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Felipe Augusto Soares Salgado, Luiz Octávio Gavião, Leonardo Augusto dos Santos Oliveira, José Cristiano Pereira

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Felipe Augusto Soares Salgado,
Luiz Octávio Gavião* and
Leonardo Augusto dos Santos Oliveira

Postgraduate Program in International Security and Defense,
Brazilian War College,
Rio de Janeiro, RJ, Brazil
Email: felipesalgado.jornalismo@hotmail.com
Email: luiz.gaviao67@gmail.com
Email: laso80@outlook.com
*Corresponding author

José Cristiano Pereira

Department of Engineering Systems,
Petropolis Catholic University,
Petropolis, RJ, Brazil
Email: pereirajosecristiano084@gmail.com

Abstract: This paper examines the selection of polar research vessels as a reference for procurement by the Brazilian Antarctic Program (PROANTAR). The methodology is based on a hybrid model, combining multicriteria decision support methods (AHP and TOPSIS) and capability-based planning to improve the navy's decision-making process. Four modern research vessels were analysed in this research. The dataset for the AHP and TOPSIS assessments was obtained from questionnaires to Brazilian Navy officers with a background in naval sciences, management of Antarctic operations and experience with polar vessels. The expected divergences in the assessments were submitted to a Monte Carlo simulation procedure, emulating new data with probability distributions to alleviate these disturbances. The results presented an order of preference for these vessels, in addition to illustrating the application of a new model to support the navy's decision-making process.

Keywords: Antarctic vessel; polar vessel; AHP-TOPSIS; capability-based planning; CBP.

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Biographical notes: Felipe Augusto Soares Salgado is a journalist specialised in the offshore and naval sector. He has been covering the oil and gas sector for ten years, with an emphasis on subsea production systems and the construction of drilling platforms and rigs. He holds a Master's in International Security and

Defence from the Brazilian War College, MBA in Oil and Gas Economics and Postgraduate in Environmental Management from Federal University of Rio de Janeiro (UFRJ), Brazil. Currently, he works as the Editor-in-Chief of the PetróleoHoje, website from Brasil Energia.

Luiz Octávio Gavião received his DSc and MSc in Industrial Engineering from the Fluminense Federal University (UFF). He is a 1989 graduate of the Brazilian Naval Academy and served 30 years in the Brazilian Navy. His operational command includes the 3rd Infantry Battalion (Brazilian Marines) and the 16th Contingent of the Navy in the United Nations Stabilization Mission in Haiti (MINUSTAH), in 2012. He is a Professor at the Brazilian War College (ESG), with research focus on modelling defence problems with multicriteria decision support methods.

Leonardo Augusto dos Santos Oliveira is a Civil Engineer, graduated from the Federal University of Santa Catarina (UFSC) in 2005. He is a specialist in Business Management from the Getulio Vargas Foundation (FGV) in 2011. He holds a Master's in Business Administration from the Brazilian School of Public and Business Administration (EBAPE) in 2013 and Doctor in Business Administration from Getulio Vargas Foundation (FGV) in 2017. He is currently an Adjunct Professor at the Brazilian War College (ESG).

José Cristiano Pereira is a graduate of Mechanical Engineering from the Petropolis Catholic University (UCP) in Brazil. He received his Master's in Management Systems and Doctor's in Industrial Engineering from the Fluminense Federal University (UFF), Brazil. He has been working in the field of jet engines maintenance and manufacturing for the past 36 years. He is also a Professor at the Petropolis Catholic University (UCP), Brazil. His primary research focus is risk management, reliability and safety.

1 Introduction

The Brazilian Navy is planning the acquisition of a new Antarctic support vessel, with scientific equipment and systems, lifecycle management program, integrated logistical and maintenance support and a hangar to accommodate two medium-sized helicopters. Additionally, it must have a desirable autonomy of 60 to 120 days and a range of between 15 and 20 thousand nautical miles, at a speed of 12 knots (Oliveira, 2020). The new ship will be used to provide logistical support to the Antarctic Program (PROANTAR) and to collect hydrographic, oceanographic and meteorological data (Andrade et al., 2020). Consequently, the navy should structure the decision support approach to quantifying the proposals, according to specific attributes. Considering more than two alternatives for the choice, evaluated according to more than two criteria, it is possible to frame the issue using a multicriteria decision aid method, whose literature records a significant number of techniques for the solution (de Almeida, 2000; Pomerol and Barba-Romero, 2012).

The Brazilian Navy has a specific publication to address the issue of decision support (Brazil, 2015). In this field, a variety of methods are described, all based on mathematical models, involving different levels of complexity. They identify alternatives, accept those that look promising, discard the poor ones and generate an ordering of alternatives, explaining the reason for this assessment. This study proposes a new model, integrating two decision algorithms and a reference framework: the analytic hierarchy process (AHP)

(Saaty, 1980), the technique for order preference by similarity to ideal solution (TOPSIS) (Hwang and Yoon, 1981) and capability-based planning (CBP) (Taliaferro et al., 2019), respectively.

The AHP and TOPSIS are traditional models in the scientific literature of multicriteria decision aid methods. They are helpful to reduce the subjectivity of decision makers in selecting feasible and acceptable alternatives to solve the problem (Pomerol and Barba-Romero, 2012). What is more, the CBP framework shaped the hierarchical structure of AHP-TOPSIS, setting three criteria related to scenarios, weapons system capabilities and the estimated defence budget (Taliaferro et al., 2019).

The AHP-TOPSIS-CBP approach is a novelty in the literature of decision support and contributes to the acquisition management and procurement processes in the maritime industry. This model was applied using experts' preferences in a sample of polar vessels, to identify reference models for the new Antarctic support vessel. In this context, four ships capable of meeting the PROANTAR requirements were used for testing the proposed model.

2 Literature review

2.1 Logistic support to the Antarctic Program

The Antarctic Treaty came into force in 1961, establishing that signatory countries must develop scientific activities in the region, to guarantee the right to vote and veto in decision-making processes related to the Antarctic continent (Secretariat, 2012; de Aguiar, 2019; Barrett, 2020). Brazil joined the Antarctic Treaty in 1975 (Câmara et al., 2021). In December 1982, the first Brazilian Antarctic Operation (OPERANTAR) was launched, using the oceanographic support vessel 'Barão de Teffé', acquired in September 1982, and the oceanographic vessel 'Professor Besnard', from the University of São Paulo (USP) (Sampaio et al., 2017; Mata et al., 2018). In 1984, Brazil built the Antarctic station 'Comandante Ferraz' on the Keller Peninsula of King George Island, in the South Shetland Archipelago, to support scientific research in the region (Sampaio et al., 2017).

The Brazilian National Defense Policy determines that the Brazilian Navy must maintain naval assets capable of supporting the PROANTAR (Abdenur and Marcondes Neto, 2014; Sampaio et al., 2017; Medeiros and de Mattos, 2019; Andrade et al., 2020). Because of these requirements, the navy employs the polar vessel 'Almirante Maximiano' and the oceanographic support vessel 'Ary Rongel', which is in the final stage of its life cycle, to provide logistical and research support for the Antarctic continent operations (Ferreira, 2009; Alejandro Sanchez, 2019).

Supporting polar research requires a major logistical effort, using high quality equipment and infrastructure and involving the expenditure of considerable resources by the country. Modern vessels represent essential assets to leverage scientific research in the region (Bekker et al., 2019; Bernard et al., 2019; Müller and Schøyen, 2021). Throughout their life cycle, ships suffer natural wear and tear from operations under adverse conditions in the southern seas. Thus, research vessels require modernisation processes, and eventually, replacement, so that the country can continue providing support on the Antarctic continent. In this regard, the navy issued a public call to tender for the construction, in a national shipyard, of an Antarctic support vessel to replace the 'Ary Rongel' (Brazil, 2019).

The oceanographic support ship 'Ary Rongel' operates with two small helicopters and accommodates up to 27 researchers. The ship carries 2,400 m^3 of cargo and has laboratories for scientific research in the fields of meteorology, physical oceanography and biology. This vessel transports most of the supplies needed for the maintenance of the Comandante Ferraz Antarctic Station (EACF), which includes fuel, supplies, cleaning products, medicines, equipment and a variety of spare parts, among other items. On the round trip, the vessel brings back to Brazil the samples collected by the researchers and waste produced in the area (Schuch et al., 2001; de Jesús and Souza, 2007; da Costa, 2009; Câmara and Carvalho-Silva, 2020).

2.2 AHP and its applications in project selection

In general, managers rely on judgements to assess the importance of alternatives in a decision-making process, using knowledge, memory, risk analysis, cost and benefit analysis, as well as other personal preferences in reaching the final choice (de Almeida, 2000; Saaty, 2005; Larrick and Lawson, 2021). In the absence of norms or protocols that determine the use of any specific algorithm for decision making, this process is open to decision-engineering methods that facilitate, guide and reduce the subjectivity of decision makers. In this case, the AHP is attractive and methodologically consistent because the pairwise comparison is simpler and more intuitive than other complex techniques (Saaty, 1990).

The scientific literature demonstrates the use of the AHP as a useful tool for decision support in selecting projects in the most varied areas. Ali et al. (2017) explored the AHP for choosing a military aircraft for the Pakistan Air Force, with a set of ten technical and economic criteria to evaluate six alternative aircraft, with a focus on counterinsurgency and defence requirements. Sánchez-Lozano and Rodríguez (2020) also applied the AHP for criteria weighting, in the context of selecting a military training aircraft for the Spanish Air Force. Wood et al. (2020) used the AHP to select complex technology that best met the capabilities prescribed by the US Department of Defense. Stimers and Lenagala (2017) associated the AHP with a geographical information system for selecting a location for the installation of Sri Lankan army bases. Hamurcu and Eren (2020) associated the AHP with TOPSIS for the choosing of unmanned aerial vehicle projects.

Designing and building ships is a process that requires complex infrastructure, involving shipyards, ship owners, engineers, supply-chain managers, certification bodies, information systems and research institutes. Moreover, the polar environment requires specific features, so that ships can withstand harsh environmental and maritime conditions (Derkani et al., 2021). In this context, several evaluation processes are triggered in different stages and scopes, offering opportunities for the AHP. Subbaiah et al. (2016) discussed the conceptual design of an oceanographic research vessel using the network analysis process (ANP). This technique is a variant of the AHP that considers the interaction between criteria. The model was used to develop new or improved products and services to increase customer satisfaction, prioritising construction requirements for ship projects. Sahin and Kum (2015) and Şahin et al. (2014) used the AHP to analyse risk factors for sailing in the Arctic Ocean. Karahalil and Özsoy (2021) employed the AHP to study the Arctic and Antarctic sea routes relevant to the scope of the polar code, with emphasis on the extent of sea ice and differences in ice conditions in the two regions, which is so essential to the safety of ships in these regions.

Ze et al. (2006) applied the AHP to evaluate and select resources for developing a naval project, as well as to selecting shipbuilding companies, by integrating the AHP with genetic algorithms and simulation. The authors evaluated three alternatives, establishing a hierarchy of criteria and sub-criteria in a context of market competition. The criteria set included construction, development time, quality and costs. For collaborative design, they explored the credit and ability of designers, the ability to collaborate and the adaptability and experience of the designers.

In other applications in the naval sector, González-Cela et al. (2018) used the AHP for selecting designs for a combat information centre for Spanish frigates. Tompkins et al. (2018) explored the AHP for selecting radar systems for US Navy vessels. Michaeli et al. (2014) studied the integration of weapons and sensor systems in ships. Zhao et al. (2013) proposed a new ship classification model using the AHP, to obtain a better performance of ship surveillance systems using synthetic aperture radars. Cho and Choi (2012) applied the AHP to improve the quality of the Korean Navy's ship acquisition and defence system export model. Brown and Kerns (2010) conducted a case study of an offshore patrol vessel project for the US Coast Guard. The ship requirements were based on capabilities while the criteria were based on costs, risks and effectiveness.

Regarding the Antarctic environment, it is also worth pointing out the studies carried out for the selection of areas to install bases and research sites, under the Turkish program (Yavaşoğlu et al., 2019), the Chinese program (Xiaoping et al., 2014), the Colombian program (Coronado-Hernández et al., 2020) and the Brazilian program (Gavião and Vivoni, 2020).

2.3 TOPSIS: concepts and integration with AHP

TOPSIS stands for technique for order preference by similarity to ideal solution (Hwang and Yoon, 1981). It is a multicriteria decision aid technique that is widely used in various fields of knowledge. Its calculation procedure is based on the concepts of positive and negative ideal solutions, with the purpose of searching for the alternative that is closest to the former and farthest from the latter. A positive ideal solution is the one that maximises the positive impact criteria (the higher the performance, the better for that alternative) and minimises the negative impact criteria (the lower the performance, the worse for that alternative). A negative ideal solution represents the inverse of the positive ideal solution.

The integrated approach of the AHP with the TOPSIS is common in the scientific literature. In general, the AHP-TOPSIS approach explores the AHP to produce criteria and sub-criteria weightings, while the TOPSIS is used for the weighted sum of possible alternatives to meet the research objective. In this regard, Aydogan (2011) applied AHP-TOPSIS to evaluate the performance indicators of four Turkish aviation companies. The author identified five features of business performance (risk, quality, effectiveness, efficiency and occupational satisfaction) to evaluate the companies. The techniques of rough sets and fuzzy sets were also applied to increase the robustness of the results. In a case study to determine selection of the most appropriate site for the installation of a solar power generation plant in India, Sindhu et al. (2017) used the AHP combined with fuzzy-TOPSIS. To determine the most satisfactory type of ship loader for maritime transportation of solid bulk materials, Celik and Akyuz (2018) presented a method that integrated AHP-TOPSIS in a type-2 fuzzy logic environment. The approach also adopted a sensitivity analysis to investigate the impact of key performance indicators under different conditions. In summary, this application aimed to provide ship owners and port managers with practices that could reduce the cost of transportation services by optimising investment decisions.

Other authors have improved AHP-TOPSIS with the addition of new techniques. Emovon (2016) combined a hybrid method that included Delphi, AHP and TOPSIS techniques to support the decision to prioritise ship maintenance strategies. Delphi and the AHP were used to select criteria and determine their respective weightings, while the TOPSIS was applied to rank ship maintenance strategies. Kandakoglu et al. (2009) added AHP, TOPSIS and SWOT analysis to support the decision-making process of ship-owners in the shipping industry. The SWOT matrix was used to structure the decision hierarchy, based on the main evaluation factors in the shipping registry, the AHP measured the relative importance of the criteria and the TOPSIS ranked the alternatives.

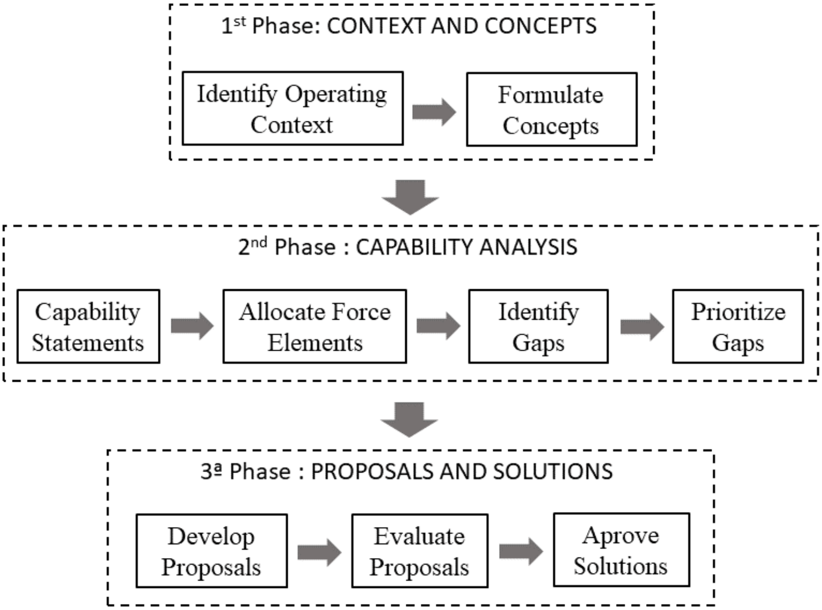
2.4 Fundamentals of CBP

By the end of the Cold War, the conventional approach of armed forces to strategic planning against predictable threats gave way to capability planning. This approach was due to the advent of threats characterised by uncertainties in general, unconventional techniques and tactics, fluidity of time and space in combat and the use of ‘digital age’ tools, among other diverse and complex features. CBP is useful to deal with these new threats, offering a different perspective from threat-based planning (Troxell, 2001; Hamilton, 2004; Pietrasz, 2018; Sayler, 2020).

As the security challenges confronting armed forces became more diverse, the challenge of justifying and defending the defence budget became much more difficult (Taliaferro et al., 2019). According to Davis (2002), CBP “is planning, under uncertainty, to provide capabilities suitable for a wide range of modern-day challenges and circumstances, while working within an economic framework that necessitates choice.” The objective of CBP is “to develop a flexible, adaptable, robust and sustainable (i.e.: technically manageable and financially affordable) force structure postured to address all the challenges associated with a given nations’ strategic defense and security environment, considering budgets and uncertainty” (Taliaferro et al., 2019).

Taliaferro et al. (2019) proposed a CBP model in three analytical phases, as illustrated in Figure 1. Phase 1 identifies the operational context and the challenges it will present to effective defence operations and to developing concepts that satisfy the success criteria in the given scenarios. Inputs to determining the operational context include the major mission areas of the armed forces, potential scenarios and any other policy guidance that obligates or restricts the actions of the armed forces. Phase 2 analyses each scenario and its corresponding concepts and identifies specific capabilities required to implement each concept. Then, existing force elements are allocated to each capability and the force structure is analysed to identify capability gaps. Finally, the gaps are prioritised and provided to the authorities for approval. Phase 3 evaluates and analyses the prioritised capability gaps approved at the end of Phase 2 for further study and the developing of solutions to close or mitigate those gaps. Approved solutions, depending on their nature, may be referred to the defence enterprise’s budget or acquisition process. Alternatively, the solution may require the armed forces to develop a new doctrine or to reorganise their force elements. Complex solutions may require all of the above.

Figure 1 Phases of CBP process



Source: Taliaferro et al. (2019)

The CBP phases comprise a useful theoretical framework to support the research challenge. These phases were adapted to three decision support criteria, serving as a reference for the evaluation of the sample of Antarctic support vessels. Thus, the AHP-TOPSIS model evaluated four ships under the criteria 'context', 'capacities' and 'costs'.

3 Materials and methods

The research involved several phases (Table 1), which list the research questions and the specific objectives initially raised, along with the steps and calculation procedures performed.

3.1 Sampling the vessels

In the first phase, polar research vessels were surveyed in the scientific literature (Table 2), as possible references for choosing the ship to be built or acquired by the Brazilian Navy, in replacement of the NApOc 'Ary Rongel'.

The navy's request for information has confidentiality restrictions. Only consortia interested in participating in the bidding process had access to the full requirements. However, press releases mentioned certain judgement criteria, indicating the vessel's capabilities. Therefore, the sample for this research prioritised ships endowed with capabilities that approximate the characteristics that were ostensibly published by the navy. In some cases, a vessel has a certain criterion identical to the navy's requirement, but it differs in other respects.

Table 1 Research design

Research challenge			
Model the preference of OPERANTAR experts to identify a reference ship for the new Antarctic support vessel for the Brazilian Navy.			
Questions	*Objectives*	*Phases*	
Can the hybrid model AHP-TOPSIS-CBP offer a consistent approach to support the multi-criteria decision to guide the acquisition process of naval assets by the Brazilian Navy?	Survey and list the polar vessels selected for the study and their capabilities.	1	Search for models of polar research ships (sample)
	Describe the hierarchical structure of criteria and sub-criteria for the ordering of selected polar research vessels.	2	Establish the hierarchical structure of the problem (variables)
What order of preference among surveyed vessels can be established, based on the choice of Brazilian Navy experts?	Based on the answers to the questionnaires, calculate and analyae the results using AHP-TOPSIS-CBP.	3	Selection of experts
		4	Questionnaires and data collection
		5	AHP algorithm and procedures
		6	TOPSIS algorithm and procedures
		7	Monte Carlo simulation
		8	Results and analysis

Table 2 Polar classes

Polar class	*Description*
PC 1	Year-round operation in all polar waters
PC 2	Year-round operation in moderate multi-year ice conditions
PC 3	Year-round operation in second-year ice, which may include multi-year ice inclusions
PC 4	Year-round operation in thick first-year ice, which may include old ice inclusions
PC 5	Year-round operation in medium first-year ice, which may include old ice inclusions
PC 6	Summer/autumn operation in medium first-year ice, which may include old ice inclusions
PC 7	Summer/autumn operation in thin first-year ice, which may include old ice inclusions

Source: Adapted from Deggim (2018)

Within the range of ships of interest to the study, another factor that exerted an influence was the year of construction. Although a ship has a relatively long useful life, we sought to consider only ships built within the last 15 years, giving priority to state-of-the-art resources. The ship ‘Akademik Tryoshnikov’ was built in 2009 (Frolov et al., 2019), the S.A. ‘Agulhas II’ in 2012 (Soal et al., 2015), the RRS ‘Sir David Attenborough’ in 2016 (Witze, 2016) and the RV ‘Kronprins Haakon’ in 2017 (Husum et al., 2020). New ships could be added to the analysis, but those ships have fully sufficient features to meet the needs of the Brazilian Navy in Antarctica.

Table 3 Sample of polar ships

Features	*Ship #1*	*Ship #2*	*Ship #3*	*Ship #4*
	RV Kronprins Haakon	*S.A. Agulhas II*	*Akademik Tryoshnikov*	*RRS Sir David Attenborough*
Displacement	9,000 tons	13,687 tons	16,539 tons	12,790 tons
Length	329 feet	440 feet	438 feet	423 feet
Draft	69 feet	34,6 feet	26,2 feet	36 feet
Polar class	Class polar 3	Class polar 5	Class polar 4	Class polar 4 (hull)/class polar 5 (propulsion)
Engine power	2 × 4.5 MW 2 × 3 MW	4 × Wärtsila 6L32 (4 × 3.000 kW)	3 diesel engines Wärtsilä (2 × 6,300 kW, 1 × 4,200 kW)	2 × Bergen B33:45L6A (2 × 3,600 kW) 2 × Bergen B33:45L9A (2 × 5,400 kW)
Propulsion	Diesel-electric, 2 Rolls-Royce US ARC 0.8 FP 2 Azimuth (2 × 5.5 MW), 2 bow thruster (2 × 1.1 MW)	Diesel-electric, 2 propeller shafts (2 x 4.500 kW), 2 controllable pitch propellers	2 propeller shafts (2 × 7,100 kW)	Diesel-elétrico, 2 propeller shafts 2 × 2.750 kW 2 controllable pitch propellers (5 blades)
Speed	15 knots	16 knots (maximum) 5 knots (2 engines) 2–3 knots (ice-braking)	16 knots (maximum) 2 knots (ice-breaking 3.6 ft deep)	17 knots (maximum) 13 knots (cruising speed) 3 knots (ice-breaking 3 ft deep)
Range	15,000 nautical miles	15,000 nautical miles – 14 knots	15,000 nautical miles	19,000 nautical miles – 13 knots
Autonomy	65 days of cruising speed	xxx	45 days	60 days
Crew	55 crew	45 crew	80 crew–60 scientists	28 crew–60 scientists
Flight deck and hangar	2 small/medium helos and hangar	2 x Atlas Oryx and hangar	2 × Bölkow Bo 105	2 small helos and hangar
Scientific systems and labs	Fishing sonar, fishing nets, hauling equipment, sub-bottom profiler (SBP) system for seismic surveys, magnetometer, gravity meter, rock drill (up to 80 m), water sampler, multibeam echo sounder, CTD sensors, hydroacoustic current profiler, Hugin underwater autonomous robot (UAV)	Fishing sonar, fishing nets, hauling equipment, sub-bottom profiler (SBP) system for seismic surveys, CTD sensors, hydroacoustic current profiler, water sampler	Sonar, fishing nets, hauling equipment, hydroacoustic current profiler, sub-bottom profiler (SBP) system for seismic surveys, magnetometer, CTD sensors, water sampler	Fishing sonar, fishing nets (3 × bongo), hauling equipment, sub-bottom profiler (SBP) system for seismic surveys, magnetometer, gravity meter, rock drill (System RD2 – 50 m), magnetometer, gravity meter, CTD sensors, water sampler

Source: IMR (2018), Müller (2018), SA (2020) and Zhongming et al. (2020)

Table 4 Criteria sets

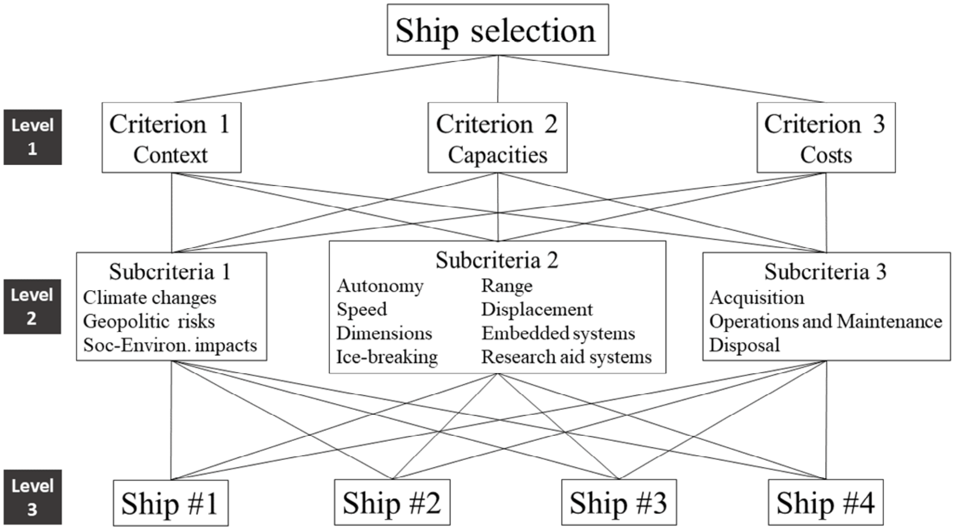
Criteria			*Sub-criteria*	*Description*	*Research design*
C1	Context	SC 1.1	Climate change	The potential for climate changes to cause irreversible damage to Antarctica's terrestrial and marine ecosystems.	Which ship best suits the different scenarios in the long-term (20 to 30 years of service)?
		SC 1.2	Geopolitical risks	The possibility of reversing the current regime of non-exploitation of mineral resources in Antarctica, which could promote disputes between nations for access to mineral, energy and water resources.	
		SC 1.3	Socio-environmental impacts	The growth of the scientific community in Antarctica, expansion of research bases and commercial activities (fishing and tourism).	
C2	Capabilities	SC 2.1	Autonomy	Maximum time and/or distance that a ship can sail without the need to restock supplies and/or fuel.	Which polar ship best attains these capabilities in the Antarctic environment?
		SC 2.2	Speed	Cruising and maximum speeds that the ship can attain.	
		SC 2.3	Displacement	Light and loaded ship displacements.	
		SC 2.4	Dimensions	Length, width and draft of the ship.	
		SC 2.5	Range	Distance the ship can sail on its total fuel capacity.	
		SC 2.6	Embedded systems	Scientific systems, technologies and equipment on board the ship.	
		SC 2.7	Icebreaking	The thickness of the ice the ship is capable of breaking.	
		SC 2.8	Research aid systems	Quantity and quality of research support laboratories, equipment and infrastructure, including hangar, flight deck and ancillary vessels.	
C3	Costs	SC 3.1	Acquisition	Direct and indirect costs of acquisition or construction.	Which ship tends to incur lower costs for the navy throughout its lifecycle?
		SC 3.2	Operations and maintenance	Direct and indirect costs of operation and ship maintenance, throughout its lifecycle.	
		SC 3.3	Disposal	Direct and indirect costs of decommissioning and demobilizing the ship and its systems.	

Source: Adapted from Bankes and Spicknall (1991), Shama (2005), Liggett et al. (2017), Saunders (2017), IMR (2018), Müller (2018), Rintoul et al. (2018), Tuan and Wei (2019), Frame (2020), Zhongming et al. (2020), SA (2020) and Müller and Schøyen (2021)

Another aspect that deserves additional explanation refers to the polar class of ships. The International Association of Classification Societies (IACS) established seven different polar class notations, ranging from PC 1 (highest) to PC 7 (lowest), with each level corresponding to the operational capability and strength of the vessel. The descriptions given in the rules are intended to guide owners, designers and administrators in selecting the appropriate polar class to match the intended voyage or service of the vessel. Ships with sufficient power and strength to undertake 'aggressive operations in ice-covered waters', such as escort and ice management operations, can be assigned an additional notation 'icebreaker'. Table 2 describes those classes.

Table 3 describes the selected polar vessels and their respective capabilities.

Figure 2 Hierarchical structure



Source: Adapted from Bankes and Spicknall (1991), Shama (2005), Liggett et al. (2017), Saunders (2017), IMR (2018), Müller (2018), Rintoul et al. (2018), Tuan and Wei (2019), Frame (2020), Zhongming et al. (2020), SA (2020) and Müller and Schøyen (2021)

3.2 *Definition of the hierarchical structure*

The second phase involves the hierarchical structuring of the situation. The first measure adopted involved breaking the situation down into a hierarchy of interrelated criteria and sub-criteria, based on the AHP and CBP, as identified in Figure 7. The chosen criteria were those proposed by Taliaferro et al. (2019), which involve the context of the challenge, the capabilities and the costs. The sub-criteria were listed on the basis of the literature review, considering the attributes raised in the scenarios forecast for the Antarctic continent (Liggett et al., 2017; Rintoul et al., 2018; Frame, 2020), the characteristics that define the capabilities of naval resources for scientific research (Saunders, 2017; IMR, 2018; Müller, 2018; SA, 2020; Zhongming et al., 2020; Müller and Schøyen, 2021) and the elements that comprise the life cycle costs of defence systems (Bankes and Spicknall, 1991; Shama, 2005; Tuan and Wei, 2019). Finally, the existing polar vessel models, with attributes resembling the operational capabilities required by the navy for the new ship, complete the hierarchical structure.

The criteria and sub-criteria are described in Table 4.

These criteria and sub-criteria were included in questionnaires directed to experts, who evaluated the variables in a pairwise manner at each hierarchical level, in relation to the higher level in the structure shown in Figure 2.

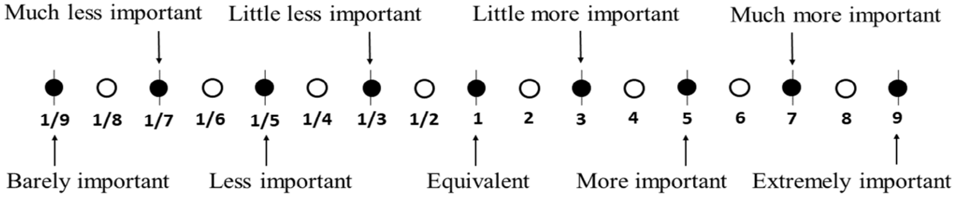
3.3 Selection of experts

The third phase selected experts for the evaluation process, considering the professional experience of navy officers obtained in OPERANTAR, preferably involving activities with Brazilian or even foreign research vessels. In view of the very specific nature of the research, involving vessels that conduct polar research, the number of experts with significant experience in the Brazilian Navy and in Antarctic projects is limited. However, preliminary research enabled the selection of 12 officers with those attributes, who contributed to the assessments as shown in Table 5. In compliance with the premise of confidentiality, the experts were identified only by numbers.

3.4 Data collection

The fourth phase involved the preparation of questionnaires and data collection from the experts selected for the survey. The design of the questionnaires was based on the data requirement for application in the AHP and TOPSIS. The questionnaire has been omitted, due to the considerable space required for its inclusion in this text, but its essential features are described here.

Figure 3 Saaty scale



Source: Adapted from Saaty (1980)

The evaluations referring to levels 1 and 2 of the hierarchical structure of the criteria and sub-criteria used the nine-point scale proposed by Saaty (1980), described in Figure 3. The scale is psychometric, with evaluations corresponding to subjective judgements, which are converted into numbers from 1/9 to 9.

This scale is used for comparative assessments between two variables. An example with three variables A, B, and C illustrates its use. Suppose that a respondent's initial choice was to evaluate Criterion B as more important than A and the same Criterion B as much less important than Criterion C. The marks of responses in the Saaty scale would be:

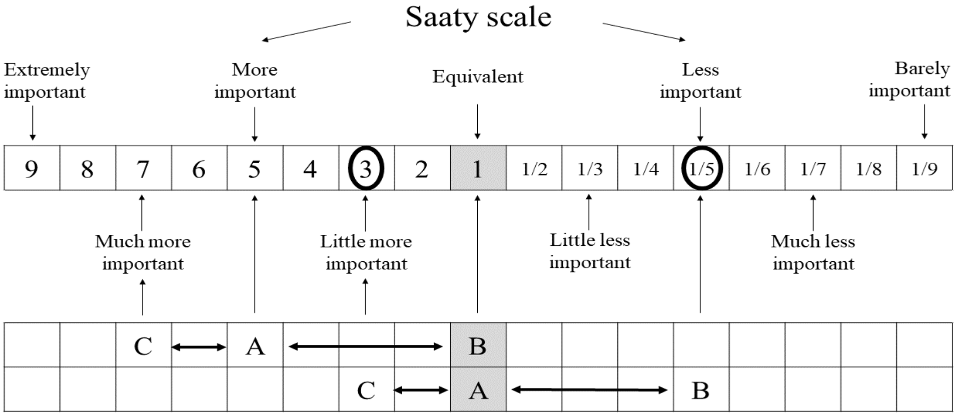
- Criterion B, in relation to Criterion A – 5
- Criterion B, in relation to Criterion C – 7.

Table 5 Experts demography

Expert	*Bachelor's degree*	*Postgraduate courses*	*Professional occupation*	*Professional experience*	*Experience in Antarctic projects*	*Experience in Antarctic ships*	*Command of Antarctic ships*	*Experience at sea (days)*
Esp 1	Naval Science – Brazilian Naval Academy	Higher Studies on National Policy and Strategy – Brazilian War College	Leadership position in the Ministry of Defense	38 years	3 years	2.5 years	2 years	+1,200
Esp 2		Higher Studies on Maritime Policy and Strategy – Naval War College	Staff officer in the Ministry of Defense	27 years	2 years	2 years	xxx	+900
Esp 3		Master's degree in Geodetic Science – Paraná Federal University	Commanding officer (Brazilian Navy)	33 years	2.5 years	2.5 years	xxx	+1,000
Esp 4		Higher Studies on Maritime Policy and Strategy – Naval War College	Staff officer in the Ministry of Defense	26 years	5 years	5 years	xxx	+1,000
Esp 5			PhD student	26 years	4 years	4 years	2 years	+1,600
Esp 6			Commanding officer (Brazilian Navy)	32 years	2 years	2 years	2 years	+1,300
Esp 7				29 years	2.3 years	2.3 years	xxx	+1,200
Esp 8				25 years	3 years	3 years	xxx	+800
Esp 9				33 years	2 years	2 years	2 years	+1,100
Esp 10			Staff officer in the Ministry of Defense	19 years	2 years	2 years	xxx	+1,200
Esp 11				30 years	2 years	2 years	xxx	+1,300
Esp 12				18 years	2.3 years	2.3 years	xxx	+1,000

In the questionnaires, the assessors had the option of choosing the variable with the greatest expertise, knowledge or experience to serve as a reference for the other pairwise evaluations. Thus, there was a need to standardise the answers for the same variable, before applying the AHP algorithms. The procedure for standardising expert assessments used the logical principle of additive transitivity, as shown by Gavião et al. (2021). This principle can be understood in a simple example. If A equals B and C, then B equals C. It is illogical for B and C to be given a different value on the Saaty scale. The use of a worksheet (Figure 4) facilitates the standardisation procedure. For instance, considering an assessment of Criterion B as more important than Criterion A (5) and much less important than Criterion C (1/7), this is equivalent to saying that Criterion A is less important than Criterion B (1/5) and slightly more important than Criterion C (3).

Figure 4 Standardisation by additive transitivity

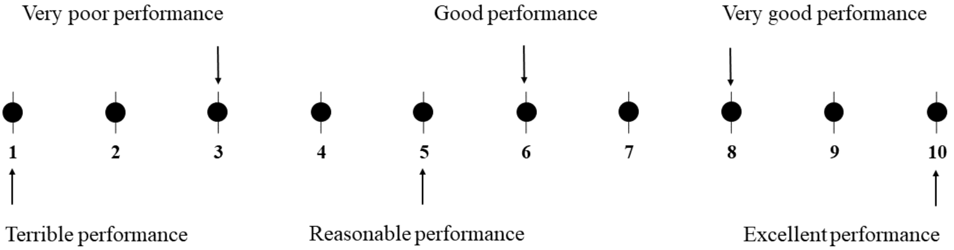


Source: Adapted from Gavião et al. (2021)

Table 6 shows the experts' evaluations, after the standardisation procedure mentioned above.

Assessments referring to level 3 (vessels) were collected for application in the TOPSIS. The psychometric assessments on the scale in Figure 5 were performed individually for each ship under each sub-criterion. Table 7 shows those expert assessments. Experts 9 and 11 did not complete their assessments of the 'costs' sub-criteria and were therefore disregarded for the TOPSIS assessments.

Figure 5 TOPSIS scale



Source: Adapted from Karahalios (2017)

Table 6 Experts' evaluations (standardised)

Level	*Reference*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E12*	*Pairwise target*
1	C 1	1	1	1	1	1	1	1	1	1	1	1	1	Crit. 1
		1/9	1/7	1/8	1/7	6	1/7	1/5	1	1/7	1/5	1/9	1/5	Crit. 2
		1/6	1/7	1/4	1	5	1/6	1/5	5	1/11	1/5	1/9	1/5	Crit. 3
2 – C1	SC 1.1	1	1	1	1	1	1	1	1	1	1	1	1	Subcrit. 1
		5	3	2	5	1/9	7	3	5	3	3	9	3	Subcrit. 2
		7	1/5	1/4	1/4	1/5	5	5	1/3	1/4	1/5	3	7	Subcrit. 3
2 – C2	SC 2.1	1	1	1	1	1	1	1	1	1	1	1	1	Subcrit. 1
		6	1	1	5	2	5	1	1	5	4	7	2	Subcrit. 2
		5	5	1/2	6	3	8	7	1	3	4	7	1/2	Subcrit. 3
		6	8	3	3	3	3	3	1	1/5	6	5	1	Subcrit. 4
		4	1	1	1	1	3	1	1/3	1	4	5	1/2	Subcrit. 5
		5	1/3	1/5	5	2	3	1	1/5	3	1/2	1/6	1/5	Subcrit. 6
		8	7	1	1/3	1	3	6	1/3	5	1/2	3	3	Subcrit. 7
		6	8	1/7	5	6	1	3	1/5	3	1	1/6	1/5	Subcrit. 8
2 – C3	SC 3.1	1	1	1	1	1	1	1	1	1	1	1	1	Subcrit. 1
		1/8	1/8	1/4	1/8	1	1/7	1/5	1/9	1/4	1/5	1/7	1	Subcrit. 2
		1	1/8	2	2	2	3	3	1/3	4	2	3	7	Subcrit. 3

Table 7 TOPSIS experts' evaluations

Criterion		*Subcriterion*		*Ship*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E12*
C1	Context	SC 1.1	Climate changes	#1	6	10	5	6.5	5	9	7.5	9	7	7	9	8
				#2	9	10	6	9.6	6	9	8.5	9	9	6	6	8
				#3	8	9	7	6.9	4	9	8	10	8	8	8	8
				#4	7	10	8	8.7	7	9	9	8	9	7	7	8
		SC 1.2	Geopolitical risks	#1	9	10	5	9.8	6	9	9	9	6	7	8	8
				#2	6	10	6	6.8	5	8	8	9	8	7	7	8
				#3	6	10	7	6.5	6	8	8	10	7	8	7	8
				#4	8	9	8	9.9	6	8	8.5	9	8	7	8	8
		SC 1.3	Socio-environmental impacts	#1	5	9	5	9.1	6	4	9	10	7	8.5	7	8
				#2	6	9	6	10	4	4	8	8	9	6	9	8
				#3	8	9	8	9	5	8	8	9	9	8	10	8
				#4	7	10	7	9.6	6	6	8.5	10	8	9	8	8
C2	Capacities	SC 2.1	Autonomy	#1	8	10	10	10	8	6	9	9	10	9	9	10
				#2	5	8	5	10	7	5	9	8	10	7	10	6
				#3	7	9	7	6.9	8	3	8	9	8	7	7	8
				#4	7	10	9	9.2	7	6	9.5	9	10	9	8	9
		SC 2.2	Speed	#1	6	9	8	8.8	7	7	7	9	8	7	7	8
				#2	7	9	9	9.4	8	7	7.5	9	9	8.5	8	9
				#3	7	9	9	9.4	8	7	7.5	9	9	8	8	9
				#4	8	8	10	10	9	8	8.5	10	10	9	9	10
		SC 2.3	Displacement	#1	6	9	7	10	8	4	7	9	7	7	7	8
				#2	7	9	9	8	8	4	8	8	9	8	9	9
				#3	8	10	10	10	7	4	8.5	10	10	9	10	10
				#4	7	9	8	9	9	4	7.5	9	9	7.5	8	9
		SC 2.4	Dimensions	#1	6	8	7	10	3	3	6.5	9	8	6	8	8
				#2	8	10	10	9	6	6	8	10	9	8	10	6
				#3	8	9	9	9.5	7	7	8.5	10	9	9	10	6
				#4	7	10	8	8	8	6	8	10	9	7	9	7

Table 7 TOPSIS experts' evaluations (continued)

Criterion		*Subcriterion*		*Ship*	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*E9*	*E10*	*E11*	*E12*
C2	Capacities	SC 2.5	Range	#1	8	10	8	9.5	7	8	9	9	9	8	9	7
				#2	8	8	9	9.5	7	8	9	9	9	8	9	7
				#3	8	9	9	9.5	7	8	8	9	9	8	9	7
				#4	9	10	10	10	6	9	9.5	10	10	9	10	8
		SC 2.6	Embedded systems	#1	9	10	10	10	8	9	9	10	9	10	9	10
				#2	7	10	7	6	7	7	8.5	8	7	6	8	8
				#3	7	10	8	6	6	7	8.5	9	8	6	8	8
				#4	8	10	9	10	8	8	9	10	9	9	9	9
		SC 2.7	Ice-breaking	#1	8	9	7	8	9	8	7.5	6	7	9	9	8
				#2	6	10	10	10	7	5	8.5	10	10	7	6	10
				#3	7	10	8	9	8	7	8	8	8	8	8	9
				#4	7	10	9	9	8	6	9	9	9	7.5	7	10
		SC 2.8	Research aid systems	#1	7	9	10	10	7	4	9	10	7	9	9	6
				#2	6	9	8	10	4	6	8	8	9	7	8	6
				#3	8	10	9	8	8	9	8	9	9	8	8	8
				#4	8	10	9	10	9	8	8.5	10	9	9	9	8
C3	Costs	SC 3.1	Acquisition	#1	5	10	7	8	4	5.5	8	9	x	6	x	7
				#2	7	10	10	9	3	5.5	8.5	10	x	8	x	8
				#3	7	10	9	10	5	5.5	9	9	x	7	x	6
				#4	6	10	8	7	5	5.5	8	9	x	6	x	7
		SC 3.2	Operations and maintenance	#1	7	9	7	2	5	4	7.5	9	x	6	x	9
				#2	7	9	10	1	4	4	9	9	x	7	x	8
				#3	7	10	9	4.5	3	4	9	8	x	7	x	8
				#4	7	9	8	3	4	4	8	9	x	6	x	7
		SC 3.3	Disposal	#1	8	9	10	8.5	3	5.5	8	8	x	7	x	6
				#2	7	9	7	5.5	3	5.5	7.5	8	x	8	x	8
				#3	7	9	8	5	3	5.5	7.5	8	x	8	x	7
				#4	8	9	9	10	3	5.5	8.5	8	x	7	x	8

3.5 AHP algorithm and procedures

The fifth phase performs the AHP calculations on the collected data. The application of the AHP requires the sequential use of equations based on linear algebra, to calculate the relative weights of the criteria and sub-criteria, in addition to the calculations of the logical consistency of the evaluations.

After completing the matrix of pairwise evaluations, described in equation (1), the sequence of equations (2) to (6) are applied in the AHP, to calculate the weightings of the criteria and sub-criteria and compute the consistency ratio (RC) of the assessments. The literature records some techniques for calculating the weightings of the AHP, but the original model is based on eigenvalues and eigenvectors of the evaluation matrices. The equations used were described in Liu and Lin (2016). RC indicates whether the expert's judgements are considered logically consistent. RC values greater than 10% are considered inconsistent, requiring a new round of expert assessments.

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{1}$$

$$w_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}} \tag{2}$$

$$A^s = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} w_1' \\ w_2' \\ \vdots \\ w_n' \end{bmatrix} \tag{3}$$

$$\lambda_{\max} = (1/n) \times \left(w_1' / w_1 + w_2' / w_2 \cdots + w_n' / w_n \right) \tag{4}$$

$$IC = \frac{\lambda_{\max} - n}{n-1} \tag{5}$$

$$RC = \frac{IC}{IR} \tag{6}$$

Notations:

A	reciprocal matrix of pairwise assessments
a_{ij}	pairwise assessment on the Saaty scale
w_i	eigenvector

$\lambda_{\max}$ maximum eigenvalue of the reciprocal matrix

IC consistency index

RC consistency ratio

IR random index, based on Table 8.

Table 8 Random indexes

Matrix order	1	2	3	4	5	6	7	8	9
Random index (IR)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

Source: Bhaskar et al. (2020)

3.6 TOPSIS algorithm and procedures

The sixth phase is the TOPSIS calculation procedures. The initial data require a decision matrix, composed of j criteria, i alternatives and evaluations of each alternative in each criterion, indicated here by x_{ij}. The scales used for decision matrix assessments are not always identical, so it is necessary to standardise them to the same scale. There are several ways to perform this standardisation, but the most common in the TOPSIS is described in equation (7), where r_{ij} represents the standardised x_{ij} values.

The decision matrix, already standardised, needs to be weighted (W), with the w_j weightings produced by the AHP or by another weighting assignment technique [equation (8)]. The ideal solution (A_b) and the anti-ideal solution (A_a) are selected according to equations (9) and (10), respectively, where J_+ represents the positive impact criteria and J_- the negative impact criteria. Then, the Euclidean distances between the evaluations of each alternative i for the ideal solution and for the anti-ideal solution are calculated, receiving the designations of D_{ib} and D_{ia} respectively, according to equations (11) and (12). Finally, the TOPSIS scores (E_i) are obtained according to equation (13), in which the highest score indicates the most preferred alternative.

$$r_{ij} = x_{ij} \Big/ \sqrt{\sum_{i=1}^{m} x_{ij}^2}\ , i = 1, 2, \ldots, m \text{ and } j = 1, 2, \ldots, n \tag{7}$$

$$W = w_j . r_{ij} \tag{8}$$

$$\begin{aligned} A_b &= \left\{ \left[\max\left(w_{ij} \mid i = 1, 2, \ldots, m \right) \mid j \in J_+ \right], \left[\min\left(w_{ij} \mid i = 1, 2, \ldots, m \right) \mid j \in J_- \right] \right\} \\ &= \left\{ \alpha_{bj} \mid j = 1, 2, \ldots, n \right\} \end{aligned} \tag{9}$$

$$\begin{aligned} A_a &= \left\{ \left[\min\left(w_{ij} \mid i = 1, 2, \ldots, m \right) \mid j \in J_+ \right], \left[\max\left(w_{ij} \mid i = 1, 2, \ldots, m \right) \mid j \in J_- \right] \right\} \\ &= \left\{ \alpha_{aij} \mid j = 1, 2, \ldots, n \right\} \end{aligned} \tag{10}$$

$$D_{ib} = \sqrt{\sum_{j=1}^{n} \left(w_{ij} - \alpha_{bj} \right)^2}\ , i = 1, 2, \ldots, m \tag{11}$$

$$D_{ia} = \sqrt{\sum_{j=1}^{n} \left(w_{ij} - \alpha_{aj} \right)^2}, \, i = 1, 2, \ldots, m \qquad (12)$$

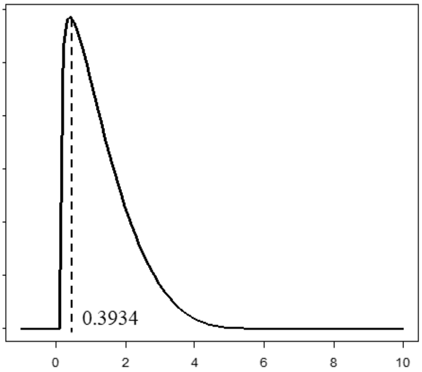
$$E_i = {D_{ia}} \Big/ {\left(D_{ia} + D_{ib} \right)}. \qquad (13)$$

3.7 Monte Carlo simulation applied to AHP and TOPSIS

In the seveth phase, a Monte Carlo simulation emulates new values at random, based on all the datasets. The study collected data from 12 experts, whose judgements were not coincident. It is natural for independent human judgements to diverge. In this study, it also occurred in the AHP and TOPSIS evaluations.

The search for convergence can take place through the aggregation of data into single values (e.g., arithmetic mean) or they can be fitted to probability distributions, for later simulation of values, retaining the same behaviour of the original dataset. In the case of samples with few data, the simulation of random values is preferable to the use of averages, to avoid distortions capable of producing unreliable results.

Figure 6 Simulation procedure (extract)

Pairwise evaluations	Parameters	Beta PERT density function
Esp.1: 5 Esp.2: 1 Esp.3: 1/2 Esp.4: 2 Esp.5: 1/3 Esp.6: 6 Esp.7: 1/5 Esp.8: 1/4 Esp.9: 4 Esp.10: 1/7 Esp.11: 1/6 Esp.12: 3	Min: 0.143 (1/7) Mode (estimative): 0.3934 Max: 6 Shape: 20	

The simulation procedure was performed from the fit of the original sample to Beta PERT distributions, which is widely used in data simulation situations (Pouillot and Delignette-Muller, 2010). These distributions require four parameters: minimum sample value, most likely value (mode), maximum value and shape, which model the kurtosis of the density function. The minimum and maximum values are easily identifiable in the dataset. The estimated mode of each sample was calculated using the ‘modeest’ package of the R statistical software (Poncet, 2019). The shape was standardised at twenty units for all samples, to generate random values closer to the estimated mode.

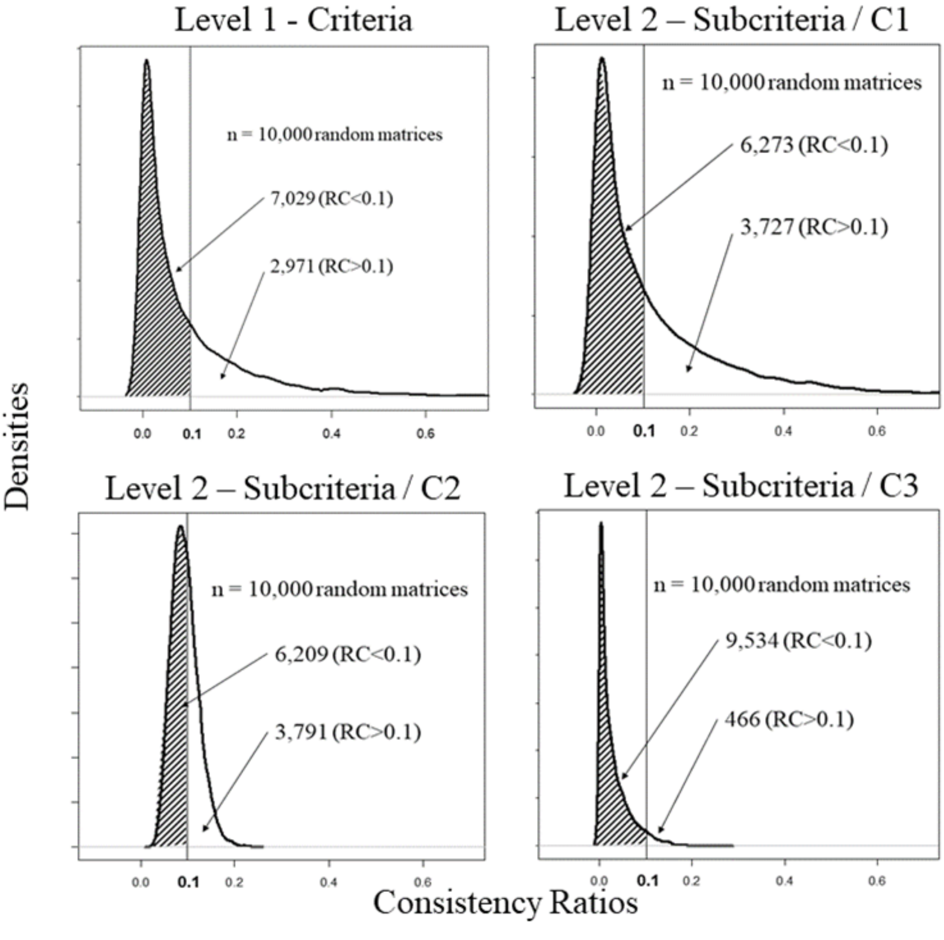
Table 9 AHP results

Decision scenarios		*Weights*													
		C1 – context			*C2 – capacities*								*C3 – costs*		
1	RC min	0.1431			0.5553								0.3016		
2	RC < 0.1 (arithmetic mean)	0.1566			0.4363								0.4071		
3	RC < 0.1 (estimated mode)	0.1565			0.4346								0.4075		
Decision scenarios		*SC 1.1*	*SC 1.2*	*SC 1.3*	*SC 2.1*	*SC 2.2*	*SC 2.3*	*SC 2.4*	*SC 2.5*	*SC 2.6*	*SC 2.7*	*SC 2.8*	*SC 3.1*	*SC 3.2*	*SC 3.3*
1	RC min	0.295	0.379	0.326	0.156	0.069	0.061	0.074	0.127	0.190	0.112	0.211	0.240	0.673	0.087
2	RC < 0.1 (mean)	0.143	0.536	0.321	0.156	0.075	0.057	0.079	0.129	0.205	0.120	0.179	0.173	0.737	0.090
3	RC < 0.1 (mode)	0.143	0.536	0.321	0.156	0.075	0.057	0.079	0.129	0.205	0.120	0.179	0.173	0.737	0.090

An instance of the simulation procedure is shown in Figure 6, for only one set of pairwise evaluations. Considering the parameters minimum = 0.143, mode = 0.3934, maximum = 6 and shape = 20, the simulation of n new values can be implemented with the 'rpert' function, in the 'mc2d' package of the R software. Equation (14) enables the generating of ten thousand random values for these indicated parameters (Pouillot and Delignette-Muller, 2010).

$$\textit{Random values} = \textit{rpert}(10000, 0.143, 0.3934, 6, 20) \tag{14}$$

Figure 7 Simulations and RC



For each set of simulated assessments, a new round of the AHP was implemented, generating the criteria and sub-criteria weightings and the logical consistency of the simulation. Results with RC < 0.1 were retained and those with RC > 0.1 were discarded. The calculations of ship preference orders considered three decision scenarios:

- Decision scenario 1: Simulation of ten thousand matrices, AHP calculations, discarding the results with RC > 0.1 and recording the generated weightings for the minimum RC.
- Decision scenario 2: Simulation of 10,000 matrices, AHP calculations, discarding the results with RC > 0.1 and calculation of the arithmetic mean of the generated weightings (only results with RC < 0.1).
- Decision scenario 3: Simulation of 10,000 matrices, AHP calculations, discarding the results with RC > 0.1 and calculation of the estimated mode of the generated weightings (only results with RC < 0.1).

Figure 7 shows the quantities of matrices that were retained, in the process for the scenario calculations, in the hatched part of the chart.

3.8 Results

In the final phase of the proposed methodology, the results of the AHP-TOPSIS were generated, which consist of the order of ship preference for the three scenarios.

Table 9 shows the results of the AHP, with a simulation of 10,000 values based on expert assessments. The lines indicate the three scenarios and the columns show the weightings obtained for the criteria and sub-criteria. Table 10 summarises the results obtained for the three scenarios, after applying the TOPSIS. There is robustness regarding the order of preference for ship #1, followed by ships #4, #3 and #2, because the three scenarios obtained the same results.

Table 10 TOPSIS results

Decision scenarios		*TOPSIS scores (arithmetic mean)*			
		Ship #1	*Ship #2*	*Ship #3*	*Ship #4*
1	RC min	0.5631890	0.4324404	0.4620787	0.5535820
	Ranking	1st	4th	3rd	2nd
2	RC < 0.1 (arithmetic mean)	0.5209212	0.4845172	0.4903763	0.5038700
	Ranking	1st	4th	3rd	2nd
3	RC < 0.1 (estimated mode)	0.5219413	0.4843358	0.4906969	0.5065956
	Ranking	1st	4th	3rd	2nd

Although ship 1 is the smallest, its preference was unanimous among the experts, even after the simulation process of 10,000 different evaluation possibilities. Some factors can justify this choice. The RV ‘Kronprins Haakon’ is the most modern vessel and its polar class 3 is the highest, providing the best operating conditions in the Antarctic environment. In addition, it has the greatest autonomy and draft, providing excellent conditions for crossing the Drake Strait, a constant challenge to be faced by the Brazilian research ships. Another issue that may have influenced the preference for RV ‘Kronprins Haakon’ is the fact that the capabilities criterion had the greatest weighting among the specialists, to the detriment of life cycle costs, as the most modern and sophisticated vessel tends to have higher production and maintenance costs.

4 Conclusions

The paper explored an actual Brazilian Navy decision-making process, recently opened for the acquisition of an Antarctic support vessel. The study proposed a hybrid model, integrating multicriteria decision support techniques with capability-based criteria. Navy experts, with experience in PROANTAR and in polar vessels expressed their preferences regarding four models of polar research vessels. This sample prioritised ships built in the last decade, from countries with a history of polar research.

The process and the results answered the two research questions:

1. Can the hybrid model AHP-TOPSIS-CBP offer a consistent approach to support the multi-criteria decision to guide the acquisition process of naval assets by the Brazilian Navy? AHP-TOPSIS guarantees the logical consistency of the experts' preferences and the hierarchical structure of capability-based criteria and sub-criteria adheres to the model of navy planning.
2. Which order of preference for surveyed vessels can be established based on the choice of Brazilian Navy experts? The order of preference confirmed the RV Kronprins Haakon (ship #1), followed by the RRS Sir David Attenborough (ship #4), Akademik Tryoshnikov (ship #3) and SA Needles II (ship #2), in all scenarios.

It is also worth noting that any model of support for multicriteria decision making is liable to the subjectivity of the experts consulted, which may have some bias in the results. To mitigate this problem, the data simulation process was used to expand the samples and reduce the effect of any partial, inconsistent, or absent assessment. Therefore, it was necessary to explore a methodological approach capable of dealing with the uncertainty inherent in the collected data.

Some limitations were encountered during the research. First, the naval vessel acquisition process is confidential, from the sending of the first formal document to countries and companies interested in selling or designing ships. As a result, the criteria and sub-criteria effectively used for the analysis of project proposals are inaccessible for academic research. However, based on consultations with experts and navy press releases, it was possible to establish a coherent set of criteria and sub-criteria to simulate the decision-making. However, it is possible to change the set of criteria and sub-criteria, including new attributes of interest to the country or research institutions. Likewise, it is also possible to increase the number of experts, with different qualifications, to compare results. Finally, other decision support methodologies can be implemented, contributing to checking the order of preference presented here.

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