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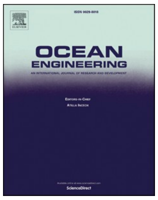

Polar research and supply vessel capabilities – An exploratory study

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ABSTRACT

Many countries engaged in polar research are commissioning polar research and supply vessels (PRSVs), inter alia, Britain's RRS *Sir David Attenborough* and Australia's RSV *Nuyina.* The prevalent climate change has placed the Arctic and Antarctic regions in the forefront of operations requiring specialist ships to support and deploy research activities. This study focuses on PRSVs and examines potential means of assessing their capabilities by identifying and gathering sources of information into a database. Further, this study presents established models of ship performance assessment in the academic literature. Links are drawn between these models, PRSV characteristics and the need for scientific capabilities and transport logistics in polar science. An adapted model is then applied to the data collected, enabling the assessment of PRSV capabilities. The assessment is based on the following key characteristics: (1) icebreaking, (2) logistics, (3) science and (4) ship size, each using attributes from the database to provide a normalised score. Data pertaining to five PRSVs are examined and the results are depicted as a radar diagram. The results show the general applicability of the model.

1. Introduction

Modern polar research vessels are launched, commissioned or planned by countries involved in polar exploration and science. Climate change has placed the Arctic and Antarctic in the forefront of research since these regions are unique for investigating past climates of the earth (Kennicutt II et al., 2019). For examples of recent extensive polar research expeditions, see the British Antarctic Survey (2015) and the multidisciplinary drifting observatory for the study of Arctic climate change (MOSAIC, 2020). As key locations for scientific operations, the polar regions require ice-strengthened vessels with cargo freight and crew capabilities for transport from mainland/home countries to remote polar research stations. PRSVs are one-off ships built by specialist shipyards. PRSVs are usually government-owned, operated and managed. Such vessels typically have a project planning duration of 5 years, building costs ranging from USD 100–400 M and average economic operational lifetime from 30 to 50 years.

A specimen of large project cargo is the German research station *Neumayer III* (Alfred-Wegener-Institut (AWI, 2020a), which was designed and fabricated in Germany. It was transported to the shelf-ice in the Antarctic by the polar research and supply vessel RV *Polarstern*, the flagship of German polar research. The combined weight of the station and facilities was 3500 tonnes (AWI, 2020a). In addition to supplying the Antarctic station with food, spares and equipment, the vessel conducts research in polar waters and operates in arctic waters during the Northern summer (AWI, 2017). This example highlights the dependency of stations and scientific projects on the maritime support deploying specialist vessels. The capability of supporting a particular station with a specific amount of supplies is a key criterion and may influence the final design of a PRSV newbuilding. Hence the starting point of this study is countries that operate permanent stations on the Antarctic continent. Fig. 1 identifies the actors on the world map.

Despite PRSV newbuilding activity and actuality across nations (Australian Antarctic Division, 2020; British Antarctic Survey, 2017; CCG, 2018; Havforskningsinstituttet, 2020; KOPRI, 2014; SANAP, 2012) the term 'Polar Research Vessel' is barely covered in the literature and similar notations are used interchangeably. The RV *Kronprins Haakon* is called 'Ice-going Research Vessel' as well as 'Polar Research Vessel' (Fincantieri S.p.A., 2017; Mikelborg, 2015). Australia's newbuilding is presented as 'Icebreaking Antarctic Supply and Research Vessel' (ASRV) (Knud E. Hansen A/S, 2017), and RV *Polarstern* is titled 'Polar Research and Supply Vessel' (BMBF, 2016; Knust, 2017). For consistency, this study refers to all types of this vessel as PRSV. The foregoing notations state the vessel's three main objectives: icebreaking, logistics supply and polar science.

Due to the actuality and planning of new PRSVs and given the lack of

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combined sources of information, this study explores and compiles a base for assessing the capabilities of current and planned PRSV. This, in turn, will facilitate defining this type of vessel and elaborate on the main characteristics. The research question is: What are the capabilities of a PRSV and how can they be assessed?

The aim of this research question is twofold, viz. to identify key characteristics of a PRSV and use these to develop a framework model based on selected criteria. This study explores and presents key capabilities of a sample of current PRSVs, as well as proposing a blueprint for evaluating PRSV design. Such a model will be an asset for present and future stakeholders involved in or considering conducting research activities in the Arctic and/or Antarctic regions. This model and data attribute explanation (see Appendix 3) can contribute to compiling an evaluation tool for 1) an ex-post evaluation of existing PRSV, 2) the planning process for future replacement and renewal of PRSVs, and 3) enabling closer cooperation and data exchange among the PRSV stakeholders.

- Polar expedition passenger vessels (tourism), military surface ships, submarines and the Russian nuclear-powered icebreaking business are excluded from this study.
- Considerations on PRSVs, plus the societal, environmental impact of their equipment resulting from building activities and end-of-life recycling are beyond the scope of this study.
- Considerations on ship intact and damage stability, cargo properties other than stowage (e.g. dangerous goods) which may be relevant when assessing ship design features, are beyond the scope of this paper.
- Not addressed are ethical considerations related to research activities on the sea floor, in the sea, on the surface, in air, land and on ice in polar areas.

The study is structured as follows: Section 2 reviews the literature on ship assessment; Section 3 presents the applied research methodology; Section 4 presents the results by gathering the data into a model and applying it to selected vessel information obtained from the research. Section 5 discusses the findings of the research and explains the constraints. The final two sections provide a conclusion as well as recommendations for further research.

2. Literature review of ship assessment

2.1. Capabilities and performance

Hafeez et al. (2002) regard capability as the ability to utilise resources to perform a task or an activity. Hence, a resource is anything tangible or intangible owned by or acquired by a firm. The capabilities are regarded as 'what the vessel is able to do' (Lu, 2007), specified in certain attributes that can be noted and are close - or equal to – resources. One example is the scientific equipment on-board a PRSV, which might be considered a resource represented by a physical sensor on-board. However, the same equipment enables the vessel to take samples from deep water (down to 11,000 m), thus it can be regarded as a capability. According to Strand (2018), capabilities refer to attributes and answerable to 'can it do something?‘, whereas performance is a result of capabilities put to use.

2.2. Sustainability assessment of marine technologies

A holistic model of the sustainability analysis of ships was presented by Cabezas-Basurko et al. (2008). Basurko and Mesbahi (2014) further developed a model of assessing marine technologies, viz. an eight-step approach including a first *Scope* step, which enables the limitation and framing of the study, showings attributes. Another example of a step included in the modelling is *Sustainability Indices*. As the results of their respective sustainability dimension modelling, these might require normalization to make them comparable with external frames such as potential legislation limits. In Section 4, Basurko and Mesbahi's model is adapted and applied to explore PRSV capability assessment, providing individual scores for the itemised ship components. Such a model also provides an option to weight priorities, enhancing flexibility.

2.3. Shipping KPI

According to Issar and Navon (2016, p. 74), "For improving operation performance, measured KPIs need to be critical, accurate and significant." BIMCO (2018) adds that they must be observable and quantifiable, sensitive to change, transparent and easy to understand as well as robust to manipulation. Wang and Hu (2016) point out that

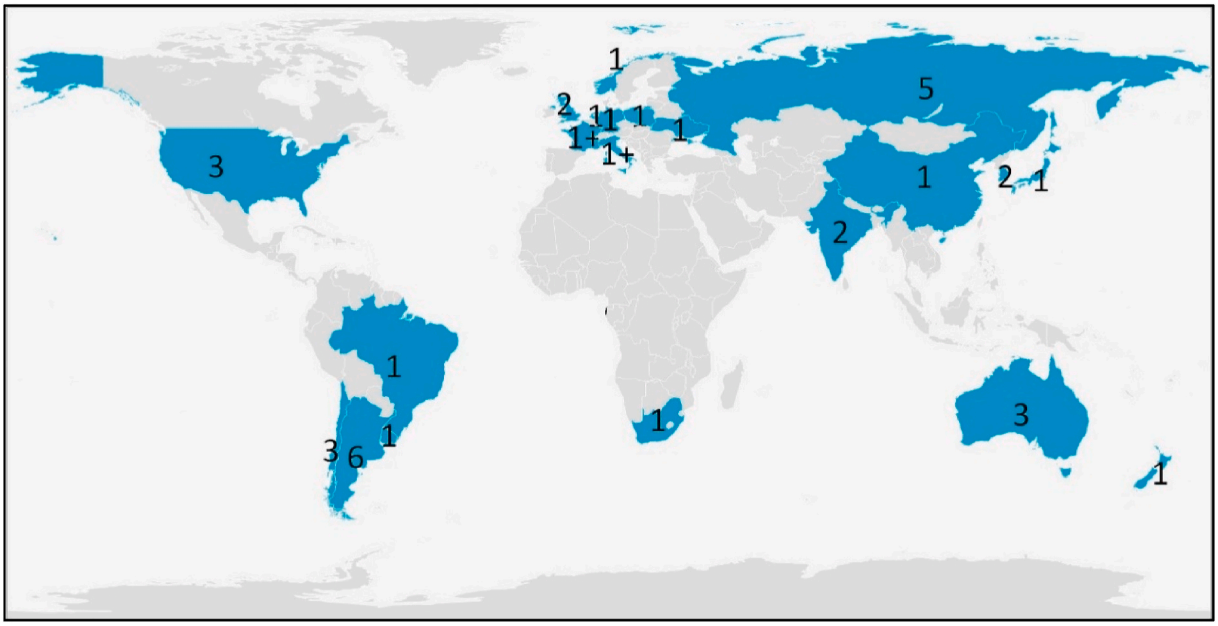

Fig. 1. Countries operating all-year Antarctic bases (number of bases). Source: COMNAP (2017). Only bases on the continent itself are included, excluding bases on islands.

having KPIs that can be benchmarked to peers is extremely valuable, and trends should be visible. These key attributes are used in the Shipping KPI system (BIMCO, 2018), see Fig. 2.

Fig. 2 shows a bottom-up KPI system designed for ship operators and relevant stakeholders. Three levels of indicators are displayed: The lowest level shows the performance indicators (PI), acting primarily as a data collector. The middle level is KPI, which combines PIs and normalises in the form of a key performance indicator (KPI). The normalization at this stage ranks from 0 to 100, with 0 being 'unacceptable' and 100 being 'outstanding performance'. One PI may be used for the calculation of multiple KPIs. The KPI rating is effectuated using a normalization formula, where KPI_{Target} is the value achieving a rating of 100 and the KPI_{MinReq} is the rating value of zero.

The top level, shipping performance indicators (SPI), provides information about overall performance (BIMCO, 2018). The final SPIs are grouped in dimensions covering the relevant activities. The focus is on the operation and excludes a life cycle approach concerning the building or the disposal (BIMCO, 2018). Duru et al. (2012) focused on the generation of the SPI using the unweighted average. Park et al. (2016) introduced the KPI method on dynamic positioning systems (DPS/DP), enabling more accurate performance measurements on vessel station keeping, and probably applicable for PRSVs as well. This study recognizes the importance of certain aspects sustainability which KPI refers to in Section 4. The next section describes the research approach, including the procedure of PRSV data collection.

3. Research methodology

To address the 'how' and 'what' research question, the adopted research strategy employs a qualitative exploratory case study technique (Yin, 2014). Data acquisition included dialogues, interviews and a survey of available primary and secondary literature (Kothari, 2003; Surbhi, 2016), combining existing findings (Brocke et al., 2009). Fig. 3 depicts the research approach.

Previous work done in this field created the starting-point of the investigation of PRSV. An extra starting-point was provided by existing scientific bases in the Antarctic that indicate which countries to focus the initial search on. A further starting-point stemmed from an overview of the major icebreakers of the world according to the United States Coast Guard featuring 127 icebreakers above 10,000 HP (USCG, 2017). This list was skimmed (Battaglia, 2008) for possible PRSVs and 16 were identified and selected for investigation, see Fig. 4.

The original information was structured and stored in an Excel database. The creation was an iterative process since information about the PRSV varied in quality and quantity. This led to decisions regarding abstraction of information. Common ground had to be established but sometimes details were omitted as similar detailed information was not obtainable for other PRSVs. This would have led to a convolution of the database and was thus avoided. A specific example of this predicament is multibeam echo sounders (MBES), which are installed on most PRSVs but vary in their operating frequencies, depth rating or data quality. Data quality from a MBES depends, among others, on installed on-board locations and possible fouling of PRSV's underwater hull. Thus, it was decided to alter the type of data from specific information to Boolean statements of 'Yes' and 'No' in many attribute categories. Comments were added in brackets where they were deemed necessary.

After identifying the scientific link to the Antarctic, the existence of databases was sought after. In particular, the European region was found to be rich in research agreements and common projects. One of these is the Eurofleets2 project, which has a vessel database linked to it (see e.g. EurOcean, 2016). It also publishes reports about the status of research vessels and their foreseeable evolution (Eurofleets2, 2014). As reports and database were closely related, cross checks on the research vessels were performed. A test on the RV *Polarstern* revealed differences in both sources. It was decided to add one more cross reference, using the operator's website for the vessel (Alfred-Wegener-Institut, 2020). An explanation or source of error about deviations between data sources cannot always be given. Although shipowners' or authorities' websites are generally less specific than both the database and the report, they are assumed to contain the most accurate information.

3.1. Database feeding

Fig. 5 depicts the process of data acquisition. The vessels were chosen in sequence, beginning with those where data was already present from the previous work (Step 1). After the selection, data sources were reviewed (Step 2). Although vessel registries contain basic information (e.g. length, draught, beam, GT), the official website of the owning or operating organisation often provided detailed aspects of the vessel. Articles about the design and fabrication were sourced from magazines and technical journals. On account of the vast amount of sources, data conflicts were discovered regularly concerning mismatches of stated values, even in basic attributes such as main dimensions. Accordingly, a hierarchy of credibility had to be established. The first tier is obtained from the vessel registries – provided data can be accessed. The second tier comprises official operator and owner websites, plus builder websites of current newbuildings. The builders of older vessels were not considered on this tier, due to possible refits in the off-season and drydocking periods. The third tier contained the remaining sources.

The collected data were compared with data from PRSV already in the list (Step 3). If there was any sufficient overlap with existing data from entries in the database, a new attribute was added (Step 4). This also included backtracking this kind of information for other vessels and finalising the data entries for the new PRSV, as well as modifying the old one with new attributes (Step 5). Due to this cross-referencing, most of the vessels were processed in sequence. At this point, only vessels with less information available remained; these were added to the, then frozen database, thus no additional attributes would be added in the database and only data matching the existing field would be accepted. The basis of the attributes covers research vessels from the United Kingdom (RRV *Sir David Attenborough*), Norway (RSV *Kronprins Haakon*), Germany (RV *Polarstern*) and Australia (RSV *Nuyina*).

3.2. Group boundary decisions

Processing these vessels' data revealed ambiguities regarding allocating certain vessels hovering between the collected data ranges of PRSV and oceanographic research vessels. The authors decided on a judgemental basis which vessels to include and exclude, based on the polar class of newbuildings. Old vessels were included due to the absence of this class before its first appearance in 2007. Vessels under polar class PC5 would be excluded from the database; this threshold value was chosen because it is the first one to classify the vessel for year-round operation in medium first-year ice, while PC6 and 7 refer only to summer/autumn operations (IACS, 2006). This resulted in the exclusion of the Peruvian newbuilding BAP *Carrasco,* which only has polar class 7 (DNV GL, 2017a). A further judgemental observation was the absence of a typical icebreaker bow, revealing the normal shape for non-ice-going ocean-sailing vessels. An additional criterion concerned the featuring of the mission and capability trinity of science, logistics and icebreaking. Accordingly, the French polar institute's vessel FNS *L'Astrolabe* was excluded since its main mission only stated defence and support (IPEV, 2017). Another boundary is given by the transition from icebreaker to PRSV. The Canadian CCGS *John G. Diefenbaker,* planned to be completed in 2029 (Berthiaume, 2020), is more powerful than most of the other PRSVs in the group, with 34 MW propulsion power and icebreaking capabilities of 2.5 m at 3 knots. The decisive feature to include it in the

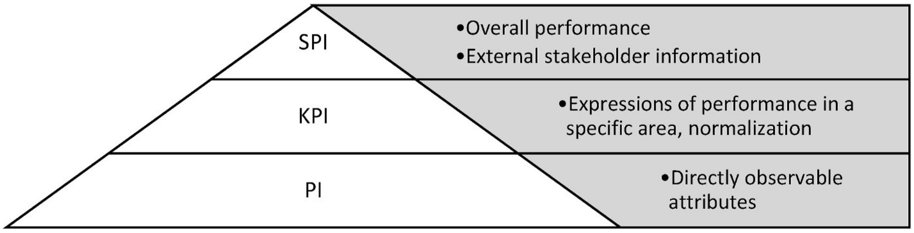

Fig. 2. BIMCO shipping KPI. Adapted from BIMCO (2018).

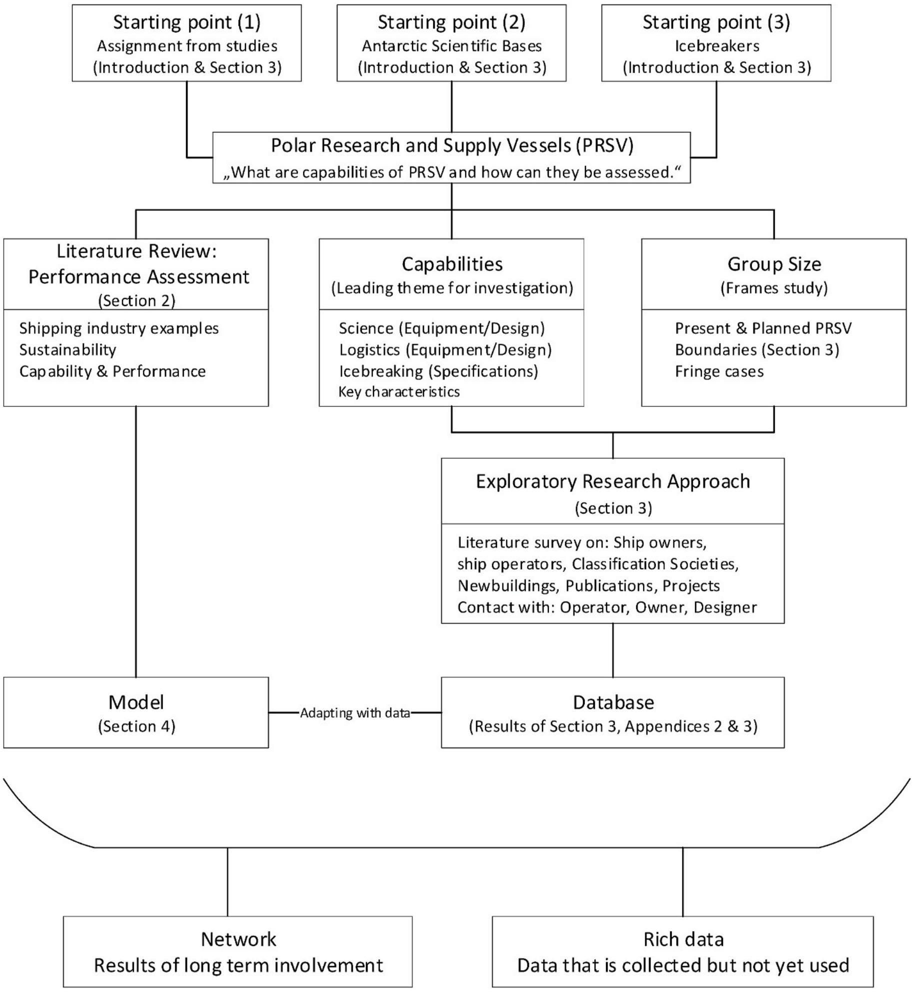

Fig. 3. Research approach. Network and rich data are beyond the scope of this study.

final list was the presence of a large moonpool for scientific instrumentation[1] and the presence of logistics facilities. Nevertheless, the capabilities of the vessel differ widely from the other considered vessels and might therefore influence the ability to apply the correct scale when assessing the capability.

3.3. Study limitations

The chosen method and procedure for data collection entail some constraints. Although much of the data were available on websites and database documents, some investigated vessels are part of the country's armed forces, thus information is classified. Additionally, major sources of information about Chinese, Japanese, Argentinian and Russian vessels were sometimes available only in their own languages. Although English translations were offered, they were often incomplete or incomprehensible. Hence the quality of the collected data constrains the conducted study. The numerous sources and often vague descriptions made it difficult to decide which source to trust, if the stated attributes conflicted with each other. A lot of the data have been collected in Boolean format, which makes the further development into quantifiable attributes challenging.

The literature was scrutinized for PRSV on-board scientific equipment and it was recognized that much of the instrumentation is portable and could be installed on a PRSV on a project basis. The database still aims to cover the main scientific areas of equipment used on PRSV.

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[1] Due to the rapid development of large autonomous underwater vehicles (AUVs) and their operation (see Table 2 and Section 5), features linked to moonpool is under reconsideration.

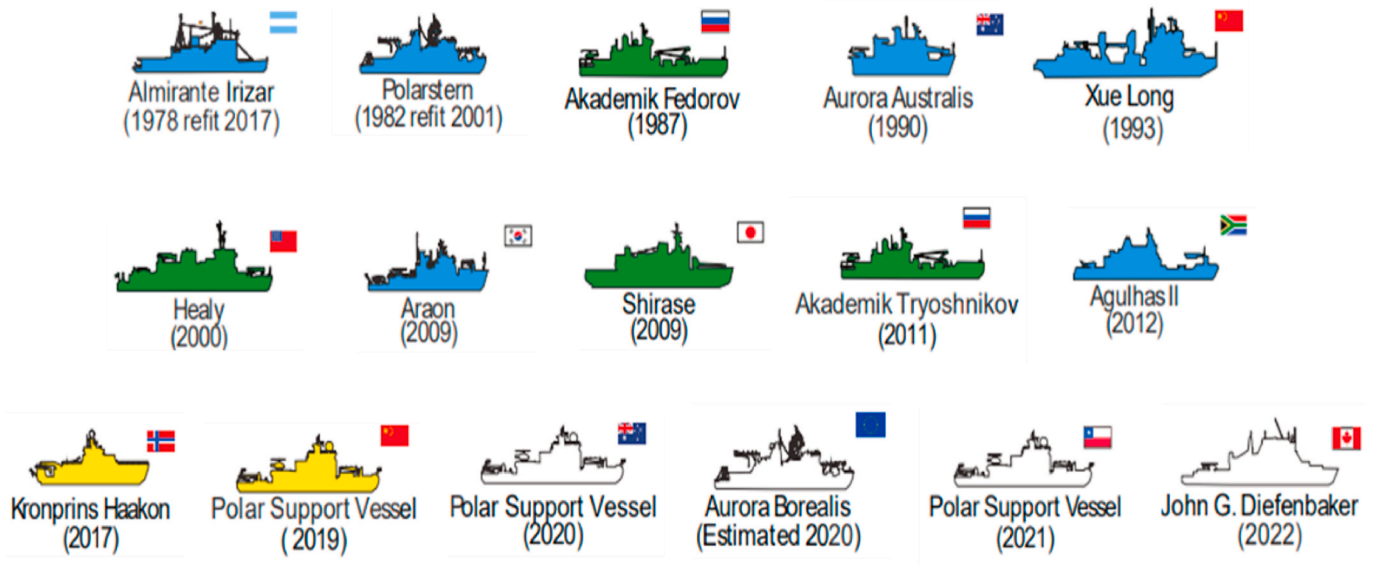

Fig. 4. Sourced from the major icebreaker chart. Adapted from USCG (2017). White: Planned, Yellow: Under construction, Blue: 10,000–20,000 HP, Green: 20, 000–45,000 HP. . (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

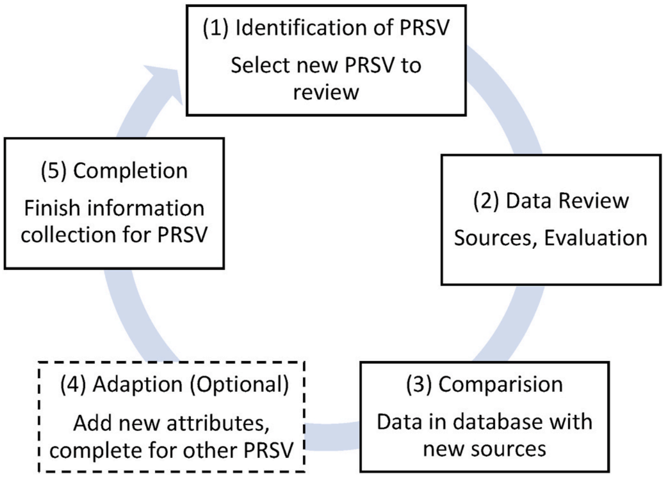

Fig. 5. Iterative work for the creation of a PRSV database.

Further refinement into permanent equipment and operational capabilities for example, linked to data accessibility and vessel communication abilities via satellites in polar areas, could have led to more nuanced results and a score (see Section 4) that better reflects the capabilities. Additionally, current trends of robotics, drones and future capabilities should be considered (Maslanik et al., 2002). Moreover, this study estimated the scientific laboratory spaces. The foregoing circumstances for scientific capabilities may have led to skewed numbers in the scientific scores, as will be discussed in Section 4. Further details of ship cranes and their arrangement, helicopters and boats were collected, but were not incorporated into logistical capabilities. Icebreaking attributes should reflect the ability of the vessels in this field, but their technical nature made consideration difficult in the scope of this study. In particular, the conversion of ice classes, referencing of external literature, allows for interpretation and may have a significant impact on the icebreaking capability score.

Summing up, in lieu of the rather modest, exploratory purpose of this study, it was decided to clean, interpret and judge the collected data according to what can be logically understood and assumed (Battaglia, 2008). Thus, the results obtained and presented in this study should be interpreted with care.

4. Results

Fig. 6 shows the countries with Antarctic scientific bases and PRSVs. The corresponding PRSVs are listed in Table 1.

Green: Antarctic scientific base and PRSV present, Green striped: Only PRSV present, Blue: Antarctic scientific base present, Orange: Base and PRSV which did not meet the Green, Green striped nor Blue criteria and are part of regular oceanographic research vessels.

18 vessels were included in the final list and used as a frame for the data collection. Based on these vessels, 57 attributes were established, see Appendices 2 and 3.

4.1. Developing an exploratory model for PRSV capabilities

The model depicted in Fig. 7 applies adapted concepts from Basurko and Mesbahi (2014) and BIMCO (2018), as presented in Section 2. The identified and established key characteristics of PRSVs are: (1) icebreaking, (2) logistics (3) science capabilities. Additionally, a fourth key characteristic, ship size, was included to reflect vessel scaling in the model. Section 4.2 details key characteristics. Societal aspects beyond ship personnel facilities (no. of personnel, see Appendix 1) were not investigated and the environmental aspects are subtly integrated with attributes and not considered separately.

Step 1 in Fig. 7 defines the scope of the assessment. The corresponding attributes (Step 2) that fit the purpose may be incorporated into the key characteristic. Next data from the database are assigned to the chosen attributes. Adjustments to the data may be necessary to allow for assessment, a step detailed in Section 4.3. Some attributes were collected as a Boolean type (e.g. is the type of equipment present or not), whereas other attributes were collected in numerical form (e.g. propulsion power and level icebreaking). Step 4 will vary slightly depending on the type of data gathered. Most of the data will be assessed using the averaging method; this is especially true for the Boolean type of data that is used in groups. Other types are calculated using the normalization method, see Shipping KPI model in Section 2, using maximum and minimum values from the PRSV to normalize the specific attributes value in relation to its group. If the key characteristics had sub-groups respective score, these are weighted according to the number of attributes corresponding to this score. Step 5, the result, is represented by three indices, each a number between 0 and 100, indicating the degree of sophistication or capability in the respective area.

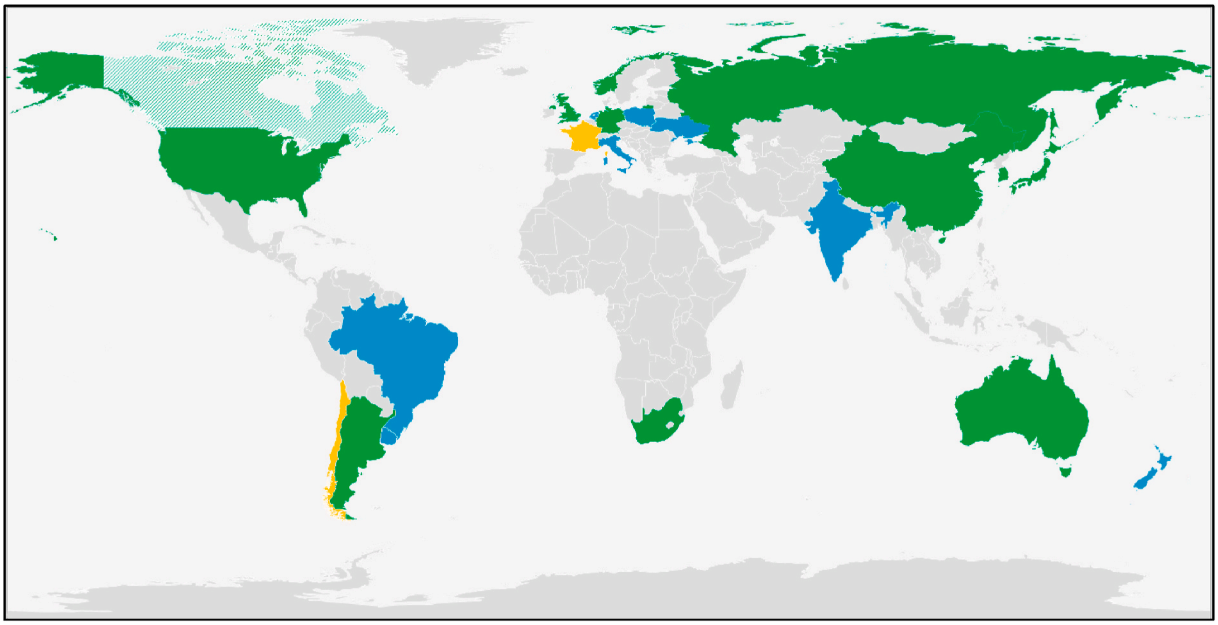

Fig. 6. PRSV results.

Table 1
List of PRSVs. Source: Author compilation.

#	Nation	PRSV ship name	Built
1	Australia	Aurora Australis	1989
2	Australia	Nuyina	2020
3	Argentina	Alimirante Irizar	1978 (Refit, 2007–2017)
4	Canada	John G Diefenbaker	~2029
5	China	Xue Long	1993
6	China	Xue Long 2	2019
7	Chile	Antárctica 1	~2021–22
8	Germany	Polarstern	1982
9	Japan	Shirase	2009
10	Norway	Kronprins Haakon	2018
11	Russia	Akademik Fedorov	2011
12	Russia	Akademik Tryoshnikov	2012
13	South Africa	S.A. Agulhas II	2012
14	South Korea	Araon	2009
15	United Kingdom	James Clark Ross	1990
16	United Kingdom	Ernest Shackleton	1995
17	United Kingdom	Sir David Attenborough	2020
18	USA	Healy	1997

4.2. *Presentation of the four key characteristics*

4.2.1. *Icebreaking capability*

This key characteristic comprises three attributes, viz. Ice class, icebreaking and propulsion power. Ice class is a numerical representation of the polar classes adapted to the group of PRSV, thus the boundaries are set by the maximum and minimum polar class or equivalent of the investigated vessels. Accordingly, the maximum value is 2 and the minimum is 6. Deciding on equivalent values is a process presented in Section 4.3. The icebreaking attribute refers to the thickness level of the ice that PRSV can break by going at a certain speed, commonly 3 knots. This often includes a snow layer on top, which has not been noted in the databases. This attribute considers the thickness of level icebreaking and does not account for the vessel speed. The propulsion power is also considered, as the polar class notation per se does not take this into consideration (Nyseth and Bertelsen, 2014). Stated values are explicitly targeted at propulsion and not at the general output of the engines. All values are normalised using the minimum and maximum values and the final score is an average of the three sub-scores.

4.2.2. *Scientific capability*

The category with the highest number of attributes, mostly aggregated in the Boolean format, contains information about scientific equipment (11 attributes, see Appendix 2) present on-board the vessel. This includes a second part, listing vessel specifics (7 attributes) such as the presence of a moonpool, dynamic positioning systems, drop keels, ROVs and AUVs. Finally, the laboratory space is evaluated by comparing the sizes (m^2). Precise information about laboratory space metrics is given in Section 4.3. The three individual scores are weighted according to their number of attributes and combined into a final score.

4.2.3. *Logistic capability*

This category has many potential attributes, but only one which delivered consistent information: the cargo hold volume, expressed in cubic metres. Additionally, a second consideration in this key characteristic is the container capacity (measured in twenty-foot equivalent unit, TEU), which is stated for some, but not all PRSVs. Additional consideration was given to extra cargo tenders, helicopter capacity, additional holds for aviation or base fuel and cranes. Generally, the information in this area lacked specificity and was discarded from calculations.

4.2.4. *Size of ship*

The model was initially concerned with the foregoing three key characteristics, but since the results lacked a way of placing them in perspective, the key characteristic ship size was added. Ideally, the gross tonnage (GT) would be a fitting reflection of most interior spaces. Unfortunately, some newbuildings (e.g. RSV *Nuyina*) did not have such information available, and substitutes had to be taken into consideration. Displacement and the main dimensions were considered (Schneekluth and Bertram, 1998). As displacement is essentially a measure of weight rather than size, it was discarded. This was also influenced by the different icebreaker design, which naturally features heavy steel plating. However, some PRSVs like the RV *Polarstern* are built with a double hull, further increasing the weight. Creating a volume by multiplication did not seem to reflect the special PRSV hull forms in an appropriate way. The final assessment method is the creation of individual scales for length, breadth and draught in a normalised way; the final score is then determined by averaging the three resulting values.

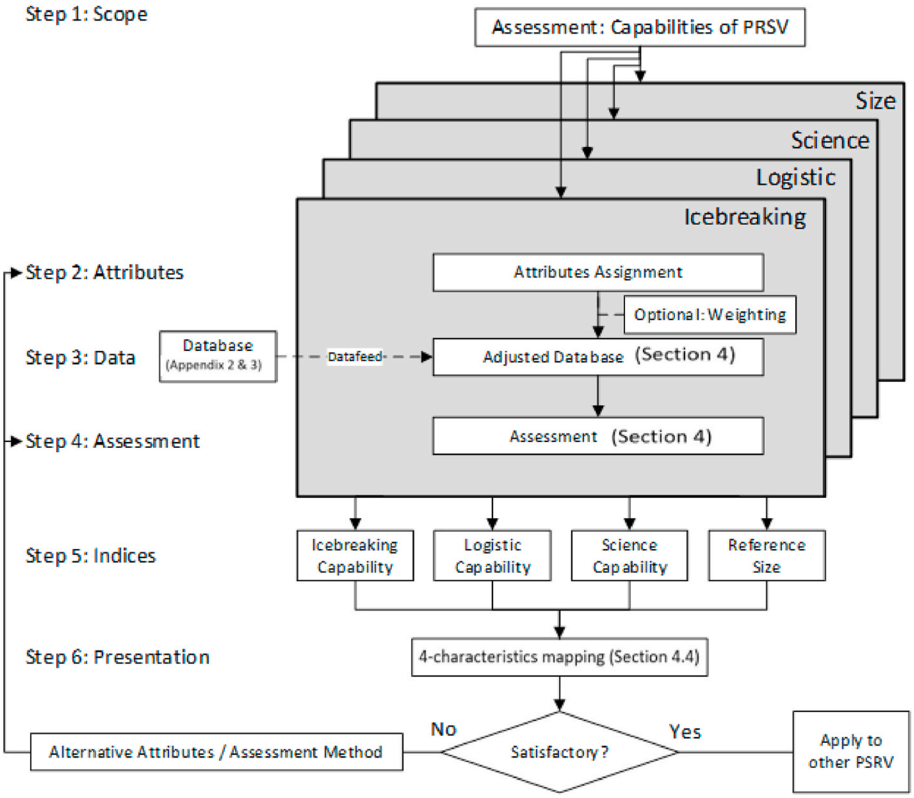

Fig. 7. Model for exploring capabilities of PRSVs. Adapted from Basurko and Mesbahi (2014) and BIMCO (2018).

4.3. *Database attribute adaption*

To use some of the attributes in the model, the values had to be made comparable. A selection of these, deemed important ones, are presented below.

4.3.1. *Laboratory spaces*

This attribute displays a large variation in detail for the investigated vessels. In some cases, only the total area is given, whereas other sources present all the laboratories on the PRSV in great detail. In rare cases, laboratories were only mentioned and neither presented nor accurately described. Space is an important criterion for research vessels and has been studied before and seen in relation with other features like deck space, ship noise or accommodation (Subbaiah et al., 2016). Consequently, the importance of the spaces is reflected in the model through the inclusion of absolute numbers. The following assumptions were established to render the information into comparable numbers:

- The size of a single laboratory is set to 20 m^2 unless otherwise expressed.
- Containerised lab spaces are calculated as 14.5 m^2 per TEU.

4.3.2. *Ice classes*

In 2007, the Polar Classes were published by the IACS to uniformize the various ice classing rules and regulations (IACS, 2006). Any direct comparison is difficult due to the varying criteria in these rules. Some classifications consider engine power, while others only focus on structural strength. The polar class was developed by experts in major ice classifications; therefore, it offers a suitable way to compare PRSVs (Daley, 2014). Comparisons of ice classes across classification societies are only possible on a case-by-case basis and should not generalised. Vessels that needed adjusting were RSV *Aurora Australis* (1AS Baltic Classes), MV *Xue Long* (1AS Baltic Classes), RRS *Ernest Shackleton* (1A1 BC), RV *Polarstern* (Arc-3 GL), *II*, *Akademik Fedorov* (Arc 7 – Russian Reg), *Akademik Tryoshnikov* (Arc 7 – RR) and IBRV *Araon (PL-10 DNV*. Vessel design and operation in both open water and ice cannot be fully covered in this study due their technical nature, see Suominen et al. (2013).

4.3.3. *Dynamic positioning*

Dynamic positioning capabilities are subject to evaluation and framing by classification societies. The IMO (1994) proposed three equipment classes based on redundancy:

- Equipment Class 1: No redundancy. Single fault can lead to loss of position.
- Equipment Class 2: Redundancy. No single fault of active components or systems will lead to positioning loss. (Components like cables, pipes, valves are allowed as causes)
- Equipment Class 3: As in Class 2, but it also must withstand fire or flooding in any compartment without system failure.

While the equipment class could be collected in a reliable manner for most vessels, the influence on the actual capabilities of the vessel is relatively scarce as they are mostly concerned with reliability instead of accuracy of position. For this reason, the detailed information in the database was reduced to a Boolean type for the assessment.

4.3.4. *Other attributes*

During the data collection, many items of information were split up with the aim of categorizing as much as possible. However, some attributes derived in this way can hardly be considered a workable definition of information. One example is biological nets and trawling gear, which were initially kept as separate entries, but since neither of the objects is fixed to a specific vessel and they are dependent on available winches, they were combined into one item in the evaluation. Similar steps were taken regarding the acoustic instrumentation, where the attribute ‘Sonar’ was deleted as it was too general.

4.4. Application of the model

This section applies the developed model from Section 4.1 to five ships with the most complete information in the database. It features the RSV *Aurora Australis*, RSV *Nuyina*, RRS *Sir David Attenborough*, RV *Polarstern* and RV *Kronprins Haakon*. The selected attributes for evaluation, with the corresponding values, are shown in Table 2.

The individual scores are combined into a matrix (Table 3) providing an overview of the capabilities of the selected PRSV. Successively, they are mapped into the four aspects and depicted in a radar diagram, see Fig. 8.

The results show a large difference in size, logistics and icebreaking, but are quite similar as regards the science capabilities. Only the RSV *Aurora Australis* ranks behind the other vessels, possibly due to her age.

5. Discussion

The approach for exploring and modelling the capabilities of PRSVs

Table 2

Adjusted database for RSV Aurora Australis, RSV Nuyina, RRS Sir David Attenborough, RV Polarstern and RV Kronprins Haakon. Source: Author compilation.

	RSV *Aurora Australis*	RSV *Nuyina*	RV *Polarstern*	RV *Kronprins Haakon*	RRS *Sir David Attenborough*		
	AUS	AUS	GER	NOR	UK		
	1989	~2020	1982	2018	2019		
SIZE						MAX	MIN
Length (m)	94.9	160.3	117.9	100.0	128.0	167.0	80.0
Length (score)	**17.1**	**92.3**	**43.6**	**23.0**	**55.2**		
Breadth (m)	20.3	25.6	25.0	21.0	24.0	28.0	17.0
Breadth (score)	**30.0**	**78.2**	**72.7**	**36.4**	**63.6**		
Draught (m)	7.9	9.3	11.2	8.5	7.0	14.4	6.4
Draught (score)	**18.3**	**36.3**	**60.0**	**26.3**	**7.5**		
Displacement (t)	8158	24,000	17,300	9000	12,790	24,000	4028
Displacement (score)	**20.7**	**100.0**	**66.5**	**24.9**	**43.9**		
GT	6574		12,614	9145	15,000	16,000	4028
Size score	**21.8**	**68.9**	**58.8**	**28.5**	**42.1**		
ICEBREAKING						MAX	MIN
Ice class	6	3	3	3	4	2	6
Ice class (score)	**0.0**	**75.0**	**75.0**	**75.0**	**50.0**		
Icebreaking	1.2	1.7	1.5	1.0	1.0	2.5	1.0
Icebreaking (score)	**15.3**	**43.3**	**33.3**	**0.0**	**0.0**		
Propulsion power (kW)	10,000	26,600	14,120	11,000	5500	34,000	5369
Propulsion power (score)	**16.2**	**74.2**	**30.6**	**19.7**	**0.5**		
Icebreaking score	**10.5**	**64.2**	**46.3**	**31.6**	**16.8**		
LOGISTIC						MAX	MIN
Cargo hold (m^3)	1790	5030	1039	1180	2200	8595	567
Cargo hold (score)	**15.2**	**55.6**	**5.9**	**7.6**	**20.3**		
TEU (cargo)	37	96	8	20		96	0
TEU (score)	**38.5**	**100.0**	**8.3**	**20.8**	0		
Logistics score	**26.9**	**77.8**	**7.1**	**14.2**	**10.2**		
	RSV *Aurora Australis*	RSV *Nuyina*	RV *Polarstern*	RV *Kronprins Haakon*	RRS *Sir David Attenborough*		
	AUS	AUS	GER	NOR	UK		
	1989	2020	1982	2018	2020		
SCIENCE						MAX	MIN
Instrumentation							
Air & aerosol sampling	Yes	Yes	Yes	Yes	Yes		
ADCP	Yes	Yes	Yes	Yes	Yes		
Fishery sonar	Yes	Yes	Yes	Yes	Yes		
Multibeam	Yes	Yes	Yes	Yes	Yes		
Sub-bottom profiler	Yes	Yes	Yes	Yes	Yes		
Nets & trawling	Yes	Yes	Yes	Yes	Yes		
Sediment corer	No	Yes	Yes	Yes	Yes		
Rock drills	No	No Info	Yes	Yes	Yes		
Seismic	No	Yes	Yes	Yes	Yes		
Magnetometer	No	No Info	Yes	Yes	Yes		
Gravimeter	No	No Info	Yes	Yes	Yes		
CTD & water sampling	Yes	Yes	Yes	Yes	Yes		
Instrumentation score	**58**	**75**	**100**	**100**	**100**		
Laboratories (m^2)	160	500	576.5	343.5	620	620	68
Laboratories (score)	**17**	**78**	**92**	**50**	**100**		
Scientific ship features							
Dynamic positioning	No	Yes	Yes	Yes	Yes		
A-Frame (Y/N)	Yes	Yes	Yes	Yes	Yes		
Drop keel (Y/N)	No	Yes	No	Yes	Yes		
Silent operation (Y/N)	No	Yes	No	Yes	Yes		
Moonpool (Y/N)	No	Yes	No	Yes	Yes		
ROV (Y/N)	No	Yes	Yes	Yes	Yes		
AUV (Y/N)	No	Yes	Yes	Yes	Yes		
Ship features score	**14**	**100**	**57**	**100**	**100**		
Science score	**40.8**	**83.9**	**82.6**	**97.5**	**100.0**		

Table 3
Resulting scores for RSV Aurora Australis, RSV Nuyina, RRS Sir David Attenborough, RV Polarstern and RV Kronprins Haakon. Source: Author compilation.

	RSV *Aurora Australis*	RSV *Nuyina*	RV *Polarstern*	RV *Kronprins Haakon*	RRS *Sir David Attenborough*
SIZE	21.8	68.9	58.8	28.5	42.1
ICEBREAKING	10.5	64.2	46.3	31.6	16.8
SCIENCE	40.8	83.9	84.6	97.5	100
LOGISTICS	26.9	77.8	32.3	14.2	10.2

was developed by adapting the insight provided by Basurko and Mesbahi (2014) and using characteristics from the Shipping KPI standard by BIMCO (2018). The result, albeit exploratory, is important because it indicates the viability of capability assessments for PRSVs. The model is built up in flexible modules of key characteristics that do not interact with each other, nor are they aggregated in a final score. Adding new key characteristics is therefore simple, as long as the underlying database supplies the necessary information. While the model copes reasonably well with past data collected in this study, there is limited ability to assess capabilities in the future. The PRSV economic lifetime may span over the next thirty years and beyond. This means that polar research and polar base supply demands that are, as yet, unknown, need to be considered and incorporated into the PRSV designs. Currently, the proposed model does not reflect these capabilities. To include such capabilities requires additional attributes to those dealt with in this study, which would naturally influence the scores of all other vessels in the group. Thus, attributes and their possible interaction must be scrutinized, also in relation to their weighting and to the importance for the scope of a PRSV.

Table 2 shows that scientific capabilities were found to be largely comparable across PRSVs. Nevertheless, current polar research pilot projects are testing new methods of scientific investigations. The Project Ocean Infinity (2018) uses multiple autonomous underwater vehicles (AUV) simultaneously, hosted by one PRSV, to multiply the area of data collection thus increasing productivity and possibly shorten expedition time. Unmanned Surface Vehicles (USV) can be used to transmit the vast amounts of data between a host PRSV and its AUVs. The scientific operation is then performed by a group of vehicles instead of a single PRSV and extensive artificial intelligence systems are used to provide autonomy to the AUVs. Interestingly, this concept could not be evaluated in this proposed model. If numerous survey capabilities are to be assessed; the attribute type AUV would have to be further developed, including reflection of how such extensive survey capability should be added to the model with the correct significant weighting.

Currently, there is no upper limit on vessels to add to the model. Possible future advanced icebreakers with large laboratory space and extensive equipment in all areas could, for example, distort the comparability of the other PRSVs in such a database since their scores would be pressed down, thus losing a lot of the ability to gain information ‘at a glance’ across PRSVs. Even the attempt to establish an upper limit, providing a frame for the group on collected data, proved much more complex for PRSVs than for many commercial shipping classes. For example, a panamax bulk carrier is stated to be between 60,000 and 75,000 tonnes deadweight, with a width restriction of 32.5 m (Stopford, 2009). To put this into perspective, the GT range of the group of PRSVs

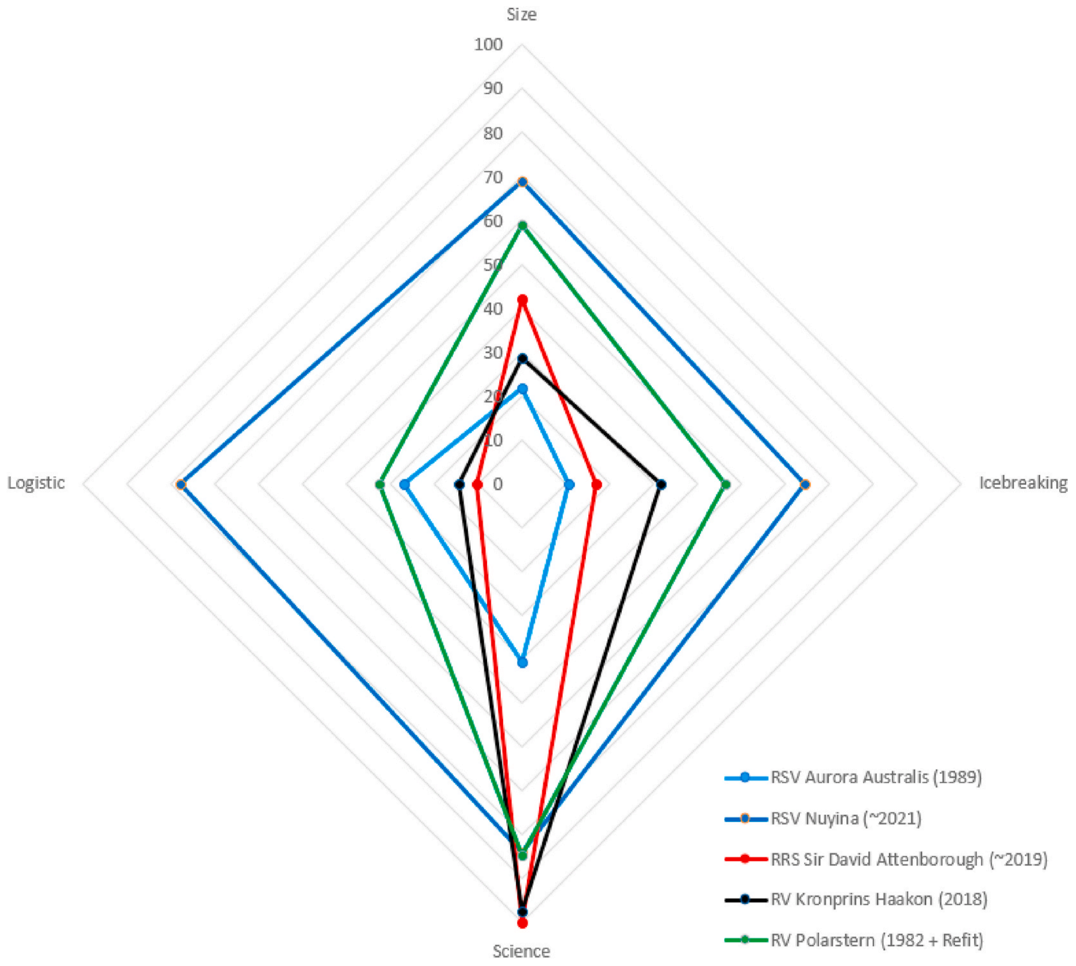

Fig. 8. Mapping of key characteristics.

considered in this study is from 4000 to 16,000, and their length varies from 80 m to 167 m. The relative differences among PRSVs are thus frequently larger and more extreme than in many other commercial shipping classes. Thus, the limits presented in this study (see Table 2) were defined with a certain elasticity and focused on creating a border to the comparatively large group of oceanographic research vessels or global research vessels (EurOcean, 2016).

A PRSV database, proposed in this study (see Appendix 2 for excerpts for **three PRSVs**) could aim at providing information about the complete group of such vessels. Current databases were found to focus on regional units or mixing them with other classes of research vessels. Unifying PRSV data into one database, established according to a common sourcing hierarchy, would provide potential users with an overall impression of the capabilities of a PRSV in question.

6. Conclusion

This study examined current and planned polar research and supply vessels. The research questions was: What are the capabilities of PRSVs and how can they be assessed? This question is explored through the development of a model, mapping the identified capabilities of size, icebreaking, science and logistics capabilities on a normalised scale and by allowing assessments within the boundaries of each capability group. The study achieved its exploratory aim and scope by providing a model, a framed group of five PRSVs and an excerpt of a database containing key characteristics of some PRSVs.

This study aimed to explore the PRSV sector, where data was found to be scattered, inconsistent and sometimes contradicting. The group of PRSVs was not framed in the literature and the sources contained data of varying quality and quantity. The assessment of capabilities of PRSVs will depend on the availability of reliable specific data. As a first step in this study, the range of such data was identified and gathered in a database. The database explanation and reference, as well as excerpts of data for three PRSVs, comprises the practical contribution of this study, providing possibilities for further development and application. The theoretical contribution of this study stems from the developed model which is adapted from the already established academic literature. and enables the basic capability assessment of PRSVs.

7. Recommendations for further research

Further research may enrich and validate the exploratory results presented. This can be achieved by considering future possibilities of science, refining the icebreaking assessment and generally increasing the number of attributes that define PRSVs. Moreover, the possibility for a viable business case for privately owned PRSVs could be explored. During data collection, the science cases of the British vessel RRS *Sir David Attenborough* indicated a need for research vessels, as the need for research platforms is currently higher than the supply (NERC, 2014). The Ocean Facilities Exchange Group (OFEG) is a barter exchange and co-operation platform for European research vessels, including France, Germany, Netherlands, Norway, Spain and the UK. OFEG features a vessel database and advances ship barter requests with ship requirement profiles. Research in this area could survey the market and propose solutions to this possible PRSV shortage. A possible enhanced, validated and transparent PRSV data base could be useful for further collaboration between PRSVs owners and managers for conducting coordinated PRSV operations and exchange of scientific data.

CRediT authorship contribution statement

Felix Müller: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition. **Halvor Schøyen:** Supervision, Methodology, Writing - original draft, Writing - review & editing, Funding acquisition, Project administration.

Declaration of competing interest

I hereby declare that there is no financial nor personal interest or belief that we consider could affect the objectivity of our study. We consider no potential conflicts to exist.

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Appendix 1. Abbreviations

BAP	Buque Armada Peruana
BAS	British Antarctic Survey
BIMCO	Baltic and International Maritime Council
CCGS	Canadian coast guard ship
DP/DPS	Dynamic positioning
GT	Gross tonnage
IACS	International Association of Classification Societies
IBRV	Ice-breaking research vessel
IHO	International Hydrographic Organisation
IMO	International Maritime Organisation
ISO	International Organisation for Standardization
KPI	Key performance indicator
MBES	Multi-beam echo sounder
PI	Performance indicator
PRSV	Polar research and supply vessel
ROV	Remotely operated vehicle
RRS	Royal research ship
RSV	Research vessel
RV	Research vessel
SPI	Shipping performance index
TEU	Twenty foot equivalent unit

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BAP	Buque Armada Peruana
UAV	Unmanned aerial vehicle
USCG	United States Coast Guard
USV	Unmanned surface vehicle

Appendix 2. Excerpts from vessel database

	Australia	Australia	Argentina
	RSV Aurora Australis	RSV Nuyina	ARA Almirante Irízar
Built	1989	2020	1978 (Refit, 2007–17)
Costs		AUD 500,000,000	
Class notation	Lloyds Register Ice Class 1 A Super Icebreaker X100A1 XLMC UMS DP(CM)	Lloyd's Register of Shipping: X100A1 Research/Supply Ship, Icebreaker (+), Ice Class PC3, *IWS, Helideck, TA3, Winterisation H(-40), D(-30), S(B), ECO (BIO, BWT, GW, NOX-2, OW, P, R, SOX, IHM, SEEMP, EnMS, IBTS), LA XLMC, UMS, DP(AA), CAC(2), PSMR* Shipright (SERS, ES, SCM)	
Operator	Australian Antarctic Division	Australian Antarctic Division	Argentinian Navy
IMO Number	8717283	9797060	7533628
Ship characteristics			
Length (m)	94.91	160.3	121.3
Breadth (m)	20.3	25.6	25
Draught (m)	7.86	9.3	9.2
Speed (Cruise)	11 kts/18t fuel p day	12 kts	
Speed (Max)	16 kts	16 kts	17.2
Icebreaking	1.23 m @ 3 kts	1.65 m @ 3 kts	1 m @ 3 kts
Ice class	1 A Super (PC6-7)	PC3	
Displacement	8158	24,000	14,899
GT	6574		10,065
DWT	3893		4600
Endurance	90 d	90 d	
Range	25,000	>16,000	
Personnel (crew)	24	32	Total 313
Personnel (project)	116	117	
Ship features			
Cranes	4 t gantry crane stern;	Bow 2 × 55 t, Side 1 × 15 t, Aft 1 × 15 t	
A-Frame	4 t	15 t	
Drop keel	No	Yes 2 x	
Dynamic positioning	“-"/DPS-0/DP (CM)	DP2/DPS-2/DP (AA)	
Silent operation	No	Yes	
Moonpool	No	Yes	
ROV	No	Yes	
AUV	No	Yes	
Laboratories (m^2)	8 labs	500 m^2 + 24 container,	415
Additional		Retractable Bow boom, Wet Well	
Propulsion			
Engine	Diesel 13,400 HP	2 x Diesel direct (19,200 kW) 2 x Electric (7400 kW)	
Propeller	1 x CPP	2 x CPP	
Propulsion power	10 MW (13,596 HP)	26,600 Kw	
Thruster bow	1 x Tunnel	3x	
Thruster stern	2 x Azimuth	3x	
Aircraft & boats			
Boat	1 x Tender	3 x Tender/1 x Science, 2 × 45 t Barges	
Helicopter	2 x M	4 x S or 2 x M	2 x M
Cargo			
Cargo hold (m^3)	1790	5030	650
TEU	37	96	
Fuel (own)		3477 t (4.09 mil l)	
Fuel (extra)	968 t (1.1 mil l)	1623 t (1.98 mil l)	
Fuel (aviation)	120 m^3	500,000 l	
Science instruments			
Air & aerosol sampling	Yes	Yes	
ADCP	Yes	Yes	
Fishery sonar	Yes	Yes	
Multibeam	Yes	Yes (11 km Range)	
Sonar	Yes	Yes	
Sub-bottom Profiler	Yes	Yes	

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	Australia	Australia	Argentina
	RSV Aurora Australis	RSV Nuyina	ARA Almirante Irízar
Nets	Yes	Yes	
Trawling gear	Yes	Yes	
Sediment corer	No	Yes (24 m)	
Rock drills	No	No Info	
Seismic	No	Yes	
Magnetometer	No	No Info	
Gravimeter	No	No info	
CTD	Yes (6,000 m)	Yes	
Water sampler	Yes (6,000 m)	Yes	

Appendix 3. Database explanation and references

Nation	Operating nation
Name	Name
Built	The year the ship was completed. There may be a difference of up to one year when it was put on a mission, depending on the Antarctic season. Dates in the future are marked with a ~ sign.
Costs	The costs of building the ship, without lifetime budget. Where information is available this is added in brackets.
Class notation	Registration type notations for classification authorities.
IMO number	Official designated IMO number, if already available (Dokkum, 2013, p. 119).
Length	Length over all (LOA) is used unless noted (Dokkum, 2013, p. 26).
Breadth	Breadth over all (BOA) is used unless noted (Dokkum, 2013, p. 28).
Draught	Maximum vertical distance between waterline and keel (Dokkum, 2013).
Speed (cruise)	Economical speed.
Speed (max)	Maximum speed.
Icebreaking	Performance stated in level of ice thickness at speed.
Ice class	Rating for operability in ice. Introduction provided by Nyseth and Bertelsen (2014).
Displacement	The weight of volume of water displaced by the ship (Dokkum, 2013, p. 30).
GT	Ships volume below main deck and all enclosed spaces above main deck (Dokkum, 2013, p. 30).
DWT	Weight the ship can load when going from lightship draught to summer load line draught. Fixed value (Dokkum, 2013, p. 30).
Endurance	Days the ship can operate without refuelling or resupplying.
Range	Range in nautical miles the ship can travel at economic speed.
Personnel (crew)	Vessel crew (Officers and Ranks).
Personnel (project)	Passengers/Scientist/Non-ship operation related persons.
Cranes	Cranes available for cargo and equipment handling.
A-frame	Special crane system usually deployed on the stern or side of the vessel. Used for ROV operations, special research, anchor handling and similar.
Drop keel	Extendable sensor platform from the keel of the vessel to increase distance from sensitive sensor to noise sources and possible air bubble streams that flow beneath the vessel.
Dynamic positioning	Unaided position keeping capabilities of vessels. Divided in classes. (IMO, 1994).
Silent operation	Ability to enable silent mode for acoustic acquisition or similar objective. Award of official notation regulated by DNV (2010).
Moon pool	Rectangular opening near the centre of gravity of the vessel. Used to conduct scientific operations while minimizing external influences or enable research in sea states where deck work is deemed too dangerous
ROV	Remotely operated vehicle used for investigation and construction projects. Can be fitted with a variety of sensors and is available in different sizes. Basic introduction in the scientific ROVs is given by Marum (2018).
AUV	Automated underwater vehicles are used for investigation along predefined routes. Different sizes and equipment. Can have extensive mapping and sensor capabilities and survey areas with ice cover that is not breakable by the PRSV (Marum, 2018).
Laboratories	No. of laboratories or space available for scientific projects on-board. If possible the area (m^2) is given.
Engine	Type of engine used.
Propeller	Type and number of propellers used (Dokkum, 2013, pp. 264–277).
Propulsion power	Power used for propulsion only (Shaft horsepower) in HP or kW.
Thruster bow	Bow thruster arrangement.
Thruster stern	Stern thruster arrangement.
Boat	Additional boats the PRSV carries e.g. crew tender, science tender or logistic barges.
Helicopter	Capability of operating and storing helicopters. Sizes given in S/M/L.
Cargo hold	Cargo capacity of the ship's hull, might be exclusive with TEU capacity.
TEU	Capacity of twenty-foot equivalent unit shipping containers. Capacity for scientific lab containers noted under laboratory space.
Fuel (own)	Vessel's own bunker capacity.
Fuel (extra)	Information about cargo fuel capacity not intended as ship fuel, for instance, as supply for Antarctic stations.
Fuel (aviation)	Information about fuel for helicopters and other aircraft stationed on the vessel or for use at Antarctic bases. The aviation fuel is Jet A1.
Extra holds	Any special arrangement that is not covered by the categories above.
Air & aerosol sampling	Atmospheric research (Australian Antarctic Division, 2020).
ADCP	Instrument to measure current speeds in the water column. Presentation given by Woods Hole Oceanographic Institution (2018a)
Fishery sonar	Mapping of the water column in different frequencies to classify fish based on air bladder size.
Multibeam	Instruments used for seafloor mapping. Versatile for other applications as well. In-depth information from L-3 Communications (2000)
Sub-bottom profiler	Instruments to investigate the upper layers of the seafloor (up to 200 m into the sediment). PRSV mostly use a special form called parametric SBP. Theory of operation presented in Wunderlich et al. (2005)
Nets & trawling gear	Ability to use nets and trawling gear, often limited by availability of cranes and winches.
Sediment corer	Instruments to sample the seafloor. Varying in lengths from a couple of cm to up to 60 m.
Rock drills	Sediment and rock drilling (Marum, 2018).
Seismic	Capabilities for operating airguns and deploying hydrophone streamers.

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Nation	Operating nation
magnetometer	Device to measure variations in the earth's magnetic field. (Woods Hole Oceanographic Institution, 2018b)
Gravimeter	Device to measure variation in the gravitational field of the earth.
CTD	Instrument to measure conductivity, temperature and water depth. Overview provided by AWI (2020b).
Water sampler	Often combined with a CTD. Recovers water sample from certain depths. Multiple sampling bottles are arranged around a frame to form a rosette.

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