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Selection of Optimal Air Independent Propulsion System using Forced Decision Matrix

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ABSTRACT

A project management decision tool viz., forced decision matrix (FDM) is implemented in this paper towards identification of a suitable optimal air independent propulsion (AIP) system for submerged vehicles. FDM is utilised in order to handle the trade-off from amongst multiple propulsion technologies. FDM is based on multi-attribute utility theory used extensively in decision analysis situations involving persuasive multiple alternatives. The efficiency and effectiveness of this methodology to tackle complex solutions is elaborated in this paper with appropriate calculations. A rational decision-making procedure is evolved using the FDM in order to select the best suited AIP technology for a submerged vehicle. It is inferred that FDM is an effective and potential tool towards identification of best suitable solution in a multi-option environment.

Keywords: Forced decision matrix; Multi-attribute utility theory; Decision analysis; Air independent propulsion

1. INTRODUCTION

The World navies are undergoing a period of inevitable transformation wherein stealthier brown water patrolling has become the need of the hour. Air independent propulsion (AIP) systems offer increased stealth and greater submerged endurance. These AIP sections are often referred as ‘plugs’ and can be catered for inclusion during the submarine design phase or retrofitted on an existing platform. The displacement of an average conventional submarine varies between 2500 tonne - 3500 tonne. The capability and exploitation of battery power on a conventional submarine is restricted to an average of 24h when operating at lower speeds (< 5 Knot) and necessitates snorkeling towards replenishment of batteries. At present, AIP technology is in its nascent stages and is often used only as supplementary powering source in addition to primary propulsive source onboard[1]. The current maximum submerged endurance of an AIP vessel is between 07 -14 day. In this paper, AIP systems have been classified into four main group and the key parameters which determines the selection of technology have been reviewed comprehensively through implementation of forced decision matrix (FDM) methodology. Identification of parameters and calculation of co-efficient has been carried out. The advantages and disadvantages of each process are evaluated to select the best possible AIP solution.

In the present scenario, a significant amount of money and time is spent by nations all around the world in order to evolve a better air independent propulsion technology which would be best suited for conventional diesel electric submarines. Conventional submarines are often considered stealthier than their nuclear counterparts. However, the only shortfall lies in their dependence to snorkel to recharge the batteries. A nuclear submarine edges the conventional submarine because of their exponential power availability for propulsion and its non-compromise on the bulkiness of the vessel and speed of transit. Even though the AIP systems are considered as an immaculate solution to bridge the gaps, there is a need to identify an idealistic AIP system for a conventional diesel electric submarine.

Most of the studies undertaken highlight the technological advantages of an AIP system, there exists very little literature available in open source towards implementation and adaptation of AIP system onboard. In this context the paper proposes FDM to evaluate the existing AIP technologies prevalent in the global scenario and aids in selection of an energy efficient system for induction onboard. FDM is a methodology which is based on the decision matrix analysis. It is a project management technique utilised in order to decipher the nuances of parameters and pitch it against each other to filter out the best amongst each parameter[2] structured in the similar way of a business decision model structure. All AIP systems installed onboard submarines usually employs a ‘Plug Concept’ where in the majority of the equipment and the control electronics are housed inside the submarine and only the hydrogen being hazardous in nature is stored outside the submarine in metal cylinders attached to the pressure hull of the submarine. Whilst taking into consideration the overall system efficiency it is important that the system availability and the associated costs involved be considered during system selection. The existing AIP technologies

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vis-à-vis their advantages and disadvantages in terms of stealth, efficiency and criticality has been brought out in this paper.

2. TYPES OF AIR INDEPENDENT PROPULSION SYSTEMS

2.1 Closed Cycle Diesel Engines

Closed cycle diesel engines (CCD) as depicted in Fig. 1 employs a technology where in the submarine utilises its conventional diesel engine on the surface and a separate diesel engine for submerged condition. This Specialised diesel engine employed combustion of liquid oxygen for its sub-surface operations[3]. However, operation of diesel engine under submerged conditions will be slightly trickier due to two distinct facts – maintaining the thermodynamic efficiency of the engine and dispensation of exhaust against the water pressure at dived depth[4–6]. List of Submarine classes on which CCD AIP was installed/envisaged is as appended in Table 1. The closed cycle diesel engine AIP system is the cheapest among the existing AIP options however the system poses an inherent disadvantage of comprised stealth due to its heavy moving parts. The Overall thermodynamic efficiency of an CCD AIP system is around 30 per cent.

Table 1. Platforms on which closed cycle diesel engine AIP technology is installed/envisaged

Submarine/Platform	AIP option utilised	Country
U-1 /Type 205	CCD	Germany
Moray Class (Design)	CCD/Spectre	Netherlands

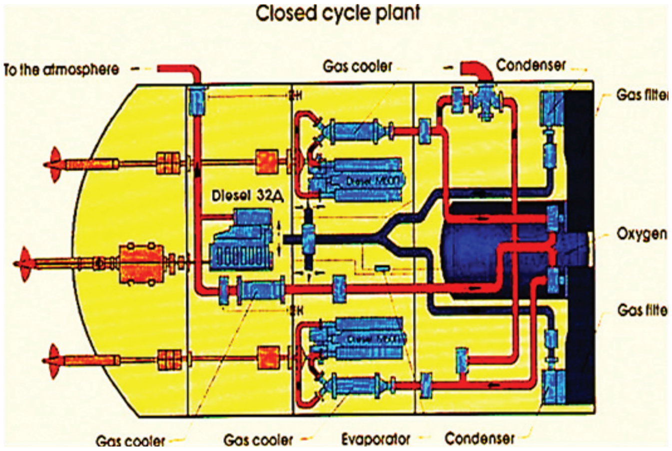

Figure 1. Closed cycle diesel engines of erstwhile quebec class Russian submarines.

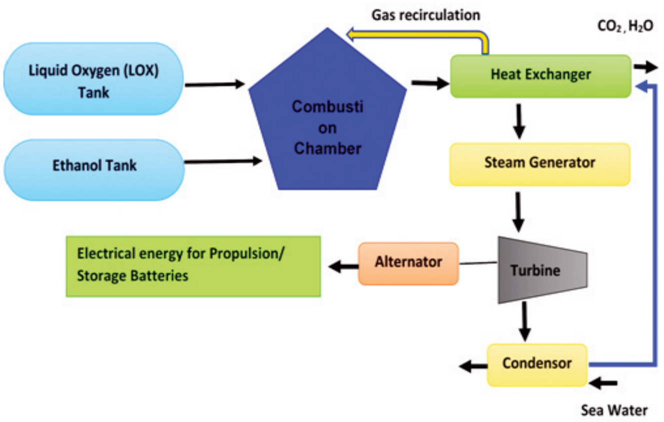

Figure 2. Schematic representation of closed cycle steam turbine module et sous marine autonome (MESMA).

2.2 Closed Cycle Steam Turbine (Module Et Sous Marine Autonome- MESMA)

Closed cycle steam turbine technology exploits the mechanical energy of the turbine coupled with an alternator to derive electrical energy. The system is based on Rankine cycle as shown in Fig. 2. The system burns liquid oxygen (LOX) along with Ethanol used as main fuel in the system at a temperature in excess of 600 °C. The heat generated is transferred to the steam circuit which in turns drives the turbine. The alternator coupled to the turbine produces the electrical energy required for propulsion machinery and auxiliary circuits. MESMA has slightly edged out CCD in stealth by the employment of a rotational machinery (turbine) as compared to reciprocating system (diesel engine) in CCD. Presently CCD is exploited only by a single nation (France). The technology is known by its abbreviation ‘MESMA’ which stands module D’Energie sous marine autonome[7]. The design of the MESMA is based on steam Rankine cycle and the technology is similar to that of the turbine system of a nuclear submarine. Combustion of ethanol in presence of oxygen causes generation of steam which in turn powers the turbine for generation of power[7]. It is pertinent to mention that the MESMA technology possess the least efficiency (≤ 25%) amongst the four prevalent AIP technologies in the world[8]. In the current scenario, France is the only country which holds monopoly in closed cycle steam turbine technology as shown in Table 2.

Table 2. Platforms on which Closed Cycle steam Engine AIP technology is installed/envisaged

Submarine/Platform	AIP option utilised	Country
Agosta-90B	MESMA	Pakistan/France
Scorpene (Envisaged)	MESMA	India/France

2.3 Stirling Engine

Stirling engines generate power by combustion of liquid oxygen with diesel fuel oil. The system is based on stirling cycle as depicted in Fig. 3. The source of energy is extracted from the working fluid which is permanently contained as part of the system. The engine is run using the heat extracted from the working fluid. Then the extracted energy is used either to recharge batteries or for direct propulsive load of the submarine[9] . The resultant exhaust gases are thrown overboard the submarine by means of scrubbers. The Major advantage the system could offer is utilisation of diesel as its main fuel source hence reduces the complexity during refuelling operations. These systems are inherently bulkier and poses reduction in stealth when compared with the silent fuel cell AIP systems. The diving depth of the submarine will be restricted due to the interlock with the dispensation of exhaust gases overboard due to the running of the engine. Due to the flexibility, reduction in retrofit systems and cheaper operational costs feature as the

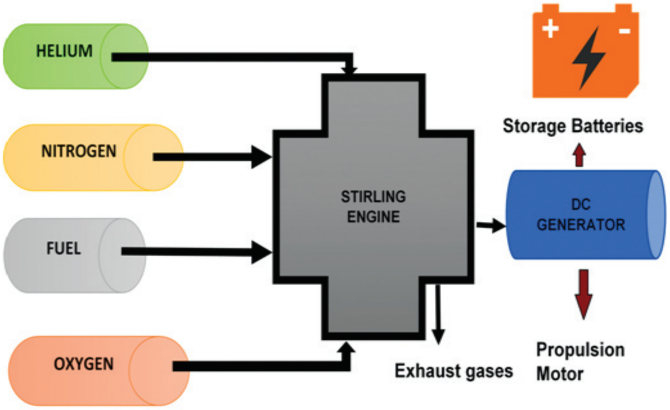

Figure 3. Schematic representation of Stirling engine.

unique selling point (USP) for stirling AIP system. The biggest advantage of the system is the ability of the system to utilise the onboard fuel. Thought the fuel storage space is saved it is equal compensated by inclusion of a large Internal combustion diesel engine. Currently the Swedish, Chinese and Japanese are the biggest employers of Stirling air independent propulsion onboard their submarines[10]. The list of platforms on which the Stirling -AIP option is employed is highlighted in Table 3.

Table 3. Platforms on which Stirling Engine AIP technology is installed/envisaged

Submarine/Platform	Country
Nacken Class	Sweden
Gotland Class (Design)	Sweden
Sodermanland Class	Sweden
Archer Class	Singapore
Soryu Class	Japan
Harushio Class (Test & trials)	Japan
Type-039A Class	China
Type-041 Class (Yuan)	China
Type- 032 (Qing)	China

2.4 Fuel Cell

Fuel cells are emerging as the widely sought-after technology and probably may emerge as a flag bearer of the AIP technologies in future. The System works on the basic principle of combination of Hydrogen and oxygen molecules to produce electrical energy with water as its primary waste product as shown in Fig. 4. The waste water produced can be expelled outboard using the submarines water dispensation system. Fuel cells are heavily researched everyday both in commercial and military sectors due to its many distinct advantages including size, stealth and exhaust dispensation[11]. Employment of fuel cells onboard submarines started way back in early 80's[12] and is still progressing ahead with a rapid pace solely owing to the innovation and flexibility of growth in the field area[13]. With an efficiency of 50-70% fuel cells provide the much-needed flexibility, ease of operation and enhanced stealth when compared to other AIP systems. The utilisation of fuel cell onboard submarines is as appended in Table 4.

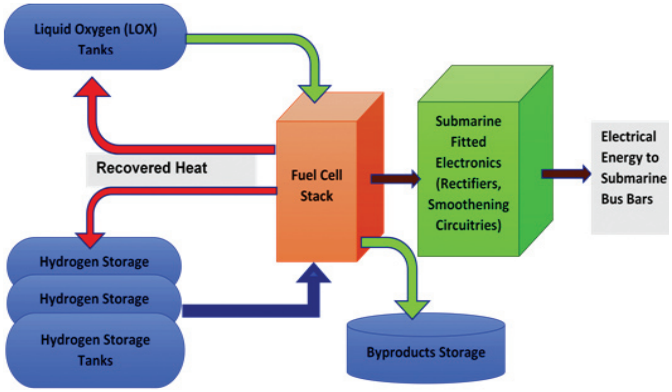

Figure 4. Schematic representation of fuel cell system in a submerged platform.

Table 4. Platforms on which fuel Cell AIP technology is installed/envisaged

Submarine/Platform	Country
Dolphin class	Israel/Germany
Type-209 (Export)	Germany
Type 212	Germany
Type 214	Germany
Type 218	Germany
S-80 Class	Spain
Project 677 (Lada class)	Russia
Project 1650 (Amur class)	Russia
Kalvari Class	India

3. IMPLEMENTATION OF FORCED DECISION MATRIX

Forced decision matrix (FDM) has been utilised in this paper to determine the best suited AIP system for submarines. Critical factors towards differentiation of AIP systems amongst each other are enlisted in the parameter identification (Table 5). Forced decision matrix enables us to prioritise the best option in a logical manner. The FDM is structured on the decision matrix analysis, a management technique which is employed for multiple criteria decision analysis (MCDA). This paper utilises the selection of all AIP options on similar lines of a business decision making methodologies based on subjective data. Decision matrix is often employed when there are multiple alternatives and multiple interlink factors governing each alternative.

Table 5. Parameter selection

Unique identification parameter	Value
Investment cost	1
Technological advancement/ maturity	2
Submerged endurance	3
Replenishment/routine maintenance/lay-off period	4
Ease of operation	5
Augmentation ability	6
Stealth	7

3.1 Identification of Critical Parameters

The important parameters which governs the implementation of an AIP system onboard viz. Cost, stealth submerged endurance, operational exploitability, system down time, future expandability has been identified and is as tabulated in Table 5.

3.2 Calculation of Attributed Weight Coefficient

The calculation of the attributed weight coefficient (AWC) is based on a matrix approach of pitting the unique parameters against each other in pair in order to determine the relative weightage. The most essential parameters for technology selection are as enlisted in Table 5. The calculation of AWC is undertaken utilising the weighted values of these parameters. The most important parameter is assigned the value '1' and the least is assigned '0'. The weights provided to different parameters are summed and divided with the total number of comparisons made in the matrix. For ease of understanding the first row calculation of AWC is depicted in the following steps:

(a) Summation of first row – (0+0+1+1+1+0) = 3.
(b) Attributed weight coefficient of 1st row depicting investment cost = (Summation of first row /7) = 3/7.
(c) AWC = 3/7 = 0. 4285≃0. 43.

The same methodology is utilised for calculation of AWC values for other respective critical parameters as shown in Table 6.

Table 6. Calculation of attributed weight coefficient

	1	2	3	4	5	6	7	AWC
1		0	0	1	1	1	0	.43
2	1		0	0	0	1	1	.43
3	1	1		0	1	0	1	.57
4	0	0	0		1	0	0	.14
5	0	1	0	0		1	0	.29
6	0	1	0	0	0		1	.29
7	1	1	1	0	1	1		.83

3.3 Determination of Sample Weight Coefficient

To address the continual question to determine the best of the technology, seven critical parameters were identified common to the four existing AIP technologies and were compared against each other in pairs with respect to each parameter separately. The results of individual parameter comparison are formulated as a definitive matrix. The most important parameter is given a weightage of' '1' and least is assigned a value '0'. Finally, the individual parameter weightage is added and the sum is divided by the total number of comparisons from the matrix. Sample weight coefficient (SWC) is calculated for each critical parameter as per the steps appended below

(a) Step1: Summation of first row
(b) Step 2: Sample Weight Coefficient of 1st row = (Summation of first row /4)
(c) Step 3: Approximated decimal value of SWC for every AIP technology is calculated.

3.3.1 SWC for Investment Cost

Investment cost plays a vital role in the acquisition of the technology. This cost later transforms itself into operation and maintenance costs. The operation costs of fuel cells are much higher when compared to that of the CCD/Stirling engines. The major cost component of Fuel cell system is the storage system required for the liquid oxygen[14] as well as the hydrogen, the two essential components of the Fuel cell. Usage of methanol makes the MESMA a high-priced system next to Fuel cell[15]. The CCD/Stirling engines are relatively low priced when compared to their counterpart AIP systems as they utilize the diesel oil of the conventional submarines to generate power[15]. The sample weight coefficient calculated for investment cost parameter is as tabulated in Table 7.

Table 7. Calculation of SWC: Investment cost

	CCD	MESMA	STIRLING	FC	SWC
CCD		0	0	1	0.25
MESMA	0		1	1	0.5
STIRLING	0	1		1	0.5
FC	1	1	1		0.75

3.3.2 SWC for Technological advancement/maturity

Technological maturity will provide a clear advantage in choosing a technology which has been implemented onboard a vessel. Its performance characteristics can be assessed and a definitive opinion can be drawn on its output. These systems will have a low risk rate. Investments for further research towards betterment of such mature technologies will generally be dried up. The Soryu (Japan), Yuan (China) and Sodermanland (Sweden) class of submarines and are fitted with Stirling engines[16]. Technological advancements play a pivotal role towards acquisition and further aids in development and augmentation of the system. Ease of usage and replacement changes drastically when compared between a fuel cell AIP system with a CCD AIP system. It is learnt that the German 209s/214s export variant[17] fitted with fuel cells are providing a stiff competition to the MESMA and Stirling engine submarines. The sample weight coefficient calculated for technological advancement/maturity parameter is as tabulated in Table 8.

Table 8. Calculation of SWC: Technological advancement/maturity

	CCD	MESMA	STIRLING	FC	SWC
CCD		0	0	0	0
MESMA	0		1	0	0.25
STIRLING	1	1		0	0.5

FC	1	1	1		0.75

3.3.3 *SWC for Submerged Endurance*

The submerged endurance of the AIP system is directly proportional to the amount of fuel that is present in the storage tanks[18]. The consumption of LOX plays a major role in determination of the endurance. MESMA is the largest consumer of LOX amongst the existing AIP systems and has a lowest efficiency rate of 25~30%[19]. The CCD systems when active in service had an efficiency rate of 30 ~ 35%[19]. The Stirling engines has an efficiency rate of 40% [19]. Comparative lesser consumption of oxygen results in an overall optimal sizing of a fuel cell AIP system. These fuel cell systems have a high efficiency rate of over 70 %[20]. The sample weight coefficient calculated for submerged endurance parameter is as tabulated in Table 9.

Table 9. Calculation of SWC: Submerged endurance

	CCD	MESMA	STIRLING	FC	SWC
CCD		0	0	1	0.25
MESMA	1		0	1	0.5
STIRLING	1	1		1	0.75
FC	1	1	1		0.75

3.3.4 *SWC for Replenishment/Maintenance/Lay off Period*

Replenishment of expended fuel plays a vital part for operation and exploitation of an AIP system. The fuel cell which mainly functions of Hydrogen and oxygen will require suitable infrastructural development for catering to its specific needs. Storage of H_2/O_2 are extremely complex in nature and a specialised local support team must be dedicated in order to the cater the needs of the submarine[21]. Replenishment of diesel oils utilized in CCD/Stirling engines are found to be less simple when compared to liquid oxygen, hydrogen and ethanol used in fuel cell and MESMA systems. The maintenance routines are far lesser in a fuel cell system when compared with MESMA, CCD or Stirling engine systems. The sample weight coefficient calculated for replenishment/maintenance/lay off period parameter is as tabulated in Table 10.

Table 10.Calculation of SWC: Replenishment/Lay-off period

	CCD	MESMA	STIRLING	FC	SWC
CCD		0	0	0	0
MESMA	0		1	1	0.5
STIRLING	0	1		1	0.5
FC	1	1	1		0.75

3.3.5 *SWC for Ease of Operation*

The Stirling engine, CCD and MESMA systems will be comparatively easier to operate from the crew's point of the view as the operation of these systems will not greatly vary from the operation of conventional diesel engines which are being operated on a daily basis[22]. Fuel cell systems though will appear tough and sophisticated at the beginning, proper training with adequate exposure in operation of the system will enable the crew to exploit the system in an optimal manner. The sample weight coefficient calculated for ease of operation parameter is as tabulated in Table 11.

Table 11.Calculation of SWC: Ease of operation

	CCD	MESMA	STIRLING	FC	SWC
CCD		1	0	0	0.25
MESMA	1		0	0	0.25
STIRLING	1	1		0	0.5
FC	1	1	0		0.5

3.3.6 *SWC for Augmentation Ability*

The fuel cell system is widely researched all around the world and the research work will continue its growth exponentially in the forthcoming years. With huge investments being pumped in Fuel cell research coupled with outstanding efficiency rates compared to other AIP technologies, fuel cell (FC) will be the best suited technology which stands a better future for any major augmentation/overhaul to an existing design. The biggest challenge faced by the Fuel cell system is its storage of hydrogen and oxygen fuels both onboard the submarine as well as in the yard. The sample weight coefficient calculated for augmentation ability parameter is as tabulated in Table 12.

Table 12. Calculation of SWC: Augmentation ability/growth

	CCD	MESMA	STIRLING	FC	SWC
CCD		0	0	0	0
MESMA	1		0	0	0.25
STIRLING	1	1		0	0.5
FC	1	1	1		0.75

3.3.7 *SWC for Stealth*

The stealth forms the most important parameter during acquisition of any major equipment which is going to be fitted onboard a submarine. The CCD, Stirling engines and the MESMA creates a large amount of vibrational noise due to the rotational noise created by the steam turbines. In addition, the carbon dioxide which is expelled as a by-product is expelled overboard through a muffler arrangement which still creates a disturbance in the ambient environment[23]. Fuel Cell is the quietest amongst all the AIP technologies and paves way for increasing the overall stealth of the conventional diesel electric submarine. The sample weight coefficient calculated for stealth parameter is as tabulated in Table 13.

Table 13. Calculation of SWC: Stealth

	CCD	MESMA	STIRLING	FC	SWC
CCD		0	1	0	0.25
MESMA	0		0	0	0

STIRLING	1	0	■	1	0.5
FC	1	1	1	■	0.75

3.4 Calculation of Total Weight Co-efficient

Determination of total weight co-efficient enables us to zero in the most optimal AIP technology based on parameter optimisation.

Total weight is determined by multiplication of attributed weight co-efficient (AWC) of the individual parameter with the sample weight co-efficient (SWC) of the individual AIP technology and is as depicted in equation 1.

$$\text{Total Weight (TW)} = \text{AWC} * \text{SWC} \quad (1)$$

4. RESULTS AND DISCUSSIONS

A total weight coefficient (TWC) is calculated by summation of all individual Total weight (TW) of critical parameters. The results are as tabulated in Table 14. The results are based on the calculation of Total weight (TW) component of the particular AIP system. The calculations of CCD from Table 14 is elaborated in the following steps:

(a) AWC values obtained for every critical parameter is substituted in row 1.

(b) SWC values obtained for every critical parameter is substituted in row 2.

(c) Total weight (TW) of CCD is obtained by product of AWC *SWC for every critical parameter. The values are substituted in row 3.

(d) Total weighted coefficient is the summation of all the Total weights obtained for every critical parameter.

It is as evident from the Table 14 that Fuel cell outweighs the other AIP systems. The Project/system are ranked according to their overall scores.

Table 14. Calculation of total weight co-efficient (TWC) matrix

	ATT	1	2	3	4	5	6	7	TWC
CCD	AWC	.43	.43	.57	.14	.29	.29	.83	0.53 (IV)
	SWC	.25	0	.25	0	.25	0	.25	
	TW	.11	0	.14	0	.07	0	.21	
MESMA	AWC	.43	.43	.57	.14	.29	.29	.83	0.82 (III)
	SWC	.5	.25	.5	.5	.25	.25	0	
	TW	.21	.11	.29	.07	.07	.07	0	
STIRLING	AWC	.43	.43	.57	.14	.29	.29	.83	1.64 (II)
	SWC	.5	.5	.75	.5	.5	.5	.5	
	TW	.21	.21	.43	.07	.15	.15	.42	
FUEL CELL	AWC	.43	.43	.57	.14	.29	.29	.83	2.16 (I)
	SWC	.75	.75	.75	.75	.5	.75	.75	
	TW	.32	.32	.43	.11	.14	.22	.62	

5. CONCLUSIONS

This paper demonstrates a selection methodology using a project management technique (FDM) towards identification of optimal an AIP system for submarines. The analysis is focused on actual implementation whilst catering for long term parameters governing the installation of the system including operational limitation and supportability. Forced decision matrix[24] is powerful for analysing factors when there are more than one alternate solutions. It is understood from the table that the fuel cell has the maximum total weighted coefficient and emerges as the best solution amongst other AIP systems. Though Stirling engines have been installed onboard conventional boats and have performed consistently over the years, the technology however has reached its maturity and has very minimal scope for extraordinary improvement unlike the case of fuel cell AIP systems.

Fuel cells may initially draw high investment costs but will be beneficial in the longer run. With increased need for stealthier conventional submarines to operate in the brown waters, fuel cell technology emerges out as a clear choice of AIP option for Conventional submarines. FDM methodology can be considered as an important precursor solution towards project implementation. Further studies such as Techno economic analysis of the narrowed down project can be undertaken in future prior installation, based on the above FDM methodology.

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Contribution in the current study, he has formulated main research ideas, analysed the results, and contributed in the manuscript preparation.

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Contribution in the current study, he has provided overall guidance. Prepared the final manuscript and conducted the final checking for checking the integrity of the study.