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Design Ideation and Selection of Under-Piston Door for a Two-stroke Marine Engine Using Hybrid TRIZ-biomimetic and MCDM Methods

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ABSTRACT

Design ideation and selection of a two-stroke marine engine under-piston door employing Theory of Inventive Problem Solving (TRIZ), biomimetics, Analytical Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is presented in this paper. The study is motivated by exploring bio-composites as potentially suitable substitutes for conventional steel in engine component manufacture. As bio-composites possess lower mechanical properties compared to steel, the geometrical redesign was deemed necessary for any potential material substitution to take place. New under-piston door designs were ideated through the synergy between TRIZ and biomimetics. Computational models were developed, inspired by the Amazon waterlily, the tortoiseshell and the spider web. Mechanical simulation was performed for maximum stress (von Mises), total deformation and volume. With the simulated results of these designs, AHP and TOPSIS provided the solution's capabilities to decide the best design overall. The design inspired by the Amazon waterlily proved the best and showed lower stress and deformation values compared to the original by 45.25% and 4.5%, respectively. This research provided conclusive evidence that with refined scrutiny of the TRIZ and biomimetic methods, along with AHP and TOPSIS, potential alternatives to conventional materials that offer environmental friendliness without compromising operational requirements can be realised.

Keywords: Biomimetics, design ideation, multi-criteria decision-making methods, two-stroke marine engine, TRIZ

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INTRODUCTION

The growth of consciousness across humanity has brought about a common realisation of the importance of a sustainable way of life (Sapuan & Mansor, 2021). An increase in global awareness of the plight of human society has driven the launch of initiatives now known as the United Nations Sustainability and Development Goals (UNSDG) (United Nations, 2023). The marine industry, like others, has made strides to reduce its environmental impact with various initiatives spearheaded by the International Maritime Organization (IMO). Stringency in environmental protection has been on the increase, particularly with regard to emission control from ships as well as other forms of pollution, ranging from the discharge of pollutants into the sea to garbage and sewage management (https://tinyurl.com/4azfj6ca).

In keeping with sustainability, research has been published on the potential of alternative naturally sourced materials over conventional synthetics presently used across industries (Claverie et al., 2020; Moudood et al., 2019; Girijappa et al., 2019). These materials are generally categorised as natural fibre composites (NFC), made of bio-polymers reinforced by natural fibres (Pingulkar et al., 2021). In the marine industry, particularly in marine engineering, limited work has been found on using NFC as a potential substitute for conventional structural materials, particularly steel. Some literature on NFC involved its use in pleasure vessel hull construction (Ansell, 2014; Fragassa, 2017; Mouritz et al., 2001).

This paper investigates the idea generation and design selection processes of envisaging a new geometrical concept of a two-stroke marine engine under-piston door. Brief backgrounds will be presented on the topics of marine engines, the ideation tools of the Theory of Inventive Problem Solving (TRIZ) and biomimetics, and the decision-making methods of Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Analytical Hierarchy Process (AHP). A new under-piston door design is presented using these tools and methods in synergy.

Two-stroke Marine Engine

The two-stroke marine engine is responsible for powering a large percentage of the world tonnage transported across the oceans in modern times (Bilousov et al., 2020). Traditionally, these engines were run on marine diesel oil and, later, marine heavy fuel oil. These days, cleaner alternative fuels are being researched as we aim to reduce the impact of global warming (Latarche, 2021). These are slow-speed engines, with the piston assembly connected to the connecting rod via a crosshead arrangement. Cylinder aspiration is achieved by passing the turbocharged air through a scavenging space below the piston assembly, commonly known as the uniflow scavenging method. The space underneath the pistons is the scavenging or under-piston space within the marine engineering circle. Access to this scavenging space for maintenance and inspection is permitted through manhole doors, aptly called the under-piston door. The location of the under-piston door is highlighted in Figure 1.

The scavenge space is often subjected to low scavenging air pressure and temperature. Based on the ISO 3046-1:2002E (Reciprocating Internal Combustion Engines-Performance-Part 1: Declarations of Power, Fuel and Lubricating Oil Consumptions, and Test Methods - Additional Requirements for Engines for General Use), these values are placed at 25°C and 1 bar respectively. From the author's experience working with these engines while serving on board merchant ships, these values can rise to 42°C and 1.6 bar for a 60 cm bore engine charged by a single turbocharger. It has also been reported that higher scavenge pressures of up to 3.6 bar for a 90 cm bore engine equipped with three turbochargers (Livanos et al., 2003). These values may differ depending on the setup, but the variation would be minimal.

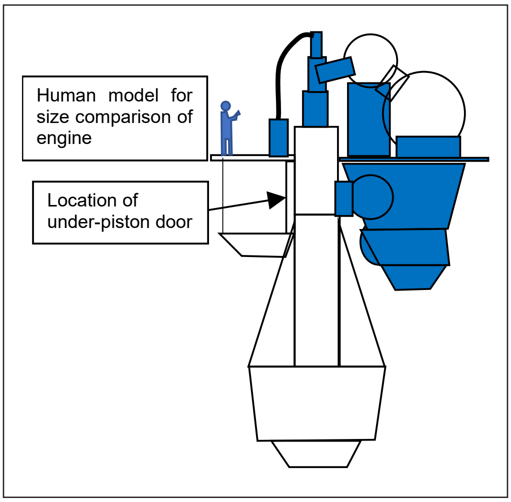


Figure 1. Location of the under-piston door on a two-stroke marine engine

Theory of Inventive Problem Solving (TRIZ)

Teoriya Resheniya Izobretatelskikh Zadatch (TRIZ) is a problem-solving method that Russian scientist Genrikh Saulovich Altshuller introduced after studying vast numbers of patents (Ekmekci & Nebati, 2019; Sheu et al., 2020). TRIZ provides different perspectives on problem-solving and idea innovation by tapping into past strategies. In recent years, TRIZ has closely been associated with eco-design in the proposed development of green products and processes (Russo & Spreafico, 2020) and improvements in the selection of greener materials (Spreafico, 2022). A sustainable innovation model was proposed based on TRIZ with an ecological innovation tool (Boavida et al., 2020). One study suggested that TRIZ provided solutions in investment strategies involving green nuclear energy (Yuan et al., 2021). TRIZ innovations have also positively influenced various environmental impact categories (Spreafico, 2021). A point has also been made that applying TRIZ in language classes improved the proficiency of students in English classes (Alkasem & Tilfarlioğlu, 2022).

Biomimetics

How living organisms evolve to adapt to their respective environments has often inspired human beings in our development of engineering solutions (Kunzmann et al., 2023). The concept of copying nature's ingenuity has been documented and is broadly categorised as "biomimetics" (Fayemi et al., 2014; Wanieck et al., 2020). Several notable innovations that can be seen today thanks to biomimetics include hook and loop fasteners, inspired by the tiny hooks on dried burdock seeds and the Shinkansen bullet train nose profile, inspired by the kingfisher's beak (Primrose, 2020). In recent times, the design of wind turbines has mimicked the profile of humpback whale flippers. Modern antifouling paints on ships adopt similar hydrophobic properties to the lotus leaf, preventing barnacles and other microorganisms from staying attached to the ship's hull (Han et al., 2021), merging TRIZ with biomimetics allowed for new valve designs with improved erosion resistance and increased service life (Cheng et al., 2019; Zhang et al., 2019).

The Analytical Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

Multi-Criteria Decision-Making (MCDM) models such as AHP and TOPSIS have long established the foundation for ranking and selection involving multiple attributes (Sahoo & Goswami, 2023) and have remained among the most preferred methods reported (Taherdoost & Madanchian, 2023). Where AHP compares each criterion and alternative pairwisely (Saaty, 1987), TOPSIS measures the distance of each alternative to the derived ideal solution (Hwang & Yoon, 1981). Recent studies have demonstrated the benefits of both methods working in series.

The hybridisation of AHP-TOPSIS has successfully selected unmanned aircraft models (Djukic et al., 2022) and bus chassis designs (James et al., 2021). A risk assessment model was based on AHP-TOPSIS, providing a decision-making method in hazard mitigation involving oil and gas pipelines (Wang & Duan, 2019). Other examples demonstrating the effectiveness of this tandem strategy include selecting the best base oil for biodiesel application (Abdulvahitoglu & Kilic, 2022) and suitable software for the study of solar radiation (Ahmad et al., 2022). Additionally, the ideal configuration of a geothermal energy system was decided using this synergistic strategy (Arslan et al., 2021). Although integrated AHP-TOPSIS strategies have been applied in various fields, limited work has been found regarding design selection in marine engines.

METHODOLOGY

The two-stroke marine engine under-piston door's design ideation and selection process can be broken down into three sub-sections. In the first, design specifications are listed to aid in developing new ideas for the under-piston door geometry. These include physical parameters as well as any regulatory requirements stated by governing bodies. The second step is to envisage ideas using a combination of TRIZ and biomimetics. Digital models of these ideas will then be drawn up and simulated with the aid of the ANSYS software. Lastly, from the simulation data, the best design will be selected using AHP and TOPSIS. Figure 2 visually represents the flow and details of these three sub-sections.

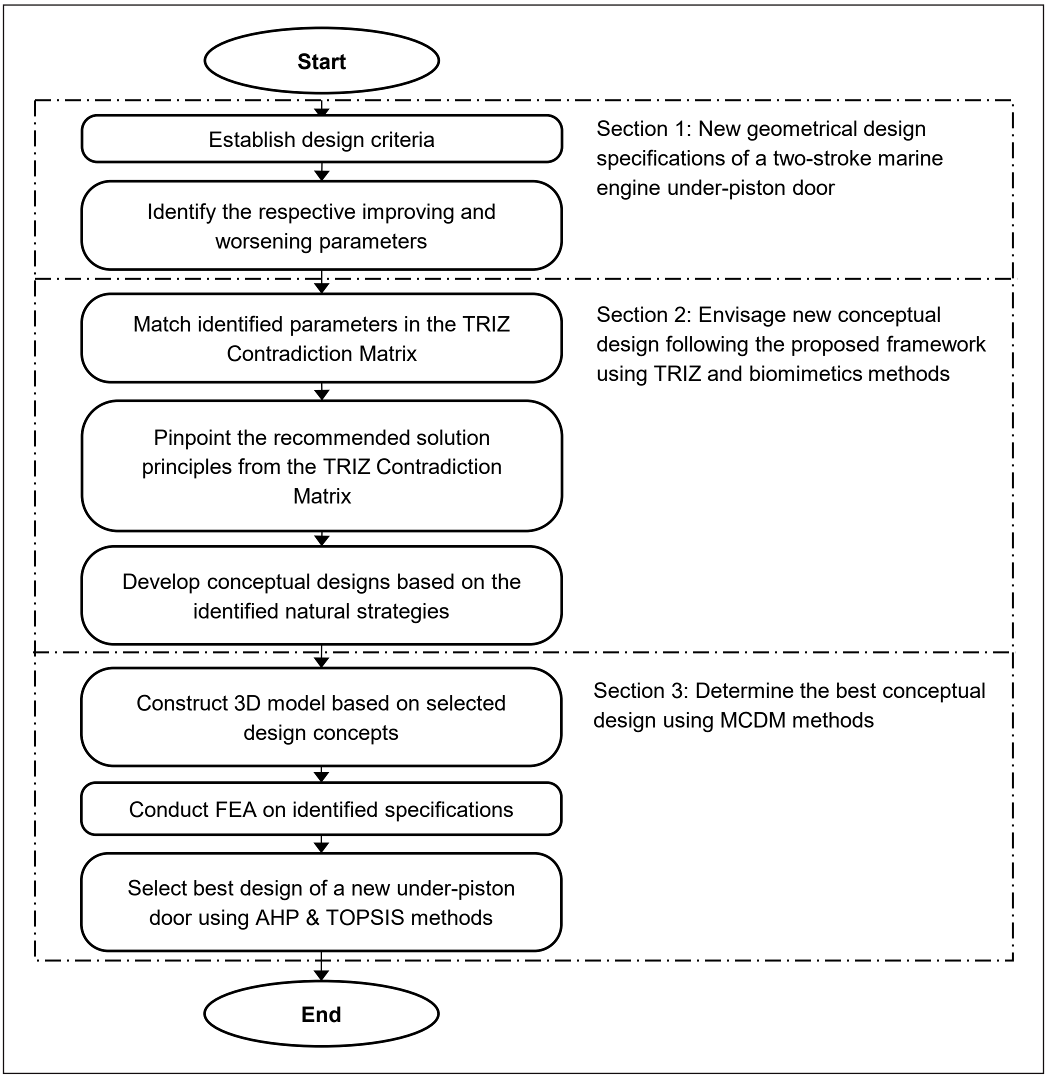


Figure 2. Flowchart of the design selection process

Establish Design Specifications

The specifications of the intended new under-piston door design can be divided into several parts. All regulatory requirements for marine engines were referenced, and guidance was sought from industry experts. From a general perspective, the main regulating body in the marine industry falls under the jurisdiction of the International Maritime Organization (IMO) (https://www.imo.org/). The International Convention for the Safety of Life at Sea (SOLAS) is the main international treaty focused on all aspects of the safety of merchant ships (https://tinyurl.com/2p9593az). SOLAS provides the framework and details involving all aspects of safety at sea, including those for the construction of seagoing vessels.

However, the authors did not come across any specific standards for applying non-metallic material in marine engine manufacturing or other related standards on engine component testing from SOLAS.

Another key aspect of safety in the marine industry is covered by the International Association of Classification Societies (IACS), which provides recommendations on the details of shipbuilding. They publish rules for the design, material selection, manufacturing methods, testing, and so on for ships and other related equipment, including marine machinery (https://iacs.org.uk/). Under IACS rules, Unified Requirements-Machinery Installations (UR M), M71 (Type Testing of Internal Combustion Engines) and M72 (Certification of Engine Components) provide details on engine certification and tests and specify the need for declaration of chemical composition and mechanical properties of materials used as well as witness of tests conducted on material samples (IACS, 2006). Another document, Unified Interpretations–SOLAS (UI SC), provides clarification on the use of non-metallic materials under SC282 (Application of Materials Other than Steel on Engine, Turbine and Gearbox Installations), in which it is mentioned that components not likely to cause release of flammable fluid to machinery and meet fire test criteria under ISO 19921:2005/19922:2005 can be manufactured using non-metallic materials (IACS, 2016).

Additionally, standards set by the International Standards Organization (ISO) were referred to in this research (*https://www.iso.org/home.html*). ISO 3046-1:2002E (Reciprocating Internal Combustion Engines - Performance - Part 1: Declarations of Power, Fuel and Lubricating Oil Consumptions, and Test Methods - Additional Requirements for Engines for General Use) defines the ambient conditions for engine aspiration at a temperature of 25°C and 1 bar gauge pressure. This standard has also been mentioned in the manuals of major marine engine makers (MAN Diesel & Turbo, 2010; Winterthur Gas & Diesel, 2023).

Incidentally, the initial motivation for the new under-piston door design was so that it could be made lighter, making it easier for removal and reinstallation during maintenance. The most obvious way to design a lighter object is to replace the material with something lighter or less dense. In line with the current drive for sustainability worldwide (United Nations, 2023), this new design for the under-piston door was intended to be made with NFC. Hence, there is a need for ingenuity in design to compensate for the loss of material strength due to the substitution of NFC. It should be highlighted that this research focuses only on the design selection. Material selection for NFC, including fibre, polymer, and fire retardant, shall be presented in a separate publication. Additionally, the physical dimensions of the under-piston door for a MAN B&W S60MC-C engine were measured and detailed in Figure 3.

Hence, for the ideation of a new under-piston door design, the criteria mainly provide setting values for the later simulation stage and the physical dimensions. The standards

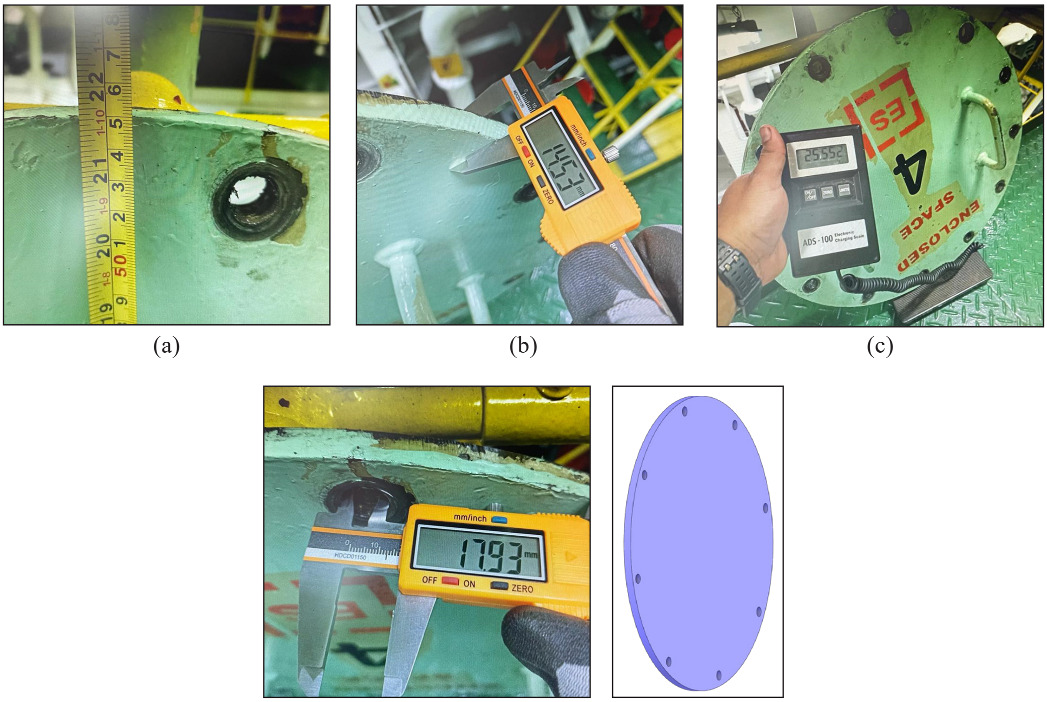


Figure 3. Measurements of an actual under-piston door for a MAN B&W 60MC-C marine engine with dimensions (a) diameter: 550 mm, (b) thickness: 15 mm, (c) weight: 25.5 kg, (d) bolt hole diameter: 18 mm, (e) CAD model of original under piston door

described were to verify that alternative materials were allowed for use in marine engines, where further tests would have to be performed, which would not be part of this research since the area of interest is limited only to the geometrical design of the said component. The details are summarised in Table 1.

Table 1
Design criteria for two-stroke marine engine under-piston door

Criteria	Description
Standard ISO 3046-1:2002E	Operating temperature: 25C Operating pressure: 1 bar
Dimensions	Diameter: 550 mm Thickness: 15 mm Bolt holes: 18 mm (diameter) × 8 nos

Design Ideation Using TRIZ and Biomimetics Methods

The intended purpose of the process was to reimagine the design of the under-piston door so that an improved and robust design could be envisioned. Although not part of this paper, the new design of the under-piston door is crucial in the wider scope of studying the potential of substituting steel with natural fibre composites. Hence, the process involves reimagining the simple bolted cover of the scavenge space of a two-stroke marine diesel engine, otherwise known commonly as the under-piston door, from a different perspective. The door is not subjected to high physical or thermal load levels, it was selected for this exercise.

The under-piston door had clearly defined parameters such as dimensions, weight, and strength. Considering these parameters carefully, two were applied to the TRIZ Contradiction Matrix (San, Jin and Li, 2009), those being “durability of a stationary object” and “strength”. This line of thought revolves around substituting steel, which has high strength, with composite material, which is of a lower strength, without losing its durability. Thus, the “durability of a stationary object” is the improving parameter, while “strength” is the worsening parameter to be applied in the Contradiction Matrix. Recommendations in the matrix are then referred to for potential solutions. However, in this case, no recommendation is specified in the matrix for these two parameters, suggesting that a wide choice of solutions can be considered for this problem.

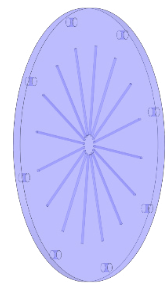
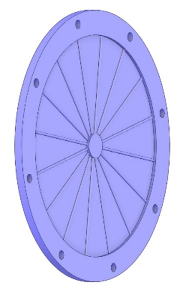
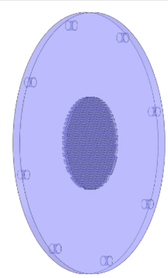
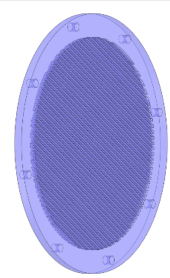
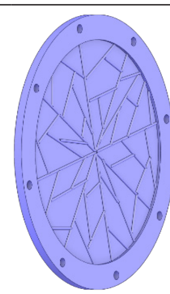
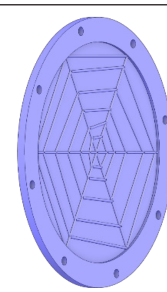
Since no recommendations were given, a careful study of all the TRIZ 40 Inventive Principles was carried out. Of the listed solutions, the decision was made to choose “Local quality”. This solution made the most sense for solving our problem, giving the idea that modifying the geometry of the under-piston door would improve its durability even if it was manufactured using material of lower strength. This solution pointed towards possible designs but still needed to suit the specifics of the under-piston door geometry. This stage demonstrates the generalised TRIZ process, whereby the specific problem is made into a generic TRIZ problem to find a generic TRIZ solution, which would then be adapted to a specific solution. It was then understood that fortifying the geometry was the way forward.

Specific solutions on structural fortification were then searched for in AskNature.org (Asknature, 2023). After going through the website’s large database of biological strategies, three strategies were identified as potential solutions for an improved under-piston door design. The first was the Amazon water lily, with its ribbed structure spanning its large leaves (Box et al., 2022). The second was the tortoiseshell, made of a sutured outer carapace and internally padded and reinforced with packings of twisted plywood-like fibrils (Achrai & Wagner, 2017). The third was the spider’s web, which is light but highly capable of absorbing the impact of flying insects that tangle in its intricate trap (Jyoti et al., 2019).

Six designs were drawn up from the biological strategies selected using ANSYS Discovery, as listed in Table 2. Design A1 has hollowed-out cylindrical sections radiating from the middle of the door. If this design was viewed externally, the observer could not tell any differences from the original design. On the other hand, A2 has a reduced thickness except for the flange area and is reinforced with cylindrical rod-like ribs radiating from the centre on the inside of the door. For B1, the internal structure of the door is made up of two rows of square-sectioned bars layered perpendicularly. Design B2 employs a similar arrangement as B1 but spreads across the whole door except for the flange. Similar to A1, both B designs are internal with no notable external difference from the original. Design

C1 and C2 have reduced door thickness with reinforcements similar to A2. C1 has eight ribs from the centre with additional randomly placed lattice reinforcements. C2, instead, has six ribs and is reinforced by random hexagonal rings. These were then simulated to obtain maximum stress (Von Mises), deformation, and volume. The simulation was performed using ANSYS Mechanical with a fixed edge support and a pressure of 4 bar on one side. These simulation results were then used in the next stage, where the best design was selected.

Table 2
Designs of under-piston doors inspired by biomimetic strategies

Biomimetic strategy	Design	
Amazon waterlily	 A1	 A2
Tortoiseshell	 B1	 B2
Spider web	 C1	 C2

Design Selection Using the AHP-TOPSIS Hybrid Method

With the obtained simulation results (Table 3), the selection process could then be performed. Through simulation with the ANSYS Mechanical software, results for each design were obtained for maximum stress (Von Mises), maximum deformation and volume. These three parameters and shape complexity would be the determinants for selecting the best design. For the shape complexity, the size of each file was taken as a reference, whereby a larger file size would represent a more complex design. The reasoning behind this is that the dimensions

Table 3
Data from simulation results for input into the TOPSIS method

Design	Maximum stress (von Mises) (MPa)	Volume ($\times 10^6$ mm^3)	Maximum deformation (mm)	Shape complexity
A1	70.506	5.47	0.361	395
A2	405.130	4.77	0.864	449
B1	89.497	5.36	0.457	1262
B2	225.950	4.73	0.809	5262
C1	413.460	4.78	0.907	689
C2	245.270	4.78	0.883	688

for the under-piston door model were the same for all designs. However, the complexity of each respective design increased the file size proportionately. Hence, it was taken as a fair representation of the design complexity suited as the fourth determining criterion.

Weightage Determination Using the Analytical Hierarchy Process (AHP)

The TOPSIS weightage for each criterion was first determined using the AHP process. AHP uses a pairwise comparison matrix, whereby each criterion is compared against the others. It has been used in previous decision-making exercises. Each pair is judged and graded based on a fundamental scale, as shown in Table 4. A decision is made based on the priority between the two compared criteria. A numerical value is given based on the decided judgment. If the comparison is found to be in between any of the stated priority levels, the corresponding numerical value is selected.

The first step in AHP is to establish the pairwise comparison and the priority vector values, *w*:

$$A = \left(a_{ij}\right)_{n\times n} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & 1 \end{bmatrix} \quad [1]$$

where $a_{ji} = {}^{1}/_{k}$ is the reciprocal value of $a_{ij} = k$, and $i, j = 1,2, \ldots, n$.

$$w = \frac{1}{n}\sum_{j=1}^{n} \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \quad [2]$$

where $i, j = 1, 2, \ldots, n$.

a_{ij} is the scale of importance.

In step two, the principal eigenvalue, λ_{max} is determined:

$$\lambda_{max} = \sum_{i=1}^{n} \frac{\sum_{j=1}^{n} a_{ij} \times w_j}{w_i}, \quad [3]$$

where $i, j = 1, 2, \ldots, n$.

In step three, the principal eigenvalue is then used to determine the consistency index, CI:

$$CI = \frac{(\lambda_{max} - n)}{(n-1)}, \quad [4]$$

Table 4
Fundamental scale for pairwise comparison

Priority level	Numerical value
Extremely less important	1/9
	1/8
Very strongly less important	1/7
	1/6
Strongly less important	1/5
	1/4
Moderately less important	1/3
	1/2
Equal importance	1
	2
Moderately more important	3
	4
Strongly more important	5
	6
Very strongly more important	7
	8
Extremely more important	9

Step four is where the consistency ratio is determined:

$$CR = \frac{CI}{RI} \qquad [5]$$

where *RI* is the random index that is selected based on the matrix size (Asadabadi et al., 2019), the Consistency Ratio, CR, should be 0.1 or less. It indicates that the results are consistent and acceptable (AL-Oqla et al., 2015; Al-Subhi, 2001).

Selection of Best Design with Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) Method

TOPSIS, as a Multi-Criteria Decision-Making (MCDM) tool, was chosen due to its suitability in engineering faculties where alternatives and evaluations can be generated (Opricovic & Tzeng, 2004). The main determining factor in TOPSIS is that the best alternative is closest to the positive ideal solution (PIS) and farthest from the negative ideal solution (NIS).

The TOPSIS method first begins with formulating the decision matrix:

$$D = \begin{vmatrix} & C_1 & C_2 & \dots & C_n \\ A_1 & X_{11} & X_{12} & \dots & X_{1n} \\ A_2 & X_{21} & X_{22} & \dots & X_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & X_{m1} & X_{m2} & \dots & X_{mn} \end{vmatrix} \qquad [6]$$

where:

A_1, A_2, ..., A_m are potential alternatives that the decision maker has to select:

C_1, C_2, ..., C_n are the criteria from which the potential alternative performances are measured:

X_{ij} is the rating of alternative A_i with reference to criterion C_j, where w_j is the weightage assigned to criterion C_j and $w_1 + w_2 + \dots w_n = 1$ (Roszkowska, 2011).

In step two, the normalised matrix, n_{ij}, is calculated:

$${}_{j} = \frac{\boldsymbol{x_{ij}}}{\sqrt{\sum_{i=1}^{m} \boldsymbol{x_{ij}^2}}} \qquad [7]$$

where $i = 1, 2, \dots, m$; j = $1, 2, \dots, n$.

Thirdly, the weighted normalised decision matrix, v_{ij}, is obtained:

$$v_{ij} = w_j n_{ij} \qquad [8]$$

where $i = 1, 2, \dots, m$; j = $1, 2, \dots, n$.

w_j is the weight of the *j*th criterion and $\sum_{j=1}^{n} w_j = 1$.

It is then followed by the fourth step to determine the ideal best, A^+ and ideal worst, A^- values, respectively:

$$A^+ = \{v_1^+, v_2^+ \dots, v_n^+\} = \left\{\left(\max_i v_{ij} \mid j \in I\right), \left(\min_i v_{ij} \mid j \in J\right)\right\} \quad [9]$$

$$A^- = \{v_1^-, v_2^- \dots, v_n^-\} = \left\{\left(\min_i v_{ij} \mid j \in I\right), \left(\max_i v_{ij} \mid j \in J\right)\right\} \quad [10]$$

Where *I* is associated with the beneficial criterion, and *J* is associated with the cost criterion.

The fifth step calculates the separation measures using the n-dimension Euclidian distance. Each alternative distance is defined as:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_i^+\right)^2} \quad [11]$$

where $i = 1, 2, \dots, m$.

$$d_j^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_i^-\right)^2} \quad [12]$$

where $i = 1, 2, \dots, m$.

The sixth step is to calculate the relative closeness to the ideal solution, A_j, with respect to A^+:

$$R_i = \frac{\boldsymbol{d_j^-}}{\left(\boldsymbol{d_j^-} + \boldsymbol{d_j^+}\right)} \quad [13]$$

where $0 \leq R_i \leq 1$, $i = 1, 2, \dots, m$.

The alternatives are ranked in descending order based on the obtained R_i values.

RESULTS AND DISCUSSION

The weightage of each criterion was determined first with AHP. The first step was establishing the pairwise comparison matrix of the four determining criteria (Table 5). It established the hierarchy of importance across the selected criterion in Table 3. The following steps were then simply to obtain the respective values for the principal eigenvalue, λ_{max}, consistency index, CI, and consistency ratio, CR (Table 6). The determined consistency ratio is 0.01997, which is less than 0.1. Hence, the results obtained are verified as acceptable. The final determined weightage of the selected criteria is reflected in Table 7, which will be used in the next phase of the design selection.

From here, the design selection process moves on to the TOPSIS method. The values obtained from the simulation (Table 3) are first normalised to bring all values under a common scale in the matrix shown in Table 8. These normalised values are then weighted

Table 5
Pairwise comparison matrix

Criteria	Maximum stress (von Mises)	Total deformation	Volume	Complexity
Maximum stress (von Mises)	1	2	5	6
Total deformation	1/2	1	4	5
Volume	1/5	1/4	1	1
Shape complexity	1/6	1/5	1	1

Table 6
Principle eigenvalue, λ_{max}, consistency index, CI, and consistency ratio, CR

Principle eigenvalue, λ_{max}	4.054
Consistency index, CI	0.01797
Consistency ratio, CR	0.01997

Table 7
Weightage values for selected criteria obtained through the AHP method

Criteria	Maximum stress (von Mises)	Volume	Total deformation	Shape complexity
Weightage	0.508	0.087	0.326	0.079

Table 8
Normalised matrix

Design	Maximum Stress (Von Mises) (MPa)	Volume (mm^3)	Maximum Deformation (mm)	Shape complexity
A1	0.104	0.447	0.197	0.071
A2	0.598	0.390	0.473	0.081
B1	0.132	0.438	0.250	0.228
B2	0.333	0.387	0.443	0.951
C1	0.610	0.391	0.496	0.125
C2	0.362	0.391	0.483	0.124

using the weightage obtained from the AHP exercise for the respective criterion (Table 9). Now that the weightage has been included, the positive ideal solution (PIS) and negative ideal solution (NIS) are determined (Table 10). The purpose of obtaining PIS and NIS is to define the range or scale of measurement for the criteria. It allows for ranking each envisioned design according to the respective criterion. Once the rankings are calculated, the Euclidean distance determines the ranking for all six designs (Table 11).

The results obtained from this research showed that the best design is A1, which was inspired by the Amazon waterlily. For comparison, the simulated data was put side by side with that of the original design of the under-piston door, as depicted in Table 12.

Table 9
Weighted normalised matrix

Design	Maximum Stress (Von Mises) (MPa)	Volume (mm^3)	Maximum Deformation (mm)	Shape complexity
A1	0.053	0.039	0.064	0.006
A2	0.304	0.034	0.154	0.006
B1	0.067	0.038	0.082	0.018
B2	0.169	0.034	0.144	0.075
C1	0.310	0.034	0.162	0.010
C2	0.184	0.034	0.157	0.010

Table 10
Positive and negative ideal solution matrix

	Maximum Stress (Von Mises) (MPa)	Volume (mm^3)	Maximum Deformation (mm)	Shape complexity
PIS	0.053	0.034	0.064	0.006
NIS	0.310	0.039	0.162	0.075

Table 11
Overall ranking of designs

Design	Positive ideal solution	Negative ideal solution	Relative closeness to the ideal solution	Ranking
A1	0.005	0.284	0.982	1
A2	0.266	0.070	0.207	5
B1	0.026	0.262	0.910	2
B2	0.158	0.142	0.474	3
C1	0.275	0.066	0.192	6
C2	0.161	0.142	0.469	4

Table 12
Comparison of simulated data of new designs with original under-piston design

Design	Maximum stress (von Mises) (MPa)	Volume ($\times 10^6$ mm^3)	Maximum deformation (mm)	Shape complexity
A1	70.506	5.47	0.361	395
A2	405.130	4.77	0.864	449
B1	89.497	5.36	0.457	1262
B2	225.950	4.73	0.809	5262
C1	413.460	4.78	0.907	689
C2	245.270	4.78	0.883	688
Original	128.80	5.53	0.378	294

Compared to the original, A1 also showed reductions in maximum stress (von Mises), volume, and deformation by 45.25%, 0,97% and 4.61%, respectively. However, there was an increase in shape complexity by 34.35%. The values of maximum stress (von Mises) and deformation provide information on the design's ability to withstand mechanical load without damage to the structure. The reduction in these two parameters for A1 indicates that this design can be better than the original when exposed to normal working conditions. Furthermore, the volume reduction directly translates to a reduced weight of the under-piston door. At the start of this research, it was not expected that new designs could have obtained better readings than the original.

The results of designs A1 and A2 indicate that hollowed-out cylindrical sections in A1 greatly reduce the stress experienced by the under-piston door compared to the added external ribs in A2. The reduced thickness in A2 can also cause an increase in deformation compared to A1 and the original. It can be suggested that the reduction in thickness of the under-piston door, as seen in designs A2, C1 and C2, led to these three designs recording the highest maximum stress (von Mises) and deformation. Design B1 ranked second place, showed improvement in maximum stress (von Mises) compared to the original. However, it did not provide ample support and instead showed an increase in deformation compared to the original. In B2, where the two rows of square bars extended across the whole door within the flange, the maximum stress (von Mises) and deformation increased greatly by 150.47% and 77.00%, respectively, compared to B1. It indicates that the extensive reduction in B2 material contributed to the weakening of the structure, considering that B2 registered the lowest volume. Furthermore, B2 was also the most complex among the simulated designs. As for designs C1 and C2, which we ranked sixth and fourth, respectively, indicate that external ribs did not provide the necessary structural compensation for the reduction in thickness, as previously justified when discussing design A2.

CONCLUSION

Six designs were evaluated across four criteria. The determined weightage calculated using the AHP method for the four criteria from highest to lowest were maximum stress (von Mises) (0.508), maximum deformation (0.326), volume (0.087) and shape complexity (0.079). Through the TOPSIS method, the best design was determined to be design A1, with relative closeness to the ideal solution of 0.982, followed by B1 (0.910), B2 (0.474), C2 (0.469), A2 (0.207) and C1 (0.192). The results obtained from the simulation exercise showed positive proof of the potential of applying TRIZ with biomimetics to improve an existing design of an under-piston door for a two-stroke marine diesel engine. When combined symbiotic, these ideation tools promote creative thinking and can push the barriers to creativity in problem-solving. As it is common today to see many applications using a combination of MCDM methods, the demonstration where AHP and TOPSIS complemented each other proved a successful collaboration. This design ideation and selection process brought together the four methods of TRIZ, biomimetics, AHP and TOPSIS to decide on an improved design of the under-piston door for a two-stroke marine engine. Future work on this subject will include the selection of the best NFC, which shall comprise natural fibre, polymer matrix and fire retardant.

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