manuscript is structured into six parts. The first part is dedicated to a literature review and the presentation of the theoretical framework related to wave energy and linear generator conversion systems. The second part describes the adopted methodological approach, including theoretical modeling, prototype design, and the setup of the experimental apparatus. The third part presents and analyses the results of modelling and small-scale experimental tests. The fourth part discusses these results and identifies the study's limitations. The fifth part introduces the integrated TRIZ-Lean approach for optimisation and industrial-scale deployment. Finally, the sixth part presents the conclusions and prospects of this work.

2. Literature Review

Wave energy, a fascinating renewable source whose conceptual exploitation dates back several centuries, has undergone structured development marked by significant advances and persistent challenges. Although Pierre-Simon Girard filed a patent as early as 1799, the 19th century remained characterised by limited experimentation, hindered by technological constraints and a lack of industrial interest [2]. The 20th century marked a turning point with the development of foundational technologies. In 1976, Japanese engineer Yoshio Masuda developed KAIMEI, a buoy system using oscillating water columns, thus laying the groundwork for modern technologies [3]. Simultaneously, the United Kingdom launched a major research program that gave rise to several fundamental concepts: Stephen Salter's "Duck," the National Engineering Laboratory's "NEL OWC," and Sir Christopher Cockerell's "Cockerell raft."

The 21st century has seen accelerated developments, driven by European policies favorable to renewable energy. In 2008, the Pelamis system became the first commercial converter connected to a national grid off the coast of Portugal. However, the bankruptcy of Pelamis Wave Power in 2014 illustrated the persistent economic challenges of the sector [2].

2.1. Diversity of Technological Approaches and Their Limitations

Today, research explores several technological pathways, each with its advantages and constraints:

- Oscillating Water Column (OWC) Systems: Using pressure variations in an air chamber, they offer indirect conversion but present challenges in sealing and turbine maintenance.
- Attenuators (like Pelamis): These articulated structures follow the wave profile but involve high mechanical complexity and significant maintenance costs.
- Overtopping Systems (like Wave Dragon): These massive platforms use the overtopping principle to accumulate water, requiring heavy infrastructure poorly suited to isolated coastal areas.
- Point Absorbers (like PowerBuoy): Distinguished by their simplicity and ability to capture

multidirectional energy, they represent a promising solution for modular deployments.

- Direct Linear Generators (Sea-based project): Directly linking wave motion to electricity production, they offer simplified conversion but require optimisation of electromagnetic coupling [3].

2.2. Persistent Challenges and Techno-Economic Barriers

Despite this diversity of approaches, several common challenges hinder the large-scale deployment of wave energy:

- Mechanical Complexity: Most devices involve complex transmission systems (hydraulic, pneumatic, or mechanical) sensitive to the corrosive marine environment.
- High Maintenance Costs: Difficult access to offshore installations and the need for specialised interventions significantly increase the levelized cost of energy (LCOE).
- Adaptation to Variable Wave Regimes: Few systems are optimised for the irregular regimes characteristic of many coastal areas, particularly in Madagascar.
- Lack of Integrated Methodological Approaches: The literature reveals a deficiency in the systematic application of innovation and optimisation methodologies throughout the development cycle, from design to industrial deployment.

2.3. Identification of the Research Gap

This review highlights a significant gap in the existing literature. While many prototypes have been developed and tested, few studies adopt an integrated methodological approach combining inventive technical optimisation (TRIZ) and process efficiency (Lean) from the design phase of a wave energy system intended for frugal industrialisation. This gap is particularly pronounced in resource-limited regions like Madagascar, where the imperatives of simplicity, robustness, and maintainability are essential. Among the technologies examined, point absorbers coupled with linear generators appear to offer the best compromise for meeting these constraints, thanks to their simplified mechanical architecture and potential for modularity. However, their optimisation for viable industrial deployment requires a more systematic, holistic design approach than is typically found in the literature. It is precisely in this space that the contribution of this study lies: proposing an integrated TRIZ-Lean methodology for the design, optimisation, and industrial-scale scaling of a wave energy system adapted to the Malagasy context, thereby bridging the gap between proof of concept and large-scale operational deployment.

3. Methodology

3.1. Research Process

The research methodology employed in this study is structured around the Lean Six Sigma DMAIC cycle (Define, Measure, Analyse, Improve, Control) and integrated with the Theory of Inventive Problem Solving (TRIZ). This structured, phased approach ensures a rigorous progression from conceptual validation to industrial readiness. The process begins with the Define phase, where industrial objectives are established, including optimising energy conversion efficiency, ensuring high maintainability in harsh maritime environments, and minimising the Levelized Cost of Energy (LCOE). A functional laboratory-scale prototype is developed at this stage to validate the core working principle and establish baseline performance metrics. The Measure phase follows, involving the systematic quantification of critical parameters, such as maximum voltage, generated power, and float speed, under controlled wave-basin conditions. This data collection establishes a reliable performance benchmark. Subsequently, the analyse phase entails a diagnostic investigation of all influencing variables, including geometry, material selection, optimal coil configuration, and the quantification of mechanical, electrical, and electromagnetic losses. This analysis identifies the root causes of performance limitations and the technical contradictions inherent in scaling the system. The Improve phase directly addresses these contradictions by applying the TRIZ methodology to generate innovative design solutions, such as modularisation, adaptive components, and magnetic guidance systems, that enhance performance while reducing complexity. Finally, the Control phase validates the improvements through numerical re-simulation, guides the development of a full-scale industrial model, and establishes procedures to ensure long-term performance stability, reliability, and manufacturability.

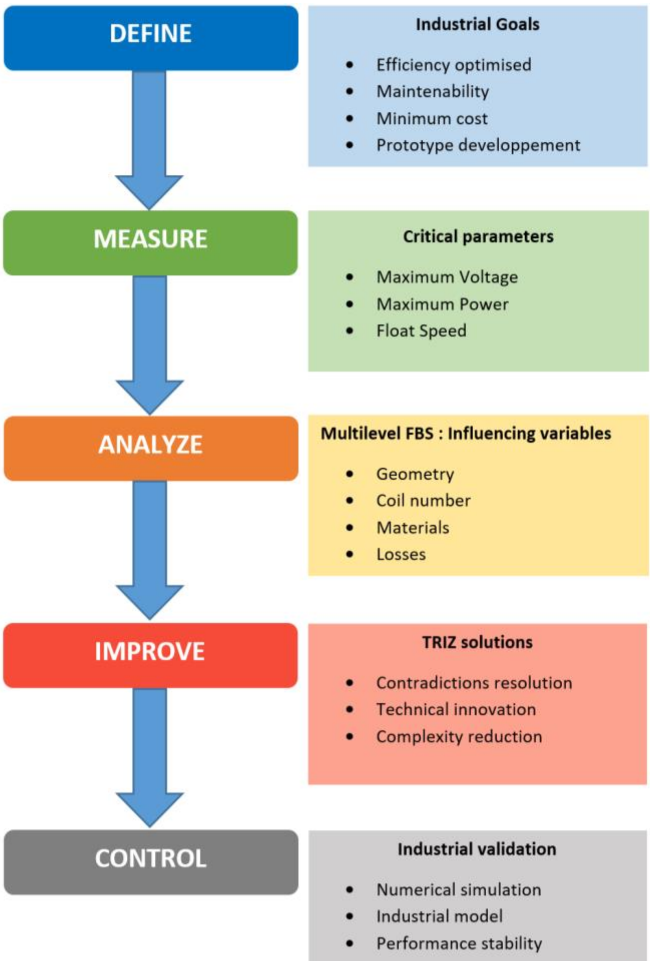


Figure 1. Research Process.

3.2. Prototype Development

The design and experimental implementation of the prototype are detailed as follows. The studied device is a point-absorber structure consisting of a float that oscillates vertically under wave action. The oscillating motion of the float is harnessed by a linear generator, which converts mechanical energy into electrical energy via electromagnetic induction from a permanent magnet moving inside a fixed coil. The experimental setup consists of a point-absorber wave energy prototype coupled to a linear generator and tested in a controlled wave test rig. The energy capture system comprises a spherical polypropylene float linked to a stainless-steel transmission rod that guides the vertical oscillatory motion.

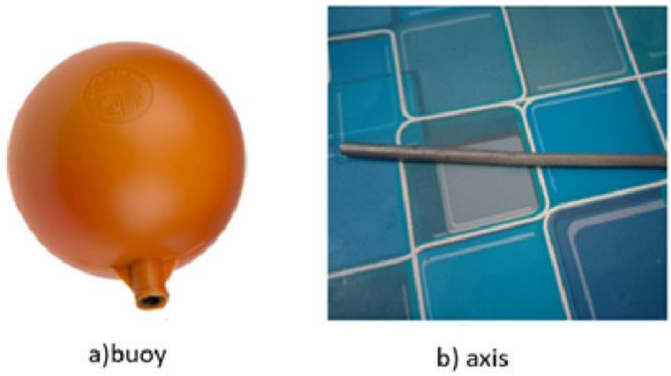


Figure 2. Point-absorber and axis.

Figure 3. Other components of the system.

Electromagnetic conversion is achieved by an NdFeB permanent magnet (grade N42) moving axially within a fixed coil composed of 500 turns of enamelled copper wire. The coil–rod assembly is protected by a sealing system that ensures electrical insulation and device reliability in a humid environment. Subsequently, the tests are conducted in a polypropylene simulation tank equipped with a wave-generation system driven by an alternating-current motor controlled by a variable-speed drive. The motor's rotary motion is converted to vertical oscillation by a crank-slider mechanism, which drives an immersed paddle to control wave frequency and amplitude.

Table 1. System specifications

Component	Material /Specification	Dimensions / Characteristics	Mass	Additional Parameters
Float	Polypropylene (spherical)	Diameter: 127 mm; Displaced volume: 1.07 L	100 g	Projected area: 126.7cm²; Density: 0.9 g/cm³
Transmission rod	Stainless steel AISI 304	Diameter: 2 mm; Effective length: 250 mm	~12 g	Finish: mechanical polishing; Guidance: vertical linear
Permanent magnet	NdFeB, grade N42	Diameter: 20 mm; Height: 10 mm; Shape: cylindrical	~23 g	Surface magnetic field: ~0.35 T; Coercive force: 955 kA/m
Coil	Enameled copper wire	500 turns; Wire diameter: 0.3 mm; Active length: 50 mm	~45 g	Resistance: 8.2 Ω; Inductance: 2.5 mH
Guiding system	PTFE (polytetrafluoroethylene)	Inner diameter: 2.1 mm; Length: 30 mm	~5 g	Friction coefficient: 0.05–0.10
Test basin	Polypropylene (transparent PP)	420 × 310 × 354 mm; Useful volume: 46 L	-	Water depth: 250 mm; Wall thickness: 5 mm
Wave generation system	AC motor + crank–connecting rod mechanism	Power: 100 W; Speed: 30–120 rpm	-	Wave amplitude: 1–3.5 cm; Frequency: 0.5–2 Hz

Once all the components are assembled, Figure 4 shows the system or prototype developed at laboratory scale.

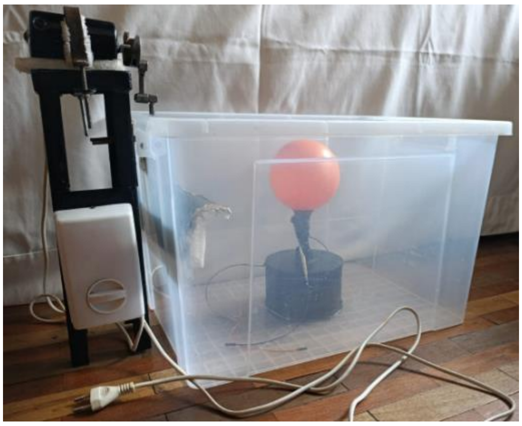


Figure 4. The prototype assembled.

3.3. Data Collection Method and Tools

For a given and assumed constant motor angular velocity, the output voltage across the terminals of the prototype is measured over a period of 30 seconds. Simultaneously, the wave height is measured using a transparent graduated ruler, which is immersed and held vertically within the tank. The instantaneous readings are recorded on video. For data extraction, a constant time interval is selected during video playback. At each corresponding instant, both the voltage value and the wave height are extracted to compile the final experimental dataset. This method allows for the synchronised acquisition of electrical output and hydrodynamic excitation, enabling direct correlation between wave characteristics and system performance.

Wave Generation: A motor-driven crank-slider mechanism converts rotary motion into the vertical oscillation of a submerged paddle (piston), producing regular waves with controllable frequency and amplitude.

Voltage Measurement: A digital multimeter or data acquisition system records the open-circuit voltage from the generator coil.

Wave Height Measurement: A fixed, transparent ruler provides a visual reference for capturing wave amplitude. The video recording ensures both signals (electrical and visual) are synchronised in time.

Data Processing: Video frames are reviewed at fixed time steps (e.g., every 0.1 s) to extract voltage readings from the meter display and corresponding water surface elevations from the ruler scale. This approach ensures repeatability and facilitates the analysis of dynamic response under controlled wave conditions.

Figure 5. Multimeter and ruler.

3.4 Mathematical Modelling

Electromagnetic induction is described by Faraday's law, which states that a time-varying magnetic flux Φ through a conducting loop induces an electromotive force (emf). This electromotive force is proportional to the rate of change of the magnetic flux and depends on the number of turns in the winding. This phenomenon underlies the conversion of mechanical energy into electrical energy in generators.

The mathematical relationship is given by:

$$\mathrm{e(t)} = -N\frac{d\Phi(\mathrm{t})}{dt} \tag{1}$$

where: e(t) is the induced electromotive force in volts (V), N is the number of turns in the winding, $\frac{d\Phi}{dt}$ is the time variation of the magnetic flux.

The magnetic flux Φ is defined by : $\Phi = B{\cdot}A$ (2)

where: B is the magnetic flux density or magnetic induction in teslas (T), A is the surface area crossed by the magnetic field.

For a linear generator, Φ varies as a function of the vertical displacement $z(t)$ of the translator. The flux variation is therefore related to the relative velocity $\upsilon = \frac{dz}{dt}$ between the magnet and the windings. Thus, the induced voltage can be written as:

$$\varepsilon = -NBL\upsilon \quad (3)$$

where: L is the active length of the windings in meters (m), υ is the relative velocity between the translator and the stator in meters per second (m/s).

Consequently, the electrical power produced in the coil is obtained by multiplying the induced voltage ε by the current I flowing through it:

$$Pcoil = \varepsilon \cdot I \quad (4)$$

Substituting ε from equation (4) into this expression yields:

$$Pcoil = NBL\upsilon I \quad (5)$$

However, it is important to account for the resistive losses, given by:

$$P_r = I^2 R \quad (6)$$

where R is the resistance of the coils.

The second phase focuses on theoretical modelling of the system, developed from the observed experimental data, to analyse the dynamic behaviour of the prototype. This modeling is based on Newton's law of motion, which describes the oscillatory motion of the float, while the electricity generation process is modeled using Faraday's law.

Newton's law of motion is expressed as follows:

$$m\ddot{z}(t) = F(t) \quad (7)$$

where m is the mass (kg), $\ddot{z}$ represents the vertical acceleration, and $F(t)$ denotes the total forces acting on the body. The study of the buoy's vertical motion is based on applying the fundamental principles of dynamics to the structure, taking into account the external forces acting on it. By isolating the buoy, a balance of forces is established in the vertical direction.

The forces considered are as follows:

- The force exerted by the linear generator, denoted as *f*PTO , extracts mechanical energy from the system.
- The weight of the buoy, mg, due to Earth's gravity g.
- The hydrodynamic forces, denoted as *f*hydro, represent the interaction between the buoy and the surrounding fluid (sea).

We then have:

$$m\ddot{z} = fhydro - fPTO - mg \quad (8)$$

Within the framework of linear potential theory, the hydrodynamic forces are interpreted as the superposition of the following components:

- The Froude-Krylov force, resulting from the pressure of incident waves on a virtual fixed body, without considering diffraction effects. It is expressed as:

$$F_{FK} = \rho V\ddot{z}(\omega) \quad (9)$$

$\ddot{z}(\omega)$ is the vertical acceleration of the body (m/s²) and V is the volume displaced by the float (m³).

- The diffraction force, generated by the reflection and deflection of waves due to the presence of the body, expressed as:

$$F_d = -\rho \int_S \left(\frac{\partial \phi_d}{\partial t} + gz\right)\vec{n}dS \quad (10)$$

where ρ is the density of water (kg/m³), z is the vertical position on the body surface (m), and Fd is the diffraction force (N).

- The radiation force, related to the structure's own motion, generates waves. It is expressed as:

$$F_r(\omega) = -[-\omega^2 M_a(\omega) + j\omega C(\omega)]Z(\omega) \quad (11)$$

where ω is the angular frequency (rad/s), j is the imaginary unit, and $Z(\omega)$ is the vertical displacement.

Meanwhile, the hydrostatic restoring force, or buoyancy, acts to return the structure to its equilibrium position. It arises from the variable hydrostatic pressure acting on the structure's wetted surface during oscillations. The hydrostatic stiffness is defined as:

$$K = \rho g\acute{A} \quad (12)$$

The hydrostatic force in the frequency domain becomes:

$$F_{hs}(\omega) = -KZ(\omega) \quad (13)$$

ρ is the density of water (kg/m³), g is the acceleration due to gravity (m/s²), $\acute{A}$ is the transverse wetted surface area of the float (m²), K is the hydrostatic stiffness constant (N/m).

Using equations (8), (9), (10), (11), and (13), the final equation of motion becomes:

$$m\ddot{z} = \rho V\ddot{z}(\omega) - \rho \int_S \left(\frac{\partial \phi_d}{\partial t} + gz\right)\vec{n}dS - KZ(\omega) - [-\omega^2 M_a(\omega) + j\omega C(\omega)]Z(\omega) - f_{PTO} - mg \quad (14)$$

3.5. Similarity Laws and Scaling Effects

In hydrodynamic experiments involving wave–structure interaction, strict dynamic similarity between laboratory models and full-scale systems is generally impossible because multiple dimensionless numbers govern the physical phenomena. In practice, experimental studies typically prioritise the Froude similarity, which is dominant in free-surface flows where gravity controls wave motion. The Froude number is expressed as [4]:

$$Fr = \frac{V}{\sqrt{gL}} \quad (15)$$

where V is the characteristic velocity, g is the gravitational acceleration, and L is the characteristic length scale. Maintaining identical Froude numbers between the model and the prototype ensures that the ratio of inertial to gravitational forces remains constant. This condition is essential to reproduce realistic wave propagation, buoy oscillation, and energy transfer from the water surface to the floating body. However, another important dimensionless parameter is the Reynolds number:

$$Re = \frac{\rho V L}{\mu} \tag{16}$$

where ρ is the fluid density and μ is the dynamic viscosity. The Reynolds number is the ratio of inertial to viscous forces. In reduced-scale laboratory experiments, it is generally impossible to maintain both Froude and Reynolds similarity simultaneously. Consequently, laboratory experiments typically preserve Froude similarity while accepting distortions in viscous effects. As a result, some hydrodynamic phenomena are faithfully reproduced while others are affected by scaling distortions. The experimental setup developed in this study is intended primarily as a proof-of-concept system to validate the physical coupling between waves, mechanical motion, and electromagnetic energy conversion. Table 2 summarises the main phenomena that are preserved or distorted in the laboratory prototype.

Table 2. Preserved or distorted in the laboratory prototype

Physical phenomenon	Representation at laboratory scale
Wave generation and propagation	Preserved (gravity-dominated regime)
Oscillatory motion of the buoy	Preserved
Mechanical transmission of vertical motion	Preserved
Electromagnetic induction principle	Preserved
Viscous hydrodynamic effects	Distorted (scale dependence)
Mechanical friction losses	Distorted
Absolute electrical power output	Distorted

3.6. TRIZ Methodology

Developed by Russian engineer Genrich Altshuller in the 1940s, TRIZ (Theory of Inventive Problem Solving) is a structured methodology for tackling complex challenges and fostering innovation. By analysing over 200,000 patents, Altshuller identified universal problem-solving principles derived from successful inventions, which now serve as a foundation for applications in engineering, product design, project management, and other fields [5]. This approach is rooted in the belief that problem-solving and innovation principles can be systematically identified and universally applied across disciplines. By analysing thousands of patents, he uncovered recurring patterns in how challenges were addressed and demonstrated that many of these principles could be generalised, forming a cross-domain toolkit for inventive thinking [5]. TRIZ is structured around four foundational concepts: ideality, which emphasises achieving optimal solutions with minimal trade-offs; the law of technical evolution, outlining predictable stages of systemic advancement; contradictions, referring to conflicts between competing parameters such as performance vs cost; and their resolution via 40 universal inventive principles. To support practical implementation, TRIZ offers tools such as the contradiction matrix and 39 standardised design parameters, enabling innovators to analyse and resolve technical challenges systematically. By bridging creative problem-solving with structured methodology, these elements empower users to transform conflicts into actionable, cross-domain solutions [5]. TRIZ addresses two types of contradictions: physical and technical. Physical contradictions arise when a single parameter must fulfill opposing requirements (e.g., an object needing to be both rigid and flexible). These are resolved through separation principles, such as separating requirements in space, time, conditions, or system hierarchy. Technical contradictions, on the other hand, occur when improving one parameter worsens another (e.g., increasing product durability raises weight). TRIZ resolves these issues using its 40 inventive principles and a contradiction matrix that links conflicting parameters to tailored solutions. By systematising these patterns from thousands of innovations, TRIZ transforms conflicts into opportunities for inventive, cross-domain solutions [6].

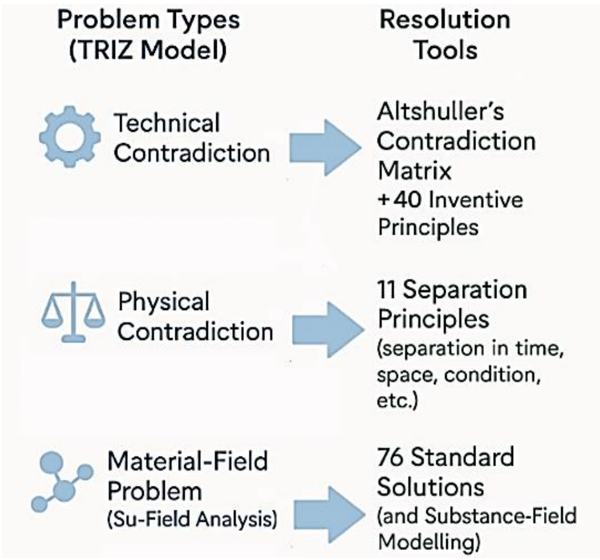


Figure 6. Problem types and resolution tools.

Figure 6 outlines the TRIZ framework, categorising problem types and their corresponding resolution tools. Technical Contradictions are addressed using Altshuller's Contradiction Matrix and the 40 Inventive Principles. Physical Contradictions leverage the 11 Separation Principles. For Material-Field problems involving incomplete or harmful system interactions, the 76 Standard Solutions and Substance-Field Modeling are applied. The TRIZ methodology follows a structured two-phase approach to solving technical problems. First, the specific problem (bottom) is reframed in a generic context using the reformulation prism: this involves abstracting the real-world situation to identify its underlying contradictions (physical or technical) and linking it to universal generic problems already solved in other domains. This step occurs in the abstract zone (clearly separated from the real zone by a distinct boundary), where TRIZ tools such as the contradiction matrix or the 40 inventive principles are applied. The vertical TRIZ arrow symbolises this ascension to abstraction, freeing thinking from contextual constraints. Once a generic solution is identified (top), the interpretation prism guides the transition back to the real zone, adapting the solution to the original context while accounting for technical, material, or economic specifics. TRIZ's power lies in its rigorous framework, which transforms seemingly unique problems into solvable patterns and reinjects systemic creativity into practice through structured abstraction and reinterpretation [7].

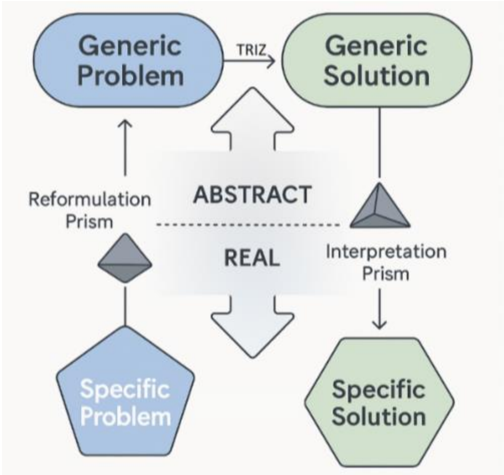


Figure 7. TRIZ methodology [8].

3.7. Multi-Level Design Perspective: Function–Behaviour–Structure (FBS) Analysis

To ensure methodological rigour and demonstrate that the TRIZ solutions emerge from systematic reasoning rather than ad hoc conceptualisation, this study integrates a multi-level design perspective based on the FBS framework enriched with topology, as proposed by Russo and Spreafico [9]. The FBS framework distinguishes between three fundamental design levels:

Function (F): What the system is intended to do (its purpose or intended goal)

Behaviour (B): How the system achieves its function (the physical principles, responses, and interactions that enable the function)

Structure (S): What the system consists of (its components, their arrangements, and geometric relationships). This tripartite distinction allows designers to separate what a system must accomplish from how it accomplishes it and what physical elements realise it [10].

This diagram of figure 8 presents a hierarchical FBS framework applied across four system levels: macro (system), meso (subsystem), micro (component), and nano/material parameters. It illustrates the downward analytical process toward detailed physical properties and the upward synthesis process toward overall system integration. The model emphasises that contradictions emerging at higher system levels can be effectively resolved through design modifications at lower levels, while ensuring coherence among material characteristics, component functions, subsystem interactions, and global system performance.

Figure 9, illustrates the FBS design process, highlighting the logical progression from design intention to final design documentation. The process begins with the formulation of system functions, followed by the synthesis of expected behaviours and the development of system structure. Through analysis and evaluation, the system's actual behaviour is compared with its expected performance. When discrepancies occur, iterative reformulations of structure, behaviour, or function are carried out to improve system performance. The process concludes with the production of a comprehensive design description, including drawings, models, and technical specifications necessary for manufacturing or implementation.

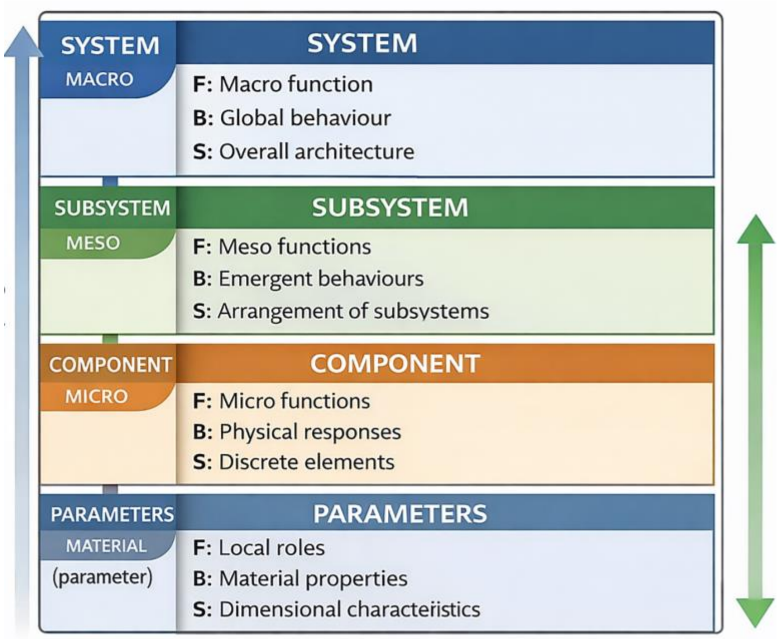


Figure 8. Multi-level FBS framework

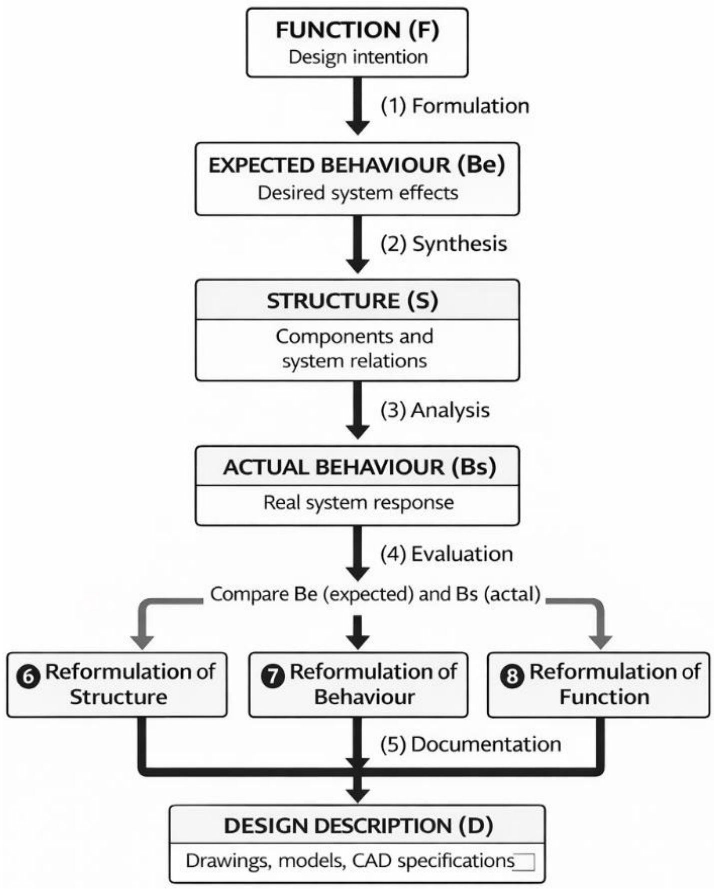
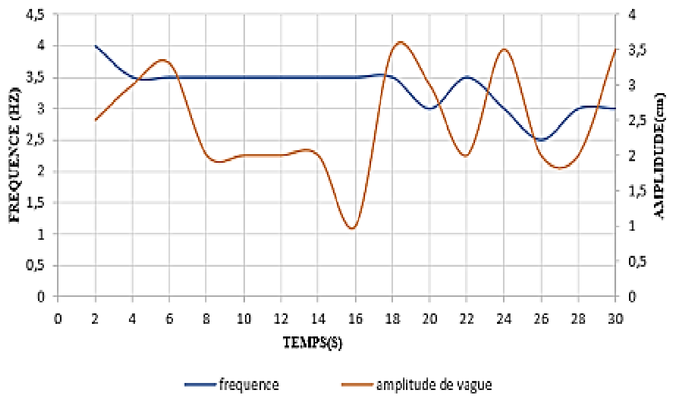


Figure 9. FBS model [10].

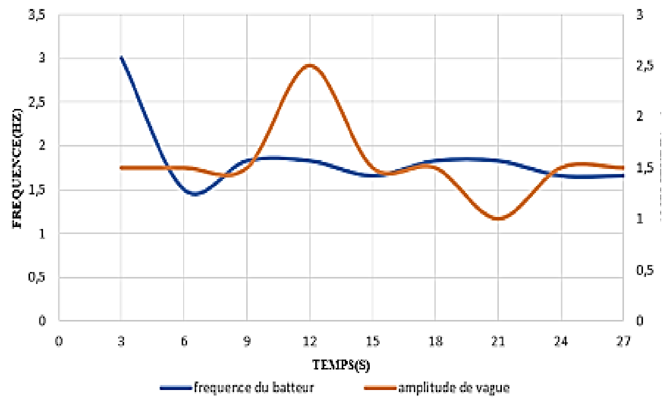
4. Results

4.1. Experimental Results

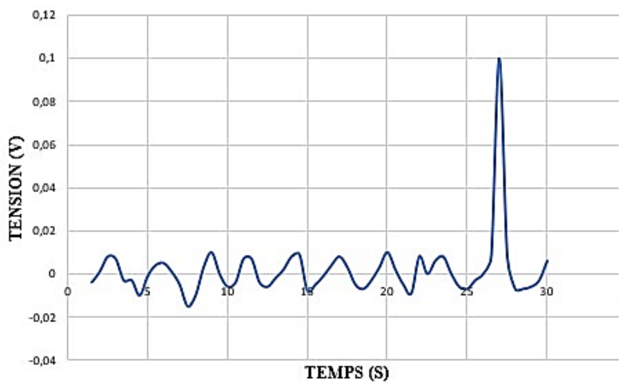
Figures 10 (a–b) present the temporal evolution of the wave amplitude generated in the wave basin under different settings. The results show non-stationary amplitude variation, with oscillations generally between about 1 cm and 3.5 cm. This dynamic reflects the influence of the wave-generator control parameters, as well as hydrodynamic effects arising from reflections at the tank walls and interference between incident and reflected waves. The third setting is characterised by a lower mean amplitude and relatively limited variability, suggesting a more stable wave regime, whereas other configurations exhibit more pronounced fluctuations. These observations demonstrate that the experimental setup can produce controlled hydrodynamic excitation, albeit with irregularities comparable to those encountered in real marine conditions.



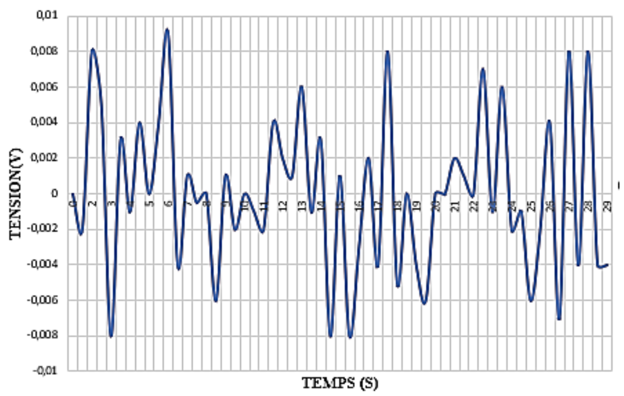
(a) Evolution of wave amplitude under excitation



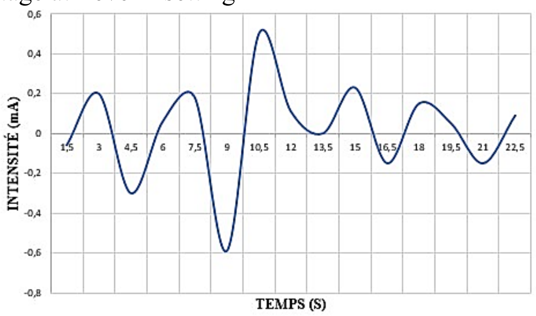
(b) Evolution of wave amplitude under excitation



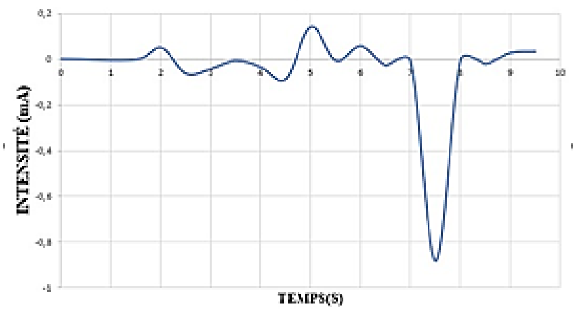
(c) Voltage at Level 4 setting



(d) Voltage at setting 3



(e) Intensity at setting 4



(f) Intensity at Adjustment Point 3

Figure 10. Experimental results.

Figure 10 illustrates the temporal signals of voltage and current measured across the terminals of the linear generator for different settings and measurement points. The set of curves highlights the production of alternating voltage and current, thereby confirming the successful conversion of wave mechanical energy into electrical energy. The voltage amplitudes remain low, below 150 mV, with transient peaks appearing for some settings, indicating phases of strong mechanical excitation of the system. The signals exhibit an irregular and non-sinusoidal shape, which reflects the non-harmonic character of the float motion. The current curves show amplitudes on the order of a few tenths of a milliamperes, consistent with the voltage measurements and the circuit's known impedance. The abrupt variations observed in some curves underscore the linear generator's sensitivity to instantaneous wave fluctuations and to the mechanical conditions of the prototype.

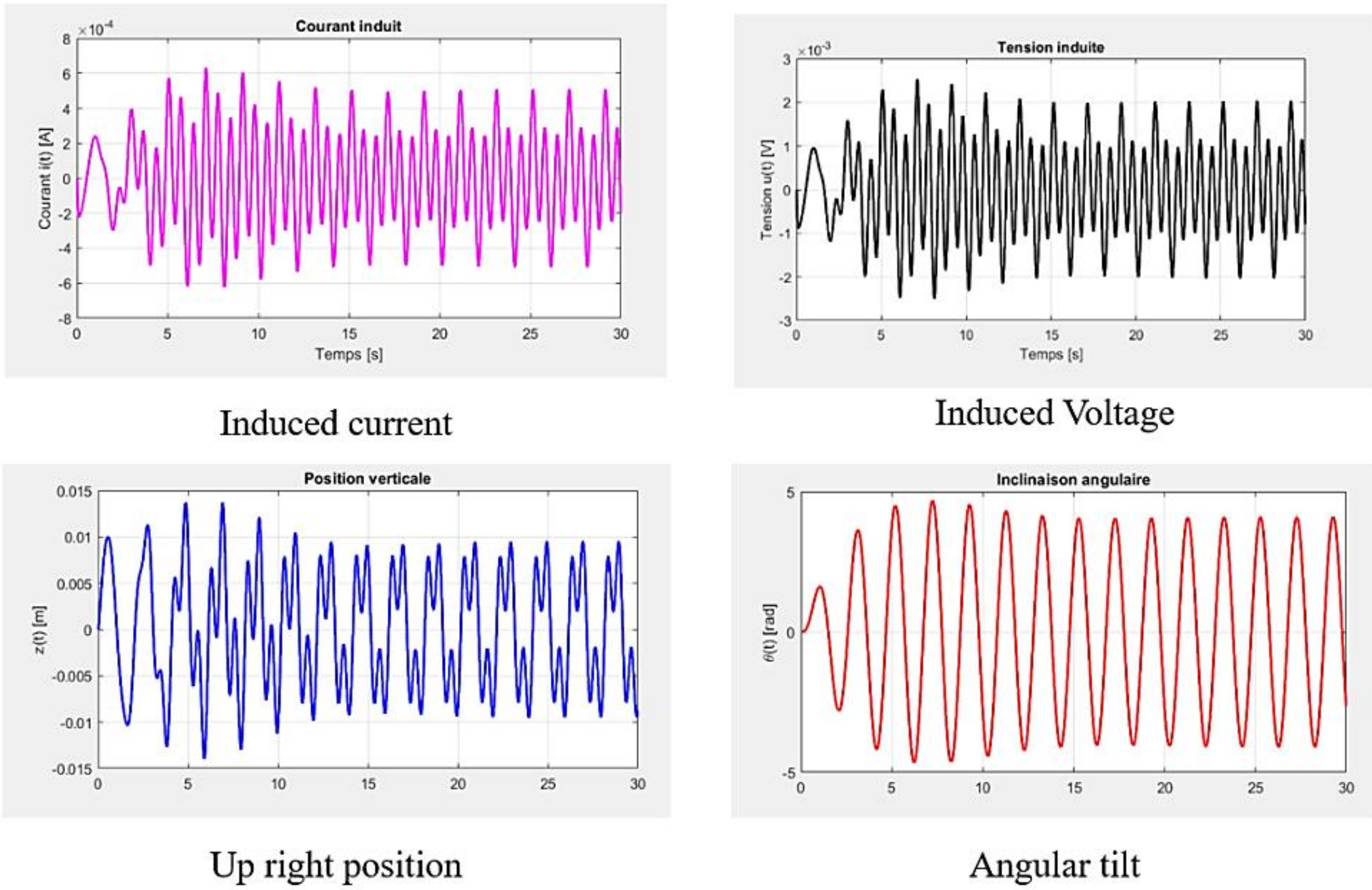


Figure 11. Theoretical simulation results.

4.2. Theoretical Simulation

Figures 7 and 8 present, respectively, the temporal evolution of the vertical position and the angular inclination of the oscillating system as obtained from simulation. The vertical position exhibits quasi-periodic oscillatory motion, with amplitudes ranging from −15 mm to +15 mm. After the initial transient, the dynamic response tends toward a more regular oscillation, indicating the system's stability under wave excitation. The angular inclination also exhibits oscillatory behaviour, with significant angular amplitudes and a constant period. These results demonstrate that the kinematic model reproduces an orderly motion consistent with what is expected for a point-absorber type wave energy device subjected to quasi-harmonic excitation.

Figure 10 illustrates the simulated induced current and voltage of the linear generator. Both signals show a regular alternation between positive and negative values, characteristic of alternating electrical production. The induced voltage reaches amplitudes of about 1 mV, while the induced current is around 0.1 mA, in agreement with the model's electromagnetic parameters. The quasi-periodic shape of the signals after the transient phase reflects the relationship between the oscillating system's velocity and the induced electromotive force, as predicted by Faraday's law. The observed variations in amplitude reflect the influence of a non-harmonic kinematic motion. Overall, the results highlight the coherence of the electromechanical model and its ability to qualitatively reproduce the wave energy prototype's electrical behaviour.

4.3. Quantitative Comparison of Simulated and Experimental Results

Table 3 provides a quantitative comparison between the simulated predictions and the corresponding experimental measurements.

Table 3. Quantitative comparison of simulated and experimental results.

Parameter	Simulation	Experiment	Absolute Error	Relative Error	RMSE
Peak voltage (mV)	3.1	3.7	0.6 mV	16.2 %	0.7 mV
RMS voltage (mV)	1.7	2.1	0.4 mV	19.0 %	0.5 mV
Peak current (mA)	0.58	0.69	0.11 mA	15.9 %	0.13 mA
Oscillation period (s)	1.02	1.10	0.08 s	7.3 %	0.09 s
Peak displacement (mm)	13.2	14.9	1.7 mm	11.4 %	1.9 mm

The correlation coefficient between the simulated and experimental voltage signals is $R^2 = 0.75$, indicating good agreement in the system's dynamic behaviour. The slightly higher amplitudes observed in the experimental signals can be attributed to hydrodynamic turbulence, mechanical friction, and non-ideal alignment between the magnet and the coil, which are not fully captured in the simplified numerical model.

4.4. FBS Analysis of the System

The following table summarises the FBS of the Wave Energy Converter system across different levels, from macro to Nano. For each element, the table presents its function, the associated behavior, and the implemented structure. Additionally, it highlights the key contradictions or trade-offs that arise at each level, providing a clear overview of challenges and design considerations inherent in optimising the system.

Table 4. Multi-level FBS analysis of the system

Level	Element	FBS Analysis	Contradictions
MACRO	WEC System	**F:** Convert wave energy to electricity **B:** Oscillation and electromagnetic induction **S:** Buoy, linear generator, electronics, Mooring structure, Mechanical guiding	Power output vs system cost Efficiency vs system mass Scale vs Parasitic losses Simplicity vs. Durability Waterproofing vs. Maintainability
		Descent	
MESO	Linear generator	**F:** Generate voltage from mechanical motion **B:** Relative magnet/coil motion creates flux variation **S:** NdFeB magnet and copper coil	Grade magnet vs cost
	Electronics box	**F:** Convert and condition energy **B:** Rectification, regulation **S:** electronics	Additional components vs weight
	buoy	**F:** Capture wave energy **B:** Vertical oscillation **S:** Diameter 127mm (lab)	Diameter vs drag forces
	Protective enclosure	**F:** Protect **B:** Physical barrier **S:** Monolithic sealed	Waterproofing vs. access Simplicity vs. corrosion
		Descent	
MICRO	Coil	**F:** Induce current **B:** Faraday's law **S:** 500 turns, 0.3mm wire, R=8.2Ω	Turns vs Joule losses
	Power electronics	**F:** Rectify and regulate voltage **B:** AC/DC conversion **S:** PCB, capacitors, MOSFETs, Resistors, regulators, and diodes.	Cooling vs. Weight
	Guidance system	**F:** Maintain vertical alignment **B:** Linear motion with friction **S:** Bearing	

			Stroke vs. friction
	Seals	**F:** Prevent water ingress **B:** Deformation **S:** flexible membrane	Seals vs. removing
		Descent	
	Coil parameters	**F:** Maximise extracted power **B:** Trade-off: V and N, Losses and I²R **S:** Wire diameter, number of turns, geometry	Turns vs Joule losses
	Interconnection cables	**F:** Connect the generator to electronics **B:** Current transport **S:** Length, section, material	Length vs. losses
NANO	Scale effects	**F:** Model losses **B:** Viscous effects underestimated **S:** Scale factor λ	Accurate loss modelling vs Non-linear scale-dependent viscous effects
	Surface treatment	**F:** Protect against corrosion **B:** Chemical/physical barrier **S:** Paint, coating	Durability / Corrosion protection vs Cost and Complexity

4.5. Contradictions Formulation and TRIZ Solutions

Large-scale deployment of an efficient wave energy converter reveals fundamental technical contradictions: improving one parameter degrades another. These contradictions are formulated below according to TRIZ logic.

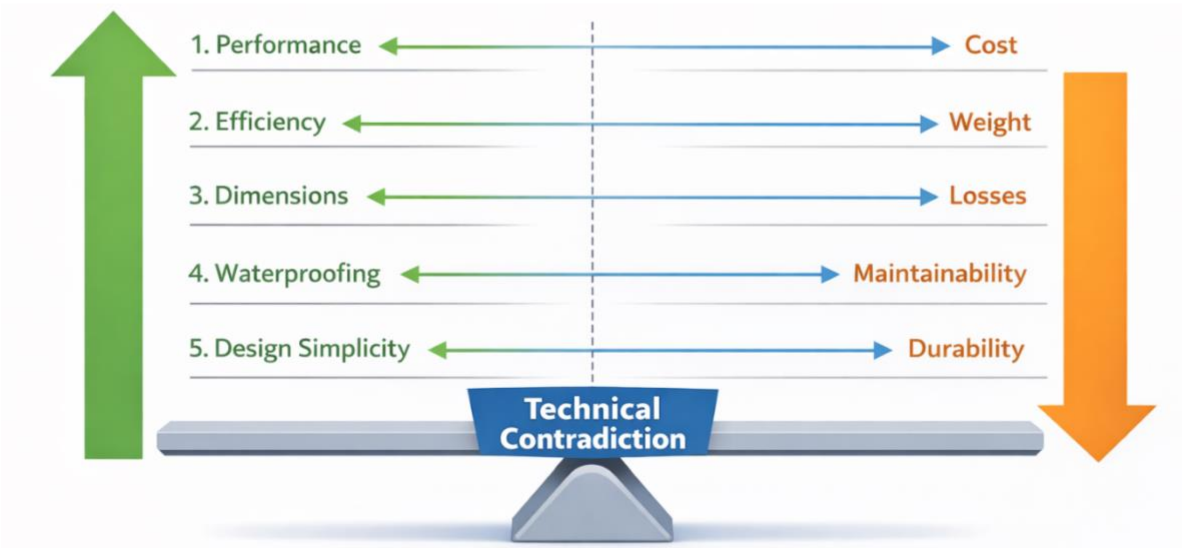


Figure 12. Technical contradictions.

4.5.1. Performance vs Cost

A core contradiction emerges between enhancing performance both in terms of electrical output and long-term reliability and managing cost. Achieving higher power and greater durability requires premium materials and components, such as high-energy NdFeB magnets and marine-grade electronics. This directly elevates the unit cost. For instance, upgrading from an N42 to an N52 magnet can increase magnetic flux by approximately 15%, but it also nearly doubles the cost of that critical component.

4.5.2. Efficiency vs Weight

The pursuit of optimal efficiency, particularly in electromagnetic coupling and system resonance, often conflicts with the goals of minimal weight and footprint. Design choices that boost efficiency, such as longer coils, ferromagnetic cores, or increased inertial mass, inevitably make the device heavier and more cumbersome. This concerns not only logistics and installation but can also introduce secondary issues; for example, a ferromagnetic core improves magnetic flux linkage but adds mass and creates new corrosion vulnerabilities.

4.5.3. Scale vs Losses

Scaling up the device's dimensions to capture more energy inadvertently amplifies parasitic losses. A larger system experiences increased mechanical friction in guidance systems, higher ohmic resistance in extended electrical windings, and greater eddy-current losses in larger metal components. A practical manifestation of this is seen in hydrodynamics: a full-scale float with a 3-meter diameter will encounter significantly greater non-linear frictional forces than its small-scale laboratory model, potentially eroding the net energy gain expected from its larger size.

4.5.4. Waterproofing vs Maintainability

Ensuring exceptional reliability and waterproofing for long-term operation in a harsh marine environment is at odds with ease of maintenance. Achieving perfect sealing typically requires complex encapsulation, permanent seals, and potting practices that maximise durability but render internal components inaccessible. A clear example is potting the generator in epoxy resin; while this virtually eliminates water ingress and protects against corrosion, it makes any future repair, component replacement, or diagnostic inspection impossible without destroying the unit.

4.5.5. Design Simplicity vs Durability

The ideal of design simplicity, which prioritises the use of basic, locally available materials and straightforward fabrication processes, can severely limit the system's ultimate performance and durability. A frugal design approach might specify standard mild steel for structural parts to keep costs low. However, in a saline, corrosive environment, this choice would lead to accelerated degradation, significantly shortening the service life and compromising reliability compared to a design using stainless steel or specialised alloys.

4.5.6. Conversion of Specific to Generic Variables

Each specific variable will be reformulated analogically into its corresponding generic variable, as shown in Figure 13.

Figure 13. Converting specific to generic variables

Table 4. Solution principles

N°	To Be Improved	Will Deteriorate	Solution Principles
1	39. Productivity	19. Energy consumption of the moving object	35, 10, 38, 19
2	22. Energy loss	4. Length of the non-moving object	6, 38, 7
3	7. Volume of the moving object	22. Energy loss	7, 15, 13, 16
4	30. Harmful external factors	34. Convenience of repair	35, 10, 2
5	36. Complexity of the structure	27. Reliability	13, 35, 1

The TRIZ methodology, through the Altshuller contradiction matrix, systematically translates identified technical conflicts into generic inventive principles. Table 2 presents the solution principles derived from this matrix for the specific contradictions outlined in our wave energy converter design. They must be interpreted and concretely translated into tangible design modifications and engineering specifications. The subsequent phase will detail how each principle is operationalised into actionable design improvements, ensuring they are practically implemented to resolve the core performance trade-offs and advance the prototype toward industrial viability.

Principle 35: Parameter change

Coil parameterisation: The application of TRIZ Principle 35 to the coil involves systematically varying its number of turns, wire diameter, and winding geometry to resolve the contradiction between increasing voltage and reducing resistive losses. This parameter change is expected to identify an optimal configuration, often a shift toward fewer turns of thicker wire that maximises power output rather than just voltage, thereby improving the overall electrical efficiency of the generator.

Magnet geometry optimisation: For the magnet, Principle 35 is applied by altering its geometry, dimensional ratios, and material grade to enhance magnetic flux density cost-effectively. Changing from a simple parallelepiped to a ring or Halbach array configuration, or upgrading to a higher-grade material, can significantly improve magnetic coupling with the coil. The recommended approach is to use finite element simulation to find the design that best balances improved performance with material and weight constraints.

Float geometry and hydrodynamic tuning: Implementing Principle 35 on the float means changing its shape, aspect ratio, and draft to better capture wave energy while minimising drag. Moving from a simple spherical shape to a streamlined, resonant form, such as a vertical cylinder or bullet shape, can dramatically increase the hydrodynamic excitation force. The key recommendation is to simulate and select a geometry specifically tuned to the dominant wave conditions to maximise the system's energy capture efficiency.

Principle 10: Prior action

Motion limiters: A core risk for the point absorber in irregular or storm waves is that the float's vertical stroke could exceed the safe mechanical range of the linear generator, resulting in destructive impact. Applying Prior Action involves integrating pre-compressed springs or elastic bumpers at the limits of the translator's travel path during assembly. These components engage before a hard stop, converting excessive kinetic energy into controlled elastic deformation. This passive, pre-emptive action prevents catastrophic failure, protects core components like the coil and magnet assembly, and enhances system longevity with zero operational maintenance.

Pre-tensioned sealing and corrosion protection: Water ingress and corrosion initiate from the first moment of deployment. Principle 10 dictates that this be addressed *in advance*. This involves pre-lubricating and pre-loading all dynamic seals during assembly to ensure optimal performance from the first cycle. Furthermore, applying protective coatings (e.g., epoxy) and installing sacrificial anodes (e.g., zinc) on critical metal parts before the system comes into contact with saltwater creates an active barrier against corrosion from day one. This prior action drastically improves long-term reliability by preventing the root cause of a major failure mode before it can start.

Pre-designed sacrificial weak link: To protect the expensive PTO system from extreme, unforeseen loads such as debris impact, a mechanically engineered weak link, or shear pin, is designed into the drivetrain. This component is calculated to fail predictably at a load above normal operation but below the threshold that would damage the generator or bend the main rod. As a prior action implemented during manufacturing, it acts as a mechanical "fuse," sacrificing itself to preserve the system's core. This turns a potential major structural repair into a simple, low-cost field replacement, significantly improving maintainability and reducing downtime.

Principle 38: Accelerated Oxidation

Anodisation of aluminium components: The application of TRIZ Principle 38 to aluminium parts involves the pre-treatment step of anodisation. Aluminium naturally forms a thin oxide layer, but in seawater, this layer is insufficient to prevent corrosion. By subjecting aluminium components such as housings and supports to a controlled electrolytic anodisation process, we rapidly and forcibly thicken the oxide layer into a hard, dense ceramic coating. This accelerated oxidation creates a highly durable barrier that resists pitting, abrasion, and chemical attack, thereby extending the lifespan of lightweight structural elements and reducing long-term maintenance needs in the marine environment.

Principle 19: Periodic Action

Cycle-based predictive maintenance scheduling: Instead of inspecting components every six months regardless of use, maintenance intervals are determined by counting the device's oscillation cycles, a direct measure of mechanical wear. After a predefined number of cycles, the system flags the need for inspection or lubrication. This method aligns maintenance actions with actual usage and stress, enabling condition-based, predictive upkeep that prevents both unnecessary interventions and unexpected failures, thereby optimising long-term reliability and resource allocation.

Principle 06: Multi-Functionality

Integration of a reverse-osmosis desalination unit: The wave energy converter can also be designed to produce freshwater. A portion of the electricity generated is used to power a compact reverse-osmosis desalination module located onshore. This dual functionality directly addresses the critical need for potable water in coastal communities, transforming the system from a pure energy generator into an integrated water-and-power hub, thereby significantly enhancing its socio-economic value and deployment rationale.

Platform as a marine sensor hub and communication relay: The boy's stable structure and built-in power supply make it an ideal platform for additional functions. It can host a suite of sensors for environmental monitoring, measuring water temperature, salinity, pH, and weather data and serve as a communication relay node with a low-power radio or cellular repeater. This multifunctional role turns the energy device into a distributed data gathering and networking asset, supporting oceanographic research, local fisheries, and coastal community connectivity while operating autonomously.

Artificial reef and marine life enhancement: The submerged components of the system can be designed with eco-friendly, textured materials and complex geometries to encourage colonisation by marine organisms. This added function transforms the infrastructure into an artificial reef, promoting local biodiversity, supporting fisheries, and providing mild coastal protection through wave attenuation. This ecological enhancement improves community acceptance and contributes to environmental sustainability.

Principle 07: Nesting

Power electronics housed within the float body: The nesting principle is applied by integrating the power electronics rectifier, DC-DC converter, and controller directly into structural cavities within the float. Rather than using a separate external enclosure, the electronic boards are mounted in moulded compartments within the composite hull of the float, then encapsulated in waterproof potting resin. This integration eliminates interconnection cables between the generator and the electronics, lowers the system's centre of gravity, and utilises the float's thermal mass for passive cooling of the components. The result is a more compact, shock- and moisture-resistant system with simplified maintenance through localised access points.

Principle 15: Optimisation

Adjustable mass: The integration of a self-adjusting oscillating mass constitutes an advanced application of the dynamisation principle, aimed at continuously optimising the resonance of the float with the wave period. Its main advantage lies in enabling active tuning**,** which adjusts the system's natural frequency to maximise oscillation amplitude and increase energy extraction by up to 40%, while also providing a protective detuning function during storms by reducing mechanical loads. Two implementation approaches are favoured: displacing a solid mass along a rail to precisely adjust inertia, or transferring liquid ballast between internal compartments to modify buoyancy and pitch. Governed by a microcontroller and potentially enhanced by a predictive system using upstream sensors, the entire mechanism is designed to ensure that the additional energy captured always exceeds the energy consumed by the adjustment system itself, thereby guaranteeing a net energy gain essential to the industrial viability of the wave energy converter.

Principle 13: Inversion

Fully floating platform: This principle first reimagines the mechanical frame of reference, transitioning from a system anchored to the seabed to one that is fully floating and autonomous, extracting energy from the relative motion of an internal oscillating mass rather than against a fixed point. This innovation eliminates the need for heavy, complex foundations, enabling scalable deployment in deep-water areas where wave energy is most abundant. Secondly, the principle inverts the approach to reliability by hermetically sealing all critical components inside a protective hull, thereby shielding moving parts from corrosive seawater and abrasive sediments, transforming the hostile marine environment into a controlled workspace. Finally, inversion redefines storm survivability: rather than over-engineering the structure to withstand surface forces, the converter is designed to be submersible, capable of diving below the wave-break zone during extreme weather. This ability to avoid storms enables a lighter, more cost-effective design that is not overbuilt for rare events, significantly reducing the levelized cost of energy and enhancing the system's economic viability for industrial deployment.

Principle 16: Partial or Excessive Action

Coil shorter than the magnet stroke: A first application of partial action concerns the electromagnetic design of the generator. A long coil covering the full stroke of the magnet theoretically maximises induced voltage, but it also leads to high inductance and resistance, which limit current and usable power, especially at low oscillation speeds. By intentionally using a coil shorter than the magnet stroke, the magnetic coupling becomes partial. The magnet interacts with the coil only during part of its motion, producing sharp voltage pulses as it enters and leaves the coil. This pulsed signal is easier to rectify and process with power electronics, while the reduced resistance and inductance improve energy transfer. Thus, a deliberately incomplete electromagnetic action results in higher overall efficiency, resolving the contradiction between high voltage and high current.

Self-limiting excessive electromagnetic action: The same principle is also effective for system protection under extreme wave conditions. Large waves can induce excessive speeds and strokes that threaten mechanical integrity. Instead of using mechanical end-stops or permanent braking, both of which are associated with wear and thermal stress, a self-limiting, excessive electromagnetic action can be employed. When the translator speed exceeds a predefined threshold, the electronics connect the coil to a very low resistive load, producing an extremely strong magnetic braking force proportional to speed. This force rapidly slows the system but automatically disappears as the speed decreases. The excessive action, being transient and contactless, provides robust**,** passive protection well suited to harsh marine environments.

Intermittent control power supply: Finally, partial action can be applied to the energy management of the control system itself. Continuously powering a microcontroller and sensors for maximum power point tracking can consume a significant share of the generated energy, especially in low-energy sea states. An innovative approach is to adopt a partial, intermittent power supply. The microcontroller remains off most of the time, while an ultra-low-power analogue circuit monitors the generated voltage. Only when this voltage exceeds a threshold for a sufficient duration, indicating exploitable wave conditions, is the controller briefly powered to perform measurements and adjustments. This strategy drastically reduces internal consumption and maximises the net energy delivered to the load.

Principle 2: Extraction

Compartments separation: The proposed solution involves physically separating the system containing the fixed coil and the power electronics by housing them in separate, isolated compartments. This compartmentalisation approach offers several significant advantages. It greatly facilitates maintenance by allowing work to be performed on one module without affecting the other, all without complicating the wiring, as their proximity is maintained to reduce electrical losses. Furthermore, this separation enhances safety and reliability by protecting the coil from the potentially adverse effects of heat dissipated by the power electronics, thereby preserving its integrity and long-term performance.

Principle 1: Segmentation

Multi coils: By replacing the single coil with a network of autonomous coils, each driven by its own dedicated power module, we transition from a single point of failure to a resilient "multi-cellular" system. This architecture enables active redundancy: the system can electronically isolate any faulty coil and continue to operate in a degraded mode, a decisive advantage for maintenance in offshore environments. Moreover, it opens the way to dynamic optimisation of the generated voltage, acting as an electronic gearbox adapted to the irregular motion of the waves, while also reducing eddy-current losses.

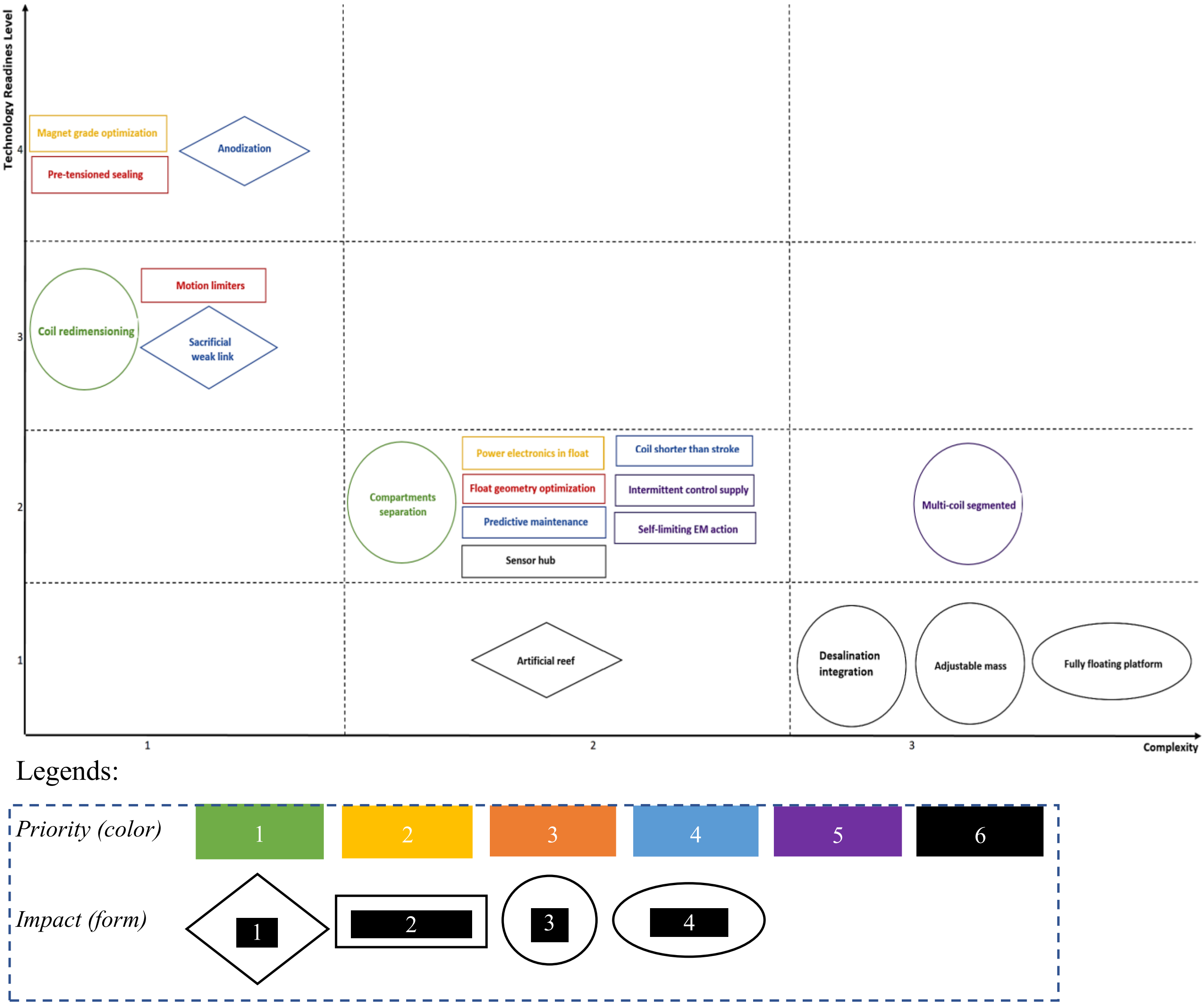


Figure 14. Classification of TRIZ solutions

4.6. Prioritisation and Feasibility Assessment of TRIZ Solutions

To guide the transition from concept to industrial deployment, the proposed TRIZ solutions are systematically evaluated and prioritised according to three criteria: Expected impact on key performance indicators (power output, reliability, maintainability), Implementation complexity (technical difficulty, cost, development time), Current Technology Readiness Level (TRL)**,** and target TRL for the Generation

2 prototype. Figure 14 presents a visual synthesis of this prioritisation. Solutions are positioned according to their priority level (vertical axis, from 1 to 4) and implementation complexity (horizontal axis, increasing from left to right). Priority 1 solutions (magnet grade optimisation, pre-terminated sealing) offer high impact with low complexity and will be integrated immediately. Priority 2 solutions (anodisation, motion limiters, coil redimensioning, sacrificial metal link) require moderate development effort. Priority 3 solutions (power electronics in float, compartment separation, flow geometry optimisation, predictive maintenance, sensor hub, coil shorter than stroke, intermittent control supply, self-limiting EM action) address advanced functionalities with medium complexity. Priority 4 solutions (multi-coil segmented generator, desalination integration, adjustable mass, fully floating platform) represent long-term research directions requiring fundamental architectural changes. This visual roadmap ensures a structured, phased approach to industrial deployment, aligning development efforts with the highest impact-to-effort ratio.

5. Discussion

The results of this study demonstrate the feasibility of wave energy conversion via a point absorber coupled with a linear generator, while clearly illustrating the recurring challenges of scaling up to an industrial level. This discussion analyses these results through the dual methodological lenses of TRIZ and Lean and contrasts them with the existing literature to assess their significance, confirming general observations while identifying a novel pathway to overcome them.

The experimental measurements confirm effective conversion of mechanical energy into electrical energy, but with low amplitudes (voltage < 150 mV, current < 0.5 mA) and irregular signals. These observations align perfectly with the literature on small-scale prototypes, which highlights the persistent gap between theoretical models and real-world performance in test basins [3, 11]. The non-sinusoidal nature of the signals, consistent with the irregular artificial waves and mechanical losses (friction), also reflects the well-established dependence of point absorbers on excitation conditions and fluid-structure coupling [12]. Thus, this study first validates a widely shared observation: conversion is possible, but nonlinearities and parasitic losses intrinsic to small-scale models limit its efficiency.

However, the divergence between our theoretical simulations (predicting ~1 mV) and experimental measurements (~9 mV) goes beyond a simple calibration error. It tangibly embodies the system's fundamental technical contradictions. The low voltage illustrates the Performance vs Cost contradiction (a more powerful magnet would increase it, but at a prohibitive cost), while friction losses in the guidance system fall under the Scale vs Losses contradiction. The literature often accepts these contradictions as inevitable compromises[12]. It is precisely at this level that this methodological approach proposes a breakthrough.

While the state of the art is rich in specific hydrodynamic or electromagnetic optimisations, it reveals a deficit in the application of systematic innovation methodologies to resolve design contradictions holistically [13]. This study positions itself in this space. It does not propose a new conversion physics but rather a structured process integrating the DMAIC cycle and TRIZ to transform a validated principle into a viable industrial product, specifically adapted to frugal contexts like those in Madagascar. A critical examination of the proposed solutions against the existing literature reveals the nuanced nature of their novelty. The concept of a segmented multi-coil generator, for instance, is not entirely unprecedented; prior research has explored multi-pole linear generator designs to improve power density, as noted in the seminal work on direct-drive conversion [14]. Similarly, system compartmentalisation for protecting sensitive electronics is a recognised principle in offshore engineering, often discussed in the context of mooring and subsystem design [15]. At first glance, our TRIZ-derived solutions could be viewed as adaptations of these established concepts.

However, the genuine novelty of our approach does not lie in the invention of these individual technical elements per se, but rather in the systematic and contextualised pathway by which they are derived and integrated. Where prior literature often presents these features as isolated, performance-focused optimisations (e.g., maximising power output [14]), our TRIZ-Lean framework generates them as a coherent set of solutions explicitly targeted at resolving the specific contradictions imposed by a frugal innovation context. For example, while multi-coil generators have been proposed elsewhere, this application of the Segmentation principle is primarily driven by the need for fault tolerance and maintainability in a remote coastal setting, transforming a performance feature into a deliberate resilience strategy. Likewise, the proposed compartmentalisation is not merely for protection, but is specifically configured via the Extraction principle to enable rapid, modular repair with basic tools, a requirement seldom prioritised in conventional designs [15]. Therefore, the key contribution is the methodological framework itself: it is this traceable, need-driven synthesis of known principles into a cohesive and context-appropriate architecture that distinguishes our work from a simple aggregation of existing techniques.

The TRIZ analysis, by translating our specific contradictions into generic parameters and generating inventive principles via the Altshuller matrix, provides a powerful innovation framework. Its application allows us to move beyond mere observation to propose bold reconceptualisations: Addressing Performance vs Cost/Simplicity: The Segmentation principle, applied to the core of the generator, proposes active redundancy. This idea aligns with recommendations for modularity in offshore systems , but its specific application to the stator winding of a linear generator and its formalisation via TRIZ constitute a concrete advance. Coupled with Parameter Change for geometric optimisation, it transforms a compromise problem into an opportunity for a resilient architecture. Addressing Waterproofing vs Maintainability, a Classic Hurdle: Rather than a compromise, the combined application of the Extraction principle (compartmentalisation) and the Prior Action principle (pre-lubricated seals, sacrificial anodes) offers an integrated solution. This approach, which designs maintainability into a waterproof system, is more innovative and proactive than classical monolithic enclosure solutions, aligning with emerging "Design for Maintenance" concepts.

An Integrative Approach in a Sectoral Literature: The strength of this TRIZ-Lean framework is its ability to synthesise. For example, the Nesting principle (integration of electronics into the float) simultaneously solves electrical, mechanical, and economic problems. Similarly, the Partial or Excessive Action principle, with a coil shorter than the stroke, offers a counterintuitive solution for optimising energy transfer. These solutions are not simple incremental improvements; they redefine the architecture and directly target the elimination of waste (Muda) in the Lean sense: waste due to failure, over-maintenance, or energy losses.

The limitations of this study, namely its simplified model and the partial experimental validation of the proposed TRIZ concepts, are acknowledged. These constraints are widely recognised within the research community, which often highlights the inherent difficulty of accurate multiphysics modeling. Precisely these limitations define the roadmap for the "Improve" and "Control" phases of the DMAIC cycle and outline clear priorities for future work.

1. Advanced Modelling: It is imperative to develop multiphysics simulations (non-linear hydrodynamics, 3D magnetism, thermal analysis) to precisely quantify the expected benefits of TRIZ solutions, such as the power and reliability gain of a segmented generator.
2. Systematic Experimental Validation: A generation 2 prototype, integrating key concepts (modularisation, compartmentalisation, nested electronics), must be tested under more realistic conditions (irregular wave basin, or even a protected marine site). This validation must also include critical mechanical design solutions not fully addressed in the current model. For instance, the dynamic seal protecting the rod guidance system requires a specific engineering design: a reinforced, accordion-shaped bellows. This envelope must be hermetically sealed at both ends using clamping flanges or high-strength industrial adhesive. The accordion shape is crucial as it allows the membrane to unfold and refold without stretching (working in flexion rather than tension), significantly extending the material's fatigue life. To prevent the bellows from collapsing under water pressure or ballooning during the rod's descent, an armoured material (a technical fabric coated with an elastomer) is advised, along with a small pressure-compensation air vent connected to the dry base compartment. Finally, the bellows' length at rest must be calculated so that at the float's maximum extension, the folds are never fully taut, preserving the integrity of the adhesive joints. Incorporating and testing such detailed solutions is essential for demonstrating real-world durability.

In summary, this research validates the well-documented challenges of small-scale wave energy conversion, but distinguishes itself by proposing and illustrating an integrated methodological framework to address them. It does not contradict the literature but enriches it by demonstrating the contribution of systematic innovation engineering. The central proposition is that the leap to industrialisation cannot rely on simple "upscaling," but requires innovative redesign, guided by the proactive resolution of contradictions. By anchoring this approach in the frugality and robustness constraints of contexts such as Madagascar, this work helps bridge the gap between laboratory proof-of-concept and the deployment of resilient, economically viable systems to electrify isolated coastal areas.

6. Conclusions

Confronted with the urgent need for decarbonisation, wave energy offers significant potential, particularly in coastal regions such as Madagascar. However, its large-scale deployment remains constrained by technical complexity, high costs, and limited system reliability. This study addresses these challenges by proposing an integrated methodology that combines Lean Six Sigma and TRIZ to guide the transition from a laboratory prototype to an industrializable system.

The developed point-absorber prototype, coupled with a linear generator, successfully validated the wave-to-wire conversion principle, achieving peak voltages of 3.7 mV and a strong correlation with simulation results (R^2 = 0.75). A multi-level Function-Behaviour-Structure analysis enabled the identification of key performance limitations and underlying technical contradictions, forming the basis for systematic innovation. TRIZ tools then reframed these contradictions into design opportunities, leading to solutions such as segmented generator architectures, system compartmentalisation, and optimised geometries.

While promising, this work remains limited to laboratory-scale validation, and the proposed solutions require experimental confirmation under real marine conditions. Future work will focus on developing a Generation 2 prototype and validating its performance in realistic environments. Ultimately, this research provides a structured, reproducible framework for bridging the gap between conceptual validation and industrial deployment of wave energy systems.

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